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A Field Investigation into the Relationship between L_{A90} and L_{Aeq} Wind Turbine Sound Level Descriptors in New Zealand

A thesis presented in part fulfilment of the requirements for the degree of
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Majoring in
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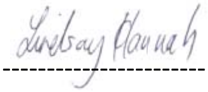
Certificate of Originality

I Lindsay John Hannah hereby state that this submission is my own work and that, to the best of my knowledge, understanding and belief, it contains no material previously published or written by another person, except where due reference, credit and full acknowledgement is made in the body of the text.



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December 2011

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Thesis Dedication

This thesis is foremost dedicated to my family, especially my late mother Elizabeth, surrogate mother Katrine, beautiful wife Michaela and daughter Sophie Elizabeth. I would also like to dedicate this thesis to my sister Alison and niece Aerin Elizabeth.

I also dedicate this thesis to everyone who has helped me with my academic studies and acoustic consulting career so far, including those mentioned beneath in the acknowledgements.

Abstract

Wind turbine generator acoustics is an issue for communities as it is people within these communities that occupy dwellings. The current New Zealand wind turbine standard NZS6808:2010 Acoustics – *Wind Farm Noise*, places priority on received sound pressure levels at dwellings remote from the wind turbine rather than from sound emission at the wind turbine generator itself.

As part of assessment under NZS6808:2010, background noise levels are required to be measured [as L_{A90}] at selected relevant receiving locations off site *before* a wind farm site can be developed. Allowable wind turbine design sound limits are then derived [as L_{Aeq}] from a comparison of the *predicted* wind turbine sound pressure levels and the *actual* measured average background noise at the nominated off site receiving location[s].

A disparity arises with the use of two different sound level descriptors used for assessment under the standard, namely the statistical L_{A90} versus the L_{Aeq} energy average sound level descriptors. In order to account for the possible variation between the L_{A90} and L_{Aeq} sound level descriptors NZS6808:2010 requires L_{Aeq} predicted sound pressure levels to be 'converted' to received L_{A90} sound pressure levels as part of the acoustic prediction process and hence NZS6808:2010 states the predicted L_{Aeq} sound pressure levels at any receiver location are to be treated as equivalent to the L_{A90} value.

At the time of commencing this study the [then] current New Zealand wind turbine standard NZS6808:1998 Acoustics – *The Assessment and Measurement of Sound from Wind Turbine Generators* stated that background noise levels were 'typically 1.5 dB to 2.5 dB' lower than the predicted L_{Aeq} sound pressure levels for wind turbine generator sound.

Unlike the current standard, NZS6808:1998 did not provide any means to account for the disparity between the background noise levels and predicted wind farm sound levels as part of the wind farm assessment process. A key implication being that under NZS6808:1998 wind turbine sound could potentially exceed the allowable 40 dBA design sound limit [or average background noise level + 5 dB] by up to a further 2.5 dB and still remain in compliance with the limits recommended under the NZS6808:1998.

The impetus and motivation behind this study has consequently been to endeavour to quantify the variability between wind turbine generator sound descriptors [L_{Aeq} and L_{A90}] both on the wind farm site and at a remote receiver dwelling location where people actually reside.

The research outcome is relevant as at the time of commencing this thesis NZS6808:1998 was being reviewed by experts and practitioners in the area of wind turbine acoustics. This review included assessing any differences in sound level descriptors.

This review provided the incentive for the thesis being particularly valuable, unique and practical so far as any actual measured field results were relative to wind turbine generators in New Zealand and the New Zealand Standards operating environment.

In order to carry out the evaluation between L_{Aeq} and L_{A90} sound level descriptors an assessment based around a semi-empirical field study of objective field measurements and subjective observations was conducted at two wind farms in the lower North Island of New Zealand. The study assessed present day, commercial class, horizontal, three bladed wind turbine generators located over heterogeneous terrain.

The principal implication of the study related to the collection of uncontaminated wind turbine sound level samples. A raw data set of 11,150 [10 minute L_{Aeq}/L_{A90} sound level samples] were collected over a 12 month period. From the total sample, merely 39 [or less than 2% of the total raw sample] were actual uncontaminated wind turbine sound samples only.

The conclusion here is that due to the high number of intervening variables it is a challenge to collect a large sample set of uncontaminated wind turbine sound data. Based on the data collected, it could potentially take several years to collect a suitable uncontaminated sample of say 1,500 [10 minute samples] from wind turbine sound only at remote locations off the wind farm site using such methods. Data collection and analysis was not an issue on the wind farm site itself due to the measurement location and wind turbine being in close proximity.

The results of the field study illustrated that based on the final data set of 10 minutes sound level sampling [n=39] the overall mean sound level difference [L_{Aeq} - L_{A90}] for wind turbine sound was 2.4 dB at a remote residential location some 1200m from the wind farm site. The overall mean sound level difference for wind turbine sound levels based on the wind farm was 1.4 dB [at the nominated R_o location].

As a result of the study's findings it is concluded that although the field data indicated a quantifiable level difference between the two sound level descriptors the current wind turbine noise standard [NZS6808:2010] rightly removes any uncertainties by stating that $L_{Aeq} = L_{A90}$ when carrying out the assessment process.

Therefore the removal of any uncertainty is chiefly due to the fact that although a quantifiable level difference between the two sound level descriptors was achieved for this study the sound level difference is prone to change and any precise or exact level difference is therefore a factor of the wind turbine generator models tested site conditions and related intervening variables.

Acknowledgements

Mr Malcolm Hunt. Director and Principal, ***Malcolm Hunt Associates Noise and Environmental Engineers***. I would like to thank Malcolm for allowing me the opportunity to complete further tertiary study. As Malcolm was on the committee for all wind turbine acoustic standards in New Zealand I would also like to thank him for assisting me with the original concept for the study. I would also like to thank Malcolm for mentoring me with university work and my consulting work in the field of acoustics. I am eternally grateful for his support over the last eleven years as an expert in the field of environmental acoustics and the support he has provided my family and I during this time as my director.

Mr Miklin Halstead. Senior Associate, ***Marshall Day Acoustics Limited***. I would like to thank Miklin for assisting me with this study in particular assistance with work relating to field equipment such as the audio field recording and taking the time to provide comment and discuss concepts around the work.

Dr Stuart McLaren - Senior Lecturer in Health Sciences and ***Dr Wyatt Page*** - Associate Professor of Acoustics and Human Health, Institute of Food Nutrition and Human Health, College of Science, ***Massey University*** [Wellington Campus].

I would like to thank both Stuart and Wyatt for their professional assistance with this work and always making themselves available to discuss the thesis. I would especially like to make mention of the support given by Stuart in terms of his holistic approach to study in terms of my consulting work, study and all important family. I would also like to thank Wyatt who came into the lead supervisor role at a very significant time and provided me with both support and guidance in the critical end stages of the thesis. Without Stuart's and Wyatt's assistance I would not have been able to complete the work to the high standard it is. I have learnt a great deal from the meetings I have had with both Stuart and Wyatt. Finally, I am eternally grateful for the long term support provided by Stuart and Wyatt while completing the thesis with a young family on a part time basis.

Mr Paul Botha. Wind Development Manager, ***Meridian Energy***. I would like to thank Paul for assisting me with sourcing the required background information regarding the all important wind data for the study sites. As Paul was on the most recent wind turbine acoustic standards committee I would like to thank Paul for taking the time to meet with me and discuss questions I had relating to the wind farm sites and the latest standard process. Without the support of Paul I would not have been able to carry out the study at the two selected sites and for this I am eternally grateful.

I would like to thank **Alison Mann** and **Michaela Hannah** for the very long periods of time spent in review and comment on the final body of work. I would like to make special mention of my wife, Michaela, who without her support I would not have been able to make literally dozens of return trips at all times of the day and night to Palmerston North and Makara to carry out the required field work.

I would like to say thank you to all the **Meridian Energy** and **Vestas staff** at the wind farm sites who helped me with the onsite logistics and allowed me to undertake onsite measurements. There are too many individuals to show individual appreciation but all were so kind and willing to help me.

I would also like to make special thanks to the occupants of 403 Makara Road who without their kind permission I could not have conducted many hours of measurements at their site.

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Chapter 1: Introduction and Purpose of the Study

Introduction

The science of acoustics describes sound by various functions including the level, frequency and duration. A sound level is commonly described alongside a related sound level descriptor [or metric] for example the time average A-weighted sound level [L_{Aeq} dB] or exceeded sound pressure level [L_{AN} dB]. The most commonly used descriptors for environmental sound assessments are the L_{A90}, L_{A10}, L_{Aeq} and $L_{Amax.}$

Any difference in sound level descriptors from wind turbine generators is a result of the statistical variability in received sound pressure levels which is a function of variations in sound output at source and in the variability induced by effects in the surrounding environment such as sound propagation.

The current New Zealand Standard for Wind Turbine Generator Acoustics, NZS6808:2010 Acoustics – *Wind Farm Noise,* requires L_{A90} background noise levels to be measured at selected relevant receiving locations *before* the wind farm is developed.

Allowable wind turbine design sound limits are then derived from a comparison of the predicted wind turbine[s] sound pressure levels [measured in terms of L_{Aeq}] and the measured average background noise level in terms of L_{A90} for each receiving location chosen. NZS6808:2010 recommends the cumulative wind turbine sound pressure level for each assessment location should not exceed L_{A90} 40 dB or the average L_{A90} background noise level + 5 dB, whichever is the greater. This was the same method adopted under NZS6808:2010 predecessor NZS6808:1998 Acoustics – *The Assessment and Measurement of Sound from Wind Turbine Generators.*

The lower centiles of sound level distributions [L_{A90}] has been chosen for the background noise level assessment as it is not entirely possible to exclude short duration sound events or environmental wind effects when using other descriptors including the L_{Aeq} sound descriptor. Hence the use of L_{A90} sound descriptor is considered by experts to be less affected for windy environs as opposed to the L_{Aeq} descriptor which is generally dominated by wind and potential transitory sound events over a reasonable measurement period. It has been shown in wind turbine acoustics that the measurement of L_{A90} is a more reliable indicator than L_{Aeq} for the assessment of background noise.

The L_{Aeq} sound descriptor is however used for the measurement and assessment of wind turbine sound *output* as per the manufacturer's warranties which are set using the L_{Aeq} sound descriptor. This is because the industry standard for wind turbine sound power levels is assessed by the use of the *International Standard IEC 61400-11: Wind Turbine Generator Systems Part 11: Acoustic Noise Measurement Techniques. Wind Turbine Sound Power Measurement Standards.* This standard is the internationally accepted standard to ensure consistent and comparable measurements of commercial wind turbine sound power levels [used to predict wind turbine sound].

The current New Zealand wind turbine acoustic standard NZS6808:2010 Acoustics – *Wind Farm Noise* took effect in 2010. The new 2010 standard now takes into account the use of two different sound level descriptors used for field measurement [L_{A90}] and future wind farm sound level predictions [L_{Aeq}] by stating that the predicted wind farm L_{Aeq} sound descriptor at any receiver location is deemed to be equivalent to the L_{A90} value. In specific ***Section C6.2.1*** of NZS6808:2010 states:

This Standard [NZS6808:2010] places priority on received sound levels at locations remote from turbines rather than emission at the turbines. For predictions based on emission values determined in accordance with IEC 61400-11, this Standard requires sound power L_{EQ} emission values to be converted to received L_{90} sound pressure levels as part of the prediction process. For the purposes of this Standard, the predicted wind farm L_{EQ} at any receiver location is deemed to be equivalent to the L_{90} value.

Therefore based on the current 2010 New Zealand Standard for wind turbine generators, it is explicit that $L_{Aeq} = L_{A90}$ [for receiving locations when comparing measured background noise to predicted expected sound levels from the wind farm].

It is understood that such a statement was included in the current standard to remove any uncertainty or possible perceived discrepancy of the actual unknown differences. This is because at the time of commencing this study the current standard being NZS6808:1998 did not specifically account for the difference in the L_{A95} and L_{Aeq} sound descriptors, other than to state that there is a range difference between the two sound level descriptors. In specific ***Section 4.2.1*** of NZS6808:1998 standard stated:

L_{95} is typically 1.5 dB – 2.5 dB lower than its L_{eq} level. It is understood the standard refers to work done in the United Kingdom by the Working Group on Noise from Wind Turbines, documented in ETSU-R-97. This work apparently showed that the L_{eq} of wind turbine noise is generally 1.5 – 2.5 dB higher than the L_{95}.

It appears from research carried out that there is narrow scientific basis provided for the comparison between the L_{eq} and L_{95} / L_{90} sound descriptors referred to in the 1998 New Zealand wind turbine standard.

The above statement from ***Section 4.2.1*** of NZS6808:1998 is not entirely clear as it is not apparent if the difference in sound descriptors referred to is on the wind turbine site itself or off site. It is however understood that the relationship between sound level descriptors explained in ***Section 4.2.1*** are based in part on measurements taken close to the wind turbine, such as at the R_o reference position recommended in IEC61400 – Part 11 which is used only to derive sound power levels of wind turbines in the near field and *not* at key receiving dwelling locations in the far field. Therefore based on the historic New Zealand Standard for wind turbine generators, it is implied for wind turbine sound measured in the near field that to get an equivalent value between the L_{Aeq} and L_{A95} descriptors that;

- $L_{Aeq} = L_{A95} + 2.5$ dB or
- $L_{A95} = L_{Aeq} - 2.5$ dB

If the stated sound level description relationships were correct, the equivalent L_{Aeq} design limit would be up to 2.5 dB above background L_{A95}. Thus, there may be a perceived discrepancy in the historic standard, as a wind farm design level which by prediction would produce a L_{Aeq} of 40 dB at a given point would actually produce an L_{A95} of 37.5 dB at this point as assessed by the compliance section of the standard.

One key implication being that wind turbine sound could *potentially* exceed the allowable 40 dBA design sound limit [or average background noise level + 5 dB] by up to a further 2.5 dB and still remain in compliance with the limits recommended under the NZS6808:1998 hence some parties believe that there was a perceived 'safety margin' between measured background noise [which set the permitted limits] and predicted sound pressure limits [which are compared to measured levels] set out in the 1998 standard.

This perceived discrepancy between L_{Aeq} and L_{A95} / L_{A90} was altered in the current 2010 standard with the L_{Aeq} at the L_{A90} values being deemed to be the same; hence a measured background noise level [measured as L_{A90}] can now be directly compared to the predicted sound pressure levels at receiver sites [specified as L_{Aeq} under *IEC 61400-11* requirements] hence removing any perceived 'safety margins' when comparing predicted levels against site specific limits.

Regardless of which standard is referenced the actual numerical relationship between L_{A90} and L_{Aeq} sound descriptors for wind turbine generators, albeit on the wind farm site, or at key off site receiving locations appears to be vague and limited in terms of both current literature. Further when the original wind turbine standard was released commercial grade wind turbine generators were much smaller with reduced electrical outputs and hence reduced sound level output, compared to modern wind turbine generators in use today.

The principal of this study is to examine the relationship between L_{A90} and L_{Aeq} sound level descriptors for both close-by reference locations [on the wind farm site at the base and *IEC 61400-11* R_o] and also assess these wind turbine sounds received at typical receiving locations remote from turbines [such as existing residential sites]. The key objective being to attempt to quantify the potential variability between wind turbine generator sound descriptors [L_{Aeq} and L_{A90}] in the typical *far field* locations where people are located and assess what the actual difference in sound pressure levels between the two sound level descriptors actually is [if any]. Whether any discrepancy would occur in practice depends on various factors including the relative temporal variations of the turbine and the background noise environment at the receiving position.

The research outcome is relevant in that at the time of commencing this research the current standard NZS6808:1998 was being reviewed by experts and practitioners in the area of wind turbine acoustics. As part of this review this included assessing the potential differences in sound level descriptors.

Although the 2010 standard was published before the conclusion of this study the proposed outcome will be to provide a description of the relationship between L_{Aeq} and L_{A90} for wind turbine sound from modern wind turbine generators which will allow for a statement on the validity of the current approach of NZS6808:2010 or offer an alternative description to this relationship depending upon the study findings.

Structure of Thesis

The thesis is set out in the following eight chapters and related appendices A to F. Only appendices A and B are included in the printed copy of the thesis. Appendices C to F are included in the attached CD.

Chapter 1: Introduction and Purpose of Study

A dialogue is set out relating to the key research question, purpose and aims of the study are presented.

Chapter 2: Wind Turbine Generator Terms and Conventions

A glossary of specific areas viewed as particularly important to provide an understanding of the topic of wind turbine generator terms and conventions is presented.

Chapter 3: Acoustic Terms and Conventions

A glossary of specific areas and overview of environmental acoustics related to wind turbine generators is presented.

Chapter 4: L_{A90} and L_{Aeq} Sound Level Descriptors in Wind Turbine Acoustics - A Literature Review

The literature study provides a comprehensive review with an aim of evaluating the most significant points of current knowledge on the research topic and provides a basis for investigative field work to be conducted.

Review of measured sound level descriptors from modern wind farm developments both locally and internationally has been carried out with the focus being on actual measured levels within New Zealand or similar operating environments.

The material studied also relates to sound production of wind turbines, types of sound produced and key assessment and measurement standards relating to wind turbine sound. Factors influencing sound beyond the wind turbine are also reviewed. Finally, key theories relating to sound production from wind turbine generators is also presented.

Chapter 5: Wind Power Generation

This chapter summarises the chief operating environment for which wind turbine generators function, the wind resource. The chapter focuses on an overview of wind evolution and development while ***Appendix A*** contains further detailed information on wind energy conversion and the science of wind power from wind turbine generators in relation to acoustics.

This chapter and related ***Appendix A*** summarises the operating modes of a modern wind turbine design and how these factors influence sound propagation from the wind turbine. Key theories relating to wind energy are also presented.

By investigating wind turbine generator acoustics the main sound sources and paths of noise from a commercial wind turbine generator were able to be assessed. Similarly by investigating the topic of wind power and wind power conversion an enhanced understanding of the environment in which wind turbine generators operate could be achieved.

Chapter 6: Aero Acoustics – Wind Turbine Generator Acoustics

This chapter summarises some basic fundamental aerodynamics relating to commercial wind turbine generators in specific rotor and blades aerodynamics while ***Appendix B*** contains further detailed information on the science of aerodynamics and acoustics from wind turbine generators.

The aerodynamics of a wind turbine is a function of the 'physical' wind turbine itself and how the individual components interact with their surrounding environment. It would not be possible to achieve an understanding of a wind turbine generator and associated acoustic measurements outputs without knowledge of the key aerodynamics characteristics.

The research into the above topic provides key information and a robust basis for investigative field works to be conducted.

Chapter 7: A Field Investigation into the Relationship Between L_{A90} and L_{Aeq} Wind Turbine Sound Level Descriptors in New Zealand

The background to the field study is summarised and discussed. A full discussion of the test methods used, including measurement procedures, test equipment, test sites and wind turbine generator types are provided for review. Analysis methods and issues with field testing are also discussed. A summary of some significant findings of the study are highlighted.

Chapter 8: Discussion

Discussions on the study's overall findings are provided. A statement relating to the difference between the wind turbine generator sound level descriptors L_{Aeq} and L_{A90} for a modern wind turbine generator in a real life environment is provided based on the measured data, field observations and test environments.

Comment on further work and the study's limitations and key assumptions are provided.

Chapter 2: Wind Turbine Generator Terms and Conventions

Introduction

The glossary below reviews specific areas namely a meta-analysis of the wind turbine generator. The summary information presented is viewed as particularly important to provide an understanding of the topic of wind turbine generators as a whole and has therefore been given additional attention.

The term 'wind turbine' is the shortened version for the accurate term 'wind turbine generator' or wind turbine power plant. The term 'wind turbine' is often used for short as is the acronym 'WTG'. A wind turbine generator produces electricity and should not be confused with a 'wind mill' or other type of device or plant which uses wind power for non-electrical production.

The function of a modern power generating wind turbine is to generate high quality, network frequency electricity. Each wind turbine must function as an automatically controlled independent "mini power station". A modern wind turbine generator is required to work unattended, with low maintenance, continuously for more than 20 years [[1]].

There are two key types of wind turbines these being either vertical or horizontal axis wind turbine generators. The latter consists of generally two or three blades connected to a hub to form the main rotor assembly and is the most common commercial type used internationally and in New Zealand.

This entire study is only concerned with commercial horizontal axis wind turbine generators, that is the wind turbine has its horizontal-axis with their main shafts parallel to the ground.

The Anatomy of a Wind Turbine Generator

The majority of modern commercial wind turbine generators in New Zealand are three-bladed horizontal axis design. **Figure 1** illustrates a front and side elevation of a modern three bladed wind turbine.

Side and Front Elevation: Wind Turbine Generator [three-bladed horizontal axis]

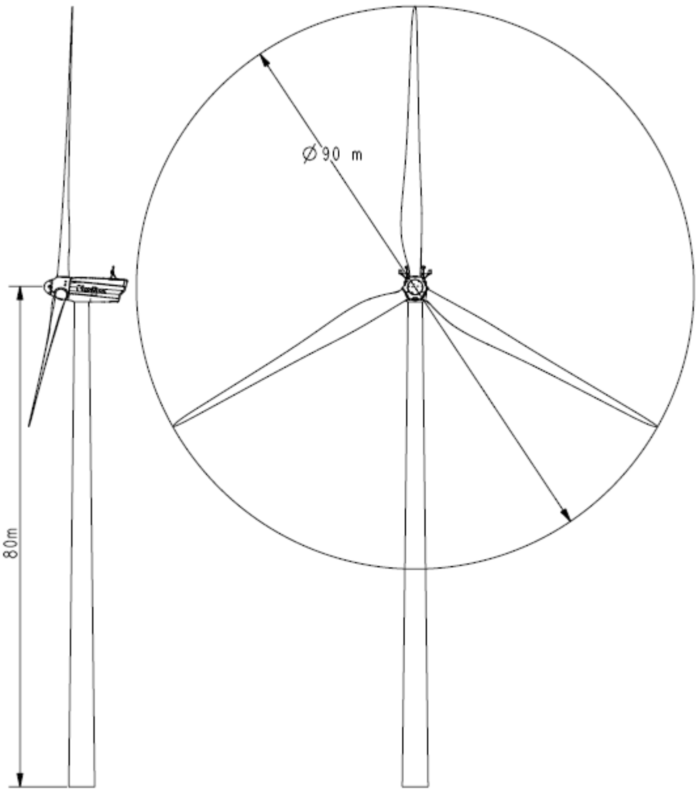


Figure 1: Front and side elevation of a three bladed horizontal wind turbine [2]

Figure 2 illustrates the configuration of a horizontal axis wind turbine generator. **Figure 3** and **Figure 4** illustrates a modern commercial three bladed horizontal wind turbine and enlargement of the rotor, hub, rotor blades and nacelle.

2D Schematic: Key Components of a Wind Turbine Generator [three-bladed horizontal axis]

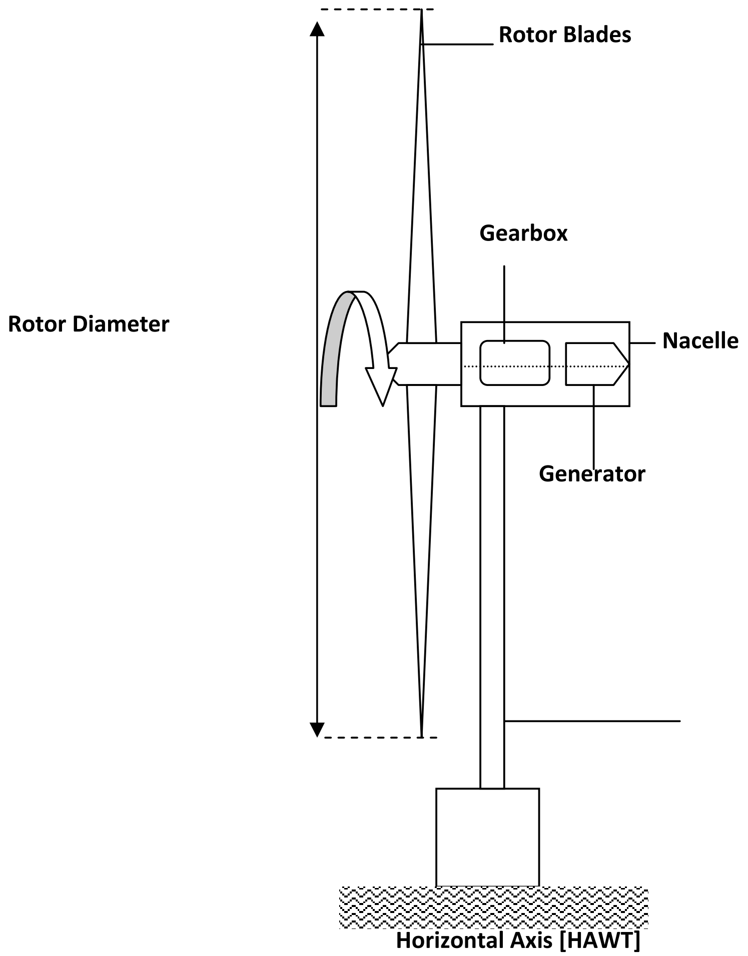


Figure 2: Simple configuration of a Horizontal wind turbine generator.

Photograph: Key Components of a Wind Turbine Generator [three-bladed horizontal axis]

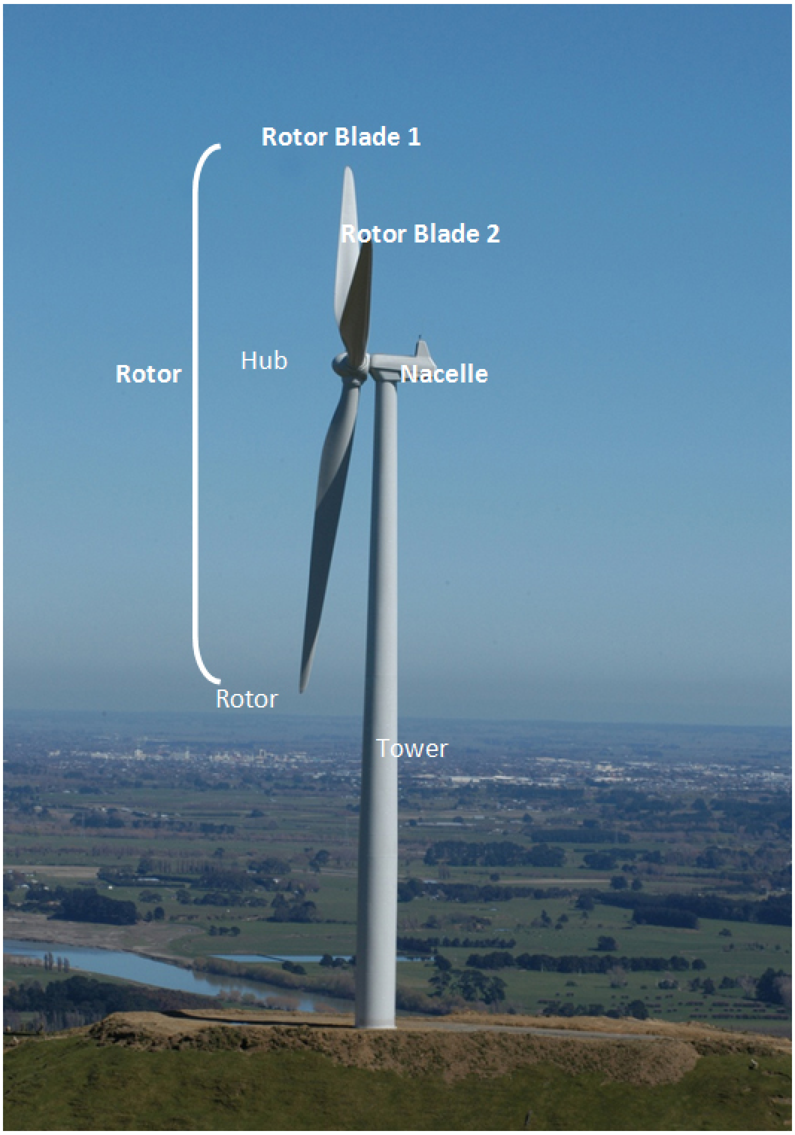


Figure 3: Photo of modern commercial three bladed horizontal wind turbine generator.

3D Schematic: Key Components of Wind Turbine Generator [three-bladed horizontal axis]

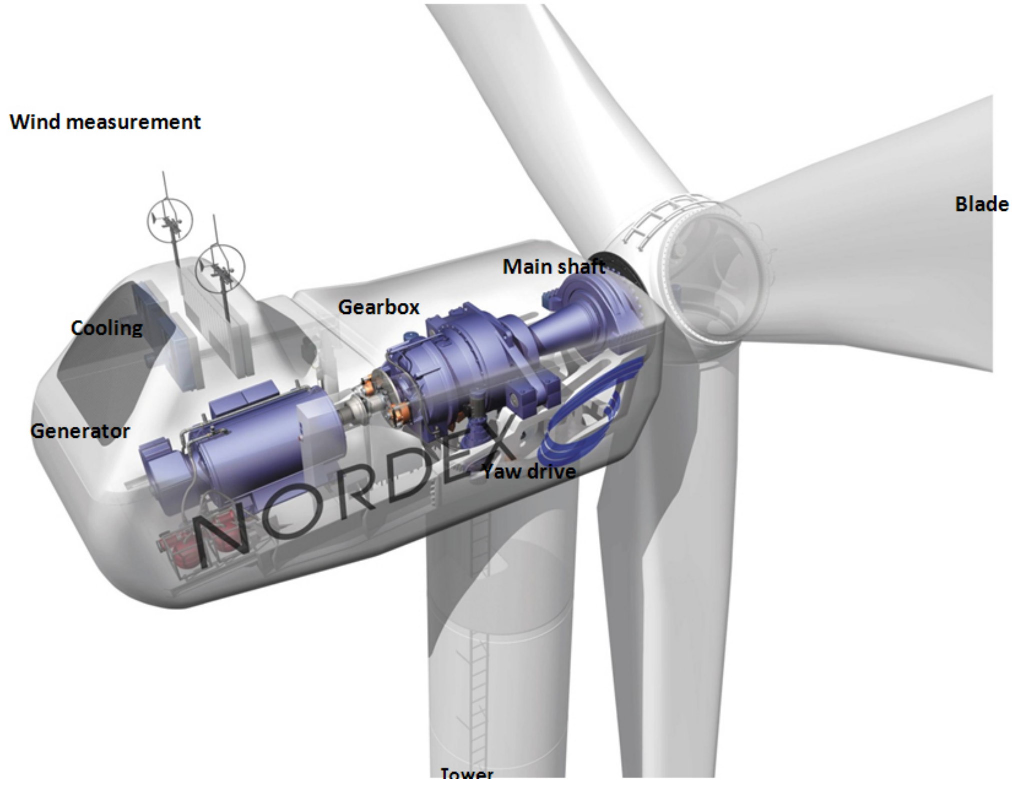


Figure 4: Modern commercial three bladed horizontal Nordex wind turbine generator – hub, rotor, blade and nacelle – Nordex WTG.

Wind Turbine Components and Concepts

The key components of a wind turbine generator are described as follows:

Mechanical Drive Train [The Transmission System]

The mechanical drive train encompasses all rotating parts from the rotor hub to the electrical generator. These components together form a functional unit and therefore should be considered collectively. **Figure 5** illustrates the mechanical drive train [[2]].

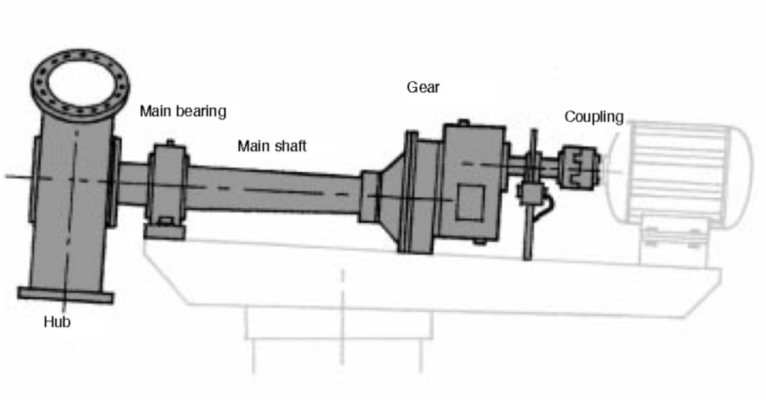


Figure 5: Mechanical drive system of a wind turbine [[2]]

There are various configurations for a drive train ranging from standard configuration of gearbox positioned 'in-line" within the nacelle to the generator being positioned in the tower base. Various issues can arise regarding sound with different configurations. One example is the WEC-500 wind turbine generator. This turbine built in 1982 had the generator in the tower base and despite care being taken in both design and construction the turbines long transmission shaft tended to oscillate. Furthermore the sound developed by the rotor which was designed to run at a very high speed was not acceptable in terms of sound emissions and placed stress on the turbines plant [[3]].

Nacelle

The nacelle is the system of machinery enclosed in the top of the turbine including the gear box, main shaft and generator. The nacelle usually sits on a support structure called the "pallet" which is connected to the tower of the wind turbine generator.

The nacelle will rotate on the tower top so that the rotor always points into the prevailing wind [the motion of moving into the wind is called 'yawing']. Most modern turbines are designed to face the prevailing wind and this is called an 'upwind' facing wind turbine generator, as opposed to one which is downwind and has the rotor facing downwind and away from the prevailing wind direction.

Each individual wind turbine constantly monitors the wind direction and will yaw so as always to face into the wind in order to maximise the energy production and minimise the loads on the structure.

Rotor

The rotor extracts kinetic energy from the wind flowing through it. Rotor control is achieved either by aerodynamic stall or by changing the pitch [angle] of the rotor blades. The rotor has differing numbers of rotor blades [also referred to as 'rotor aerofoil's' or just 'blades']. Most modern commercial machines have three rotor blades.

Rotor Blades / Blades / Rotor Aerofoil's

The rotor blades are connected to the rotor shaft by a hub [nose]. Wind turbine rotor blades are generally manufactured from glass fibre reinforced polyester resins or pre-impregnated glass reinforced epoxy resin. The blade system usually comprises of an aerodynamic shell bonded to a spar. On larger blades a carbon fibre reinforcement which adds strength while reducing weight is used. Studs are embedded in the blade root for attachment to the rotor hub.

Typically blades can rotate through 90° on the hub. This movement allows the blade pitch angle to be set between 90°, at shut down, and 0° at start-up. The pitching of the blades allows optimum power production at low wind speeds and limits the output at high wind speeds. The pitching also allows the turbine to be shut-down, and acts as an aerodynamic brake.

Shaft

The wind turbine shaft is connected to the centre of the rotor. When the rotor rotates [spins/turns], the shaft rotates [spins] as well. In this way, the rotor transfers its mechanical, rotational energy to the shaft, which enters an electrical generator on the other end and creates electrical energy.

Tower

The tower is the upright structure which connects to the ground and also supports the nacelle. Modern wind turbines use vertical tubular steel towers typically tapering from 3 m to 4 m diameter at ground level to 2.0 m to 2.5 m diameter at the nacelle. A modern 3 MW wind turbine generator with a rotor diameter of say 90 m could utilise a range of tower heights from 60 m to 120 m [+] depending on site and design factors.

Electrical System

The electrical system of a wind turbine includes all the parts of the turbine which convert mechanical energy into electrical power as well as electrical auxiliaries.

Gearbox

The main drive train on a wind turbine is the gearbox. The gearbox is designed to increase the low speed, high torque of the rotor to the high speed, low torque of the electrical generator. Gearboxes can be multi-stage helical, planetary, or hybrid designs. In terms of acoustic emissions direct drive machines are much quieter than machines with a gearbox as they tend to produce less mechanical or tonal noise.

Transformer System

Most wind turbines generate at industry standard 3 phase voltages. Connection to the electricity grid for export of the power is generally made at 33,000 volts [33 kV] depending on the total power output of the wind farm. Depending on the wind farm electrical design, voltage transformers may be installed in the nacelle, the tower base, a separate enclosure adjacent to the tower, or the wind farm export substation.

Electrical Generator System

The generator produces electricity and is connected to the turbine through a gearbox. Selection of generator type for any particular turbine depends on the operating characteristics of the turbine itself, i.e. fixed speed or variable speed. There are four common technologies used

1] Asynchronous – Induction Generator;
2] Asynchronous – Double Fed Induction Generator [DFIG];
3] Synchronous – Unsynchronised;
4] Synchronous – Synchronised generator.

Figure 6 illustrates the four common electrical systems.

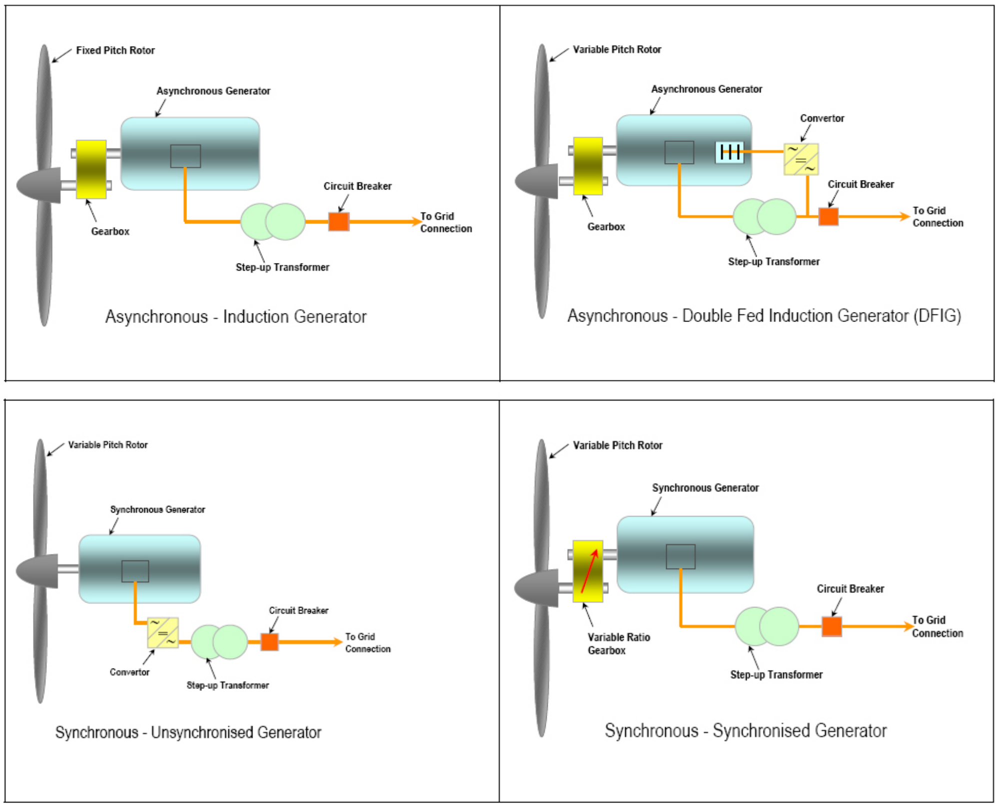


Figure 6: Common wind turbine generator technologies [4]

Electricity Distribution Systems

Most electricity distribution systems in New Zealand use alternating current [AC] for three main reasons 1] The most cost-effective way to generate large amounts of electricity is with a rotating synchronous generator, which naturally produces alternating current 2] The most economical and robust construction of motors for industrial, commercial and domestic applications are based on induction or synchronous motors, which both use alternating current. 3] With an AC system, relatively inexpensive transformers can be used to increase or decrease the voltage as needed. **Figure 7** shows a conceptual diagram of the mechanical-electrical function chain in a wind turbine.

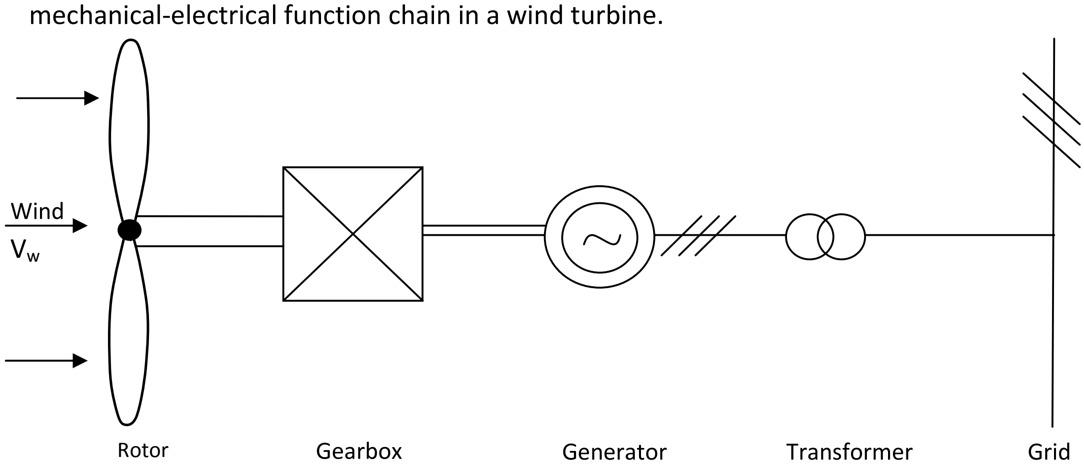


Figure 7: Conceptual diagram of the mechanical-electrical function chain in a wind turbine.

Electricity Distribution Systems Beyond the Wind Farm

Review of the electricity market has revealed that up until 1994, the New Zealand market had a system of monopoly providers of generation, transmission, distribution and retailing. Since then, a step-by-step process of industry reform has led to the separation of the monopoly elements from the contestable elements to create competition in energy generation and electricity retailing. The industry is a mixture of state-owned enterprises, Trust Owned Companies and Public Companies. Wind farm developments come under the heading "electricity generation" obviously being the first process in the delivery of electricity to consumer's i.e. generating the electricity. The other processes are electric power transmission and electricity distribution which are also key to delivering power to the end users [5].

Figure 8 provides an overview of the electricity generation, transmission and distribution to retail industries.

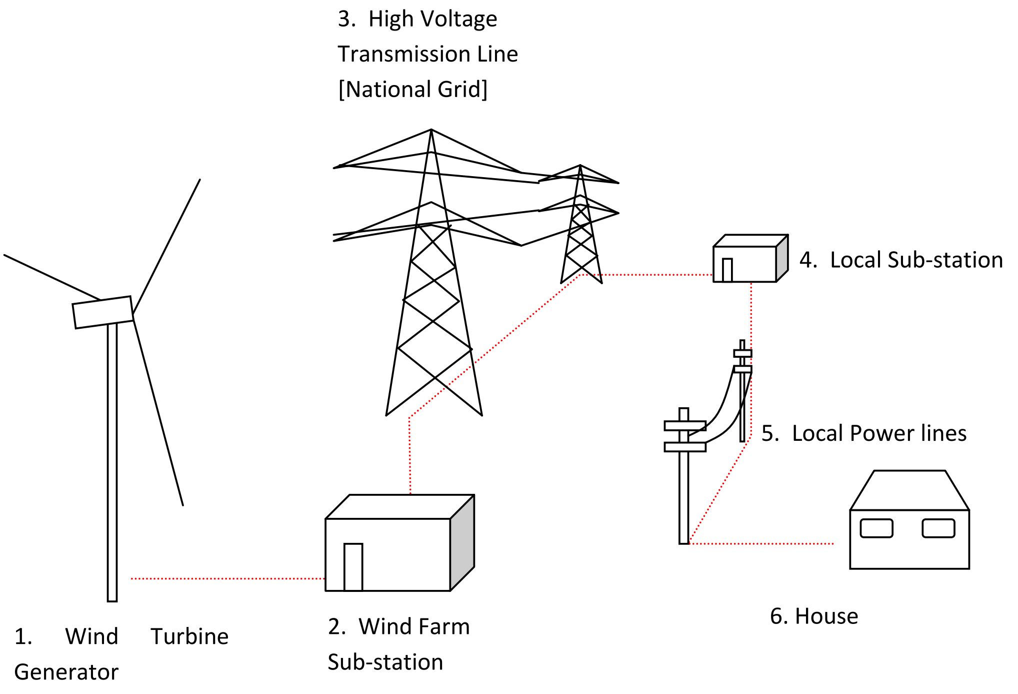


Figure 8: Overview of the electricity generation, transmission and distribution to retail industries.

Chapter 3: Acoustic Terms

Introduction

The glossary reviews specific areas namely a meta-analysis of environmental acoustics related to wind turbine generators.

The summary of information presented relating to environmental acoustics is viewed as particularly important to provide an understanding of the topic of wind turbine generator acoustics as a whole and has therefore been given additional attention as background information to the literature and following chapters presented.

Objective and Subjective Acoustics - Noise and Sound

The key to understanding the acoustic concepts presented within this Thesis in terms of fundamental acoustics is the association between *objective* and *subjective* assessments and how 'acoustical systems' are all inter-related.

Acoustics is the science of sound. Noise in its simplest definition may be defined as 'unwanted sound'.

Physically there is no unique distinction between sound and noise. Psychologically, sound is a sensory perception originating as a mental event evoked by physiological processes in the auditory brain. Other areas of the nervous system are also known to be involved. The complex pattern of sound waves is perceptually classified as "Gestalts" and labelled noise, music, speech, etc [6].

Sound is produced by any vibrating body and is transmitted in air as a longitudinal wave. It is therefore a form of mechanical energy and is classically measured in energy related units. Sound is a sensation detected by the human ear as a result of these pressure variations set up in the air by a vibrating source. Such vibrations set up a series of alternate regions of increased and decreased pressure in the surrounding air known as compressions and refractions [6].

Acoustic Concepts

Taxonomy of Acoustics

There are various major categories of acoustics. These include physical, biological and acoustical engineering. Wind turbine generator acoustics would be classified under all three key areas.

Acoustic Source

In airborne contribution measurements, one or several source points [7]. In terms of this study the 'acoustic source' under investigation is the wind turbine generator.

Airborne Sound

Sound that reaches the point of interest by propagation through air [7]. In terms of this study sound from the wind turbine generator is the airborne sound source of interest.

Sound Characteristics

A sound wave has wavelength, frequency and amplitude. Each vibration of the source produces one pressure wave in an elastic transporting medium, air in the case of wind turbine sound. Sound waves are characterised by the amplitude of sound pressure change, frequency and the velocity of sound propagation [7].

Noise Emission

Airborne sound radiated by a defined noise source [7]. In terms of this study noise emissions relate to all other noise sources other than the acoustic sound source under investigation being the wind turbine generator.

Sound Immission

Airborne sound received [at the ear of an observer or sound level meter] being the sound under investigation [7]. In terms of this study the 'sound immission points' relate to measurements carried out in the near field on the wind farm [R_o location] and in the far field at nearby residential location [403 Makara Road].

Speed of Sound

The speed of sound, frequency and wavelength are related by the following equation:

$$\lambda = c/f \qquad \textbf{[Eq 1]}$$

Where:

λ = Wavelength in metres
c = Speed of sound in metres per second
f = Frequency in Hz

The speed with which sound travels depends on the medium through which it travels particularly its elasticity and density. The speed of sound propagation in air at 20°C and 1 atmosphere pressure may be calculated using the following formula:

$$c = 332 + 0.6\ Tc \qquad \textbf{[Eq 2]}$$

Where:

Tc = temperature in °C

Alternatively the speed of sound propagation at any temperature and in any ideal gas may be calculated using the following formula:

$$c = \sqrt{(y\ R\ T_k\ /\ M)}\quad [ms^{-1}] \qquad \textbf{[Eq 3]}$$

Where:
T_k = Temperature in ^oK
R = Universal gas constant which has the value 8.314 J per mole/K,
M = Molecular weight [air is 0.029 kg/mole]
y = Ratio of specific heats [air the ratio is approx 1.402]

Propagation of Sound Wave and Simple Harmonic Motion

Sound is produced by any vibrating body and is transmitted in a medium [usually air]. As air cannot sustain a shear force the only type of wave possible is a longitudinal wave motion - where the vibrations are in the direction of the motion as illustrated in **Figure 9.**

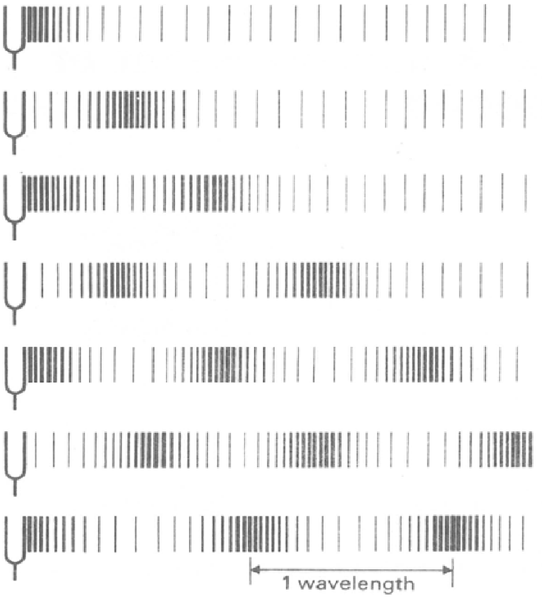


Figure 9: Propagation of a sound wave [8].

A pure sound wave, as shown in **Figure 9**, consists of regular vibrations such that its displacement from its original point is given by:

$$\text{displacement, } x = X \sin 2\pi f.t \qquad \textbf{[Eq 4]}$$

Where
f = Frequency in Hz
t = Time in seconds from original position
X = Maximum displacement or amplitude

Pressure fluctuations are caused in air due to molecules of air vibrating ‘back and forth’ about their original position but passing on some of their energy through movement. If a particular molecule has a displacement time at *t* of x = X sin 2π f *t then it is moving at a velocity of vibration given by [8]:

$$\frac{dx}{dt} = 2\,\pi f X\ \cos 2\pi f t \quad [t = 0 \text{ when } s = 0] \qquad \textbf{[Eq 5]}$$

Where t = 0 when s = 0 and is being accelerated at a rate:

$$\frac{d^2x}{dt^2} = -4\pi^2 f^2 X\ \sin\ 2\pi f t \qquad \textbf{[Eq 6]}$$

As shown in **Figure 10** due to equal positive and negative changes the average displacement and pressure fluctuations is always equal to zero, it is therefore suitable to make measurements using the root mean square pressure change [RMS value][8].

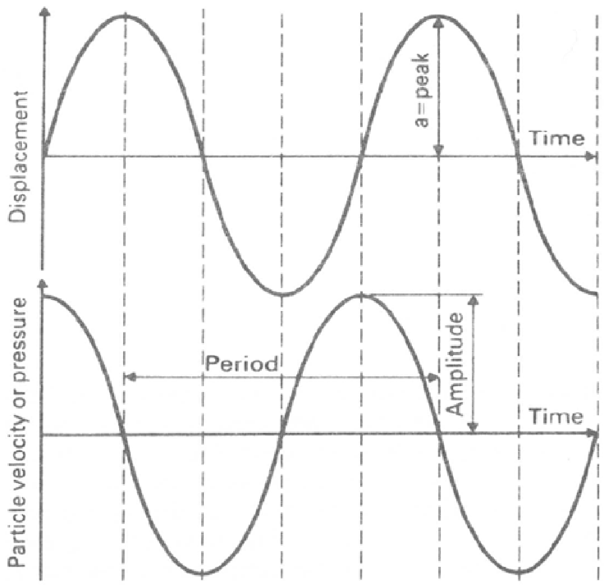


Figure 10: Displacement & pressure variation of a pure sound wave [sinusoidal pressure] [8].

Sound Intensity

The physical magnitude of sound is given by its intensity. As the human ear can be described as a “pressure sensitive mechanism” it is convenient to utilise pressure as the measure of sound magnitude. The sound intensity is the sound power per unit area of a sound wave and is related to the square of the sound pressure given as:

$$I\ \alpha\ p^2 \qquad \textbf{[Eq 7]}$$

A mechanical energy fluctuation accompanies a sound wave, and the rate at which sound energy arrives, or passes through, a unit area normal to the direction of propagation is referred to as the sound intensity. Sound intensity can be defined in any direction. For a plane wave intensity is equal to the square of the pressure divided by the product of density time velocity of sound, the product density of air times, the speed of sound in air is referred to as the characteristic acoustic “impedance of air”. In a free sound field intensity can be given by the following formula:

$$I = p^2 / (\rho c) \qquad \text{[Eq 8]}$$

Where:

p **=** Root mean square of the sound pressure [410 rayls in air at normal temperatures and pressures]

ρ = Static mass density of the medium

c = Velocity of sound in the medium

The total sound energy emitted by a source per unit time is known as the sound power and is measured in Watts [W]. Sound intensity is normally measured in Watts per square metre [W/m^2]. Therefore the threshold intensity for human hearing can be derived from the following formula:

$$\therefore \; I = \frac{p^2}{410} \; W/m^2 \qquad \text{[Eq 9]}$$

$$\begin{aligned} \text{Threshold intensity} &= \frac{[2 \times 10^{-5}]^2}{410} \; W/m^2 \qquad \text{[Eq 10]} \\ &= \frac{400 \times 10^{-12}}{410} \\ &\simeq 10^{-12} \; W/m^2 \end{aligned}$$

Sound may be described by means of time-varying sound pressure. Compared to the magnitude of the atmospheric pressure, the temporal variations in sound pressure, caused by sound are extremely small. The values of sound pressure between 10^{-5} and 10^{2} Pa [or Newton per square metre, N/m^2] are relevant for the human listener. Since the range of this varies and is so wide, it is usual to express its value on a logarithmic scale in deciBels [denoted dB] [[6]].

Decibel Scale [dB - deciBELS]

The sound output of a source constitutes its power and the intensity of sound at a point in space and is defined by the rate of energy flow per unit area. Intensity is proportional to the mean square of the sound pressure and, as the range of this variable is so wide, it is usual to express its value on a logarithmic scale, in decibels [dB]. Sound pressure has the unit Pascal [Pa], while sound pressure level has the unit dB [[6]]. A decibel is a tenth of a Bel.

Sound Pressure Level [SPL]

The measure of sound pressure level using a logarithmic scale is given by the following formula:

$$\text{Sound pressure level } L_P = 10\log_{10}\left[\frac{p}{p_o}\right]^2 \text{ dB} \qquad \textbf{[Eq 11]}$$

$$\text{Or } L_p = 20\ \log_{10}\left[\frac{p_1}{p_o}\right] \qquad \textbf{[Eq 12]}$$

Where:

p = The RMS [Root Mean Square] sound pressure fluctuation.
p_o = The reference sound pressure of audibility

It is noted that this formula is not an absolute scale but a comparative scale relating two different pressures for convenience p_o is taken as the average threshold of hearing at 1000 Hz frequency being 2 x 10^{-5} N/m^2, or 20 µPa. Hence the sound pressure level, L_p, in dB, is the ratio of the sound pressure level to a reference level.

The use of 20_{μ}Pa [taken to be the threshold of hearing] establishes an absolute level or agreed reference level for sound pressure levels expressed in dB values. The internationally agreed reference quantities for sound power levels and sound intensity level are 10^{-12} W and 10^{-12} W/m^2.

When the sound pressure level is reported, the location and distance from the source of the sound must be stated. The distance from the source and a host of other environmental factors influence the sound pressure level at a receiver. Note that if the sound pressure is doubled [p→2p] L_p increases by 6 dB.

If the sound intensity is doubled [I→2I] I_1 increases by 3 dB, this is because $I \alpha P^2$. Although the sound pressure and sound pressure levels are the most referenced quantities it is not the fundamental property of the source. Sound is a flow of energy with the source acting as a reservoir of power [rate of projection of energy [Joules/sec or Watts].

Sound Power Level [L_W or PWL, or SPW]

Sound power level, L_W, is the energy output of a source being a property of the source itself. The sound power level is a ratio of the power of a source to a reference and is quoted in dB. Sound power cannot be measured. The sound power level is given by the following formula:

$$\text{Sound power level, } L_W = 10\log_{10}\left(\frac{W_1}{W_o}\right) \qquad \textbf{[Eq 13]}$$

Where:

W_1 = The sound power of the source [watts]
W_O = The reference sound power [10^{-12} watts]
If the sound power level is doubled [W→2W] L_w increases by 3 dB.

Frequency Analysis

Noise is characterised by the way in which it varies over time. Sound energy is also made up of a range of different frequencies. The spread of sound energy across the audible frequency “spectrum” is one factor that helps to make it identifiable to the human ear. Often the sound energy will be spread over a wide band of frequencies [“audio-frequency range = 16 Hz to 16 kHz”].

A sound source may emit a noise that is concentrated in a “narrow band” of the spectrum or contains a high proportion of energy at a single frequency being a pure tone. A pure tone is the simplest kind of sound, having a sinusoidal pressure cycle that is defined in terms of a single frequency and pressure amplitude at a given time [[9]].

Frequency is related, but not identical, to the perception named pitch. Any periodic sound has a tonal character that can be ascribed a particular musical note. The note is basically defined by the fundamental frequency of the sound [[9]]. The effects of noise depend strongly upon frequency of sound-pressure oscillation. Therefore, spectrum analysis is important in noise measurement [[10]].

The audible frequency range is technically covered by 10 octave bands. An octave is the frequency interval the upper limit of which is twice the lower limit. The so-called “preferred frequencies” at the centres of the standardised octave bands are spaced at octave intervals from 16 Hz to 16,000 Hz [16 kHz] [[11]].

The octave band level at a particular centre frequency is the level of the sound measured when all acoustic energy outside this band is excluded. The 1/3 third octave band filters, subdivide each octave interval into three parts and provide a more detailed description of the sound spectrum. The sound pressure level is determined within each 1/3 octave band and the total sound pressure energy will be the sum of all the 1/3 octave band levels.

Figure 11 is a sample of measured sound pressure levels across the 1/1 octave band based on centre frequency band widths [note not all centre band shown on x axis of graph].

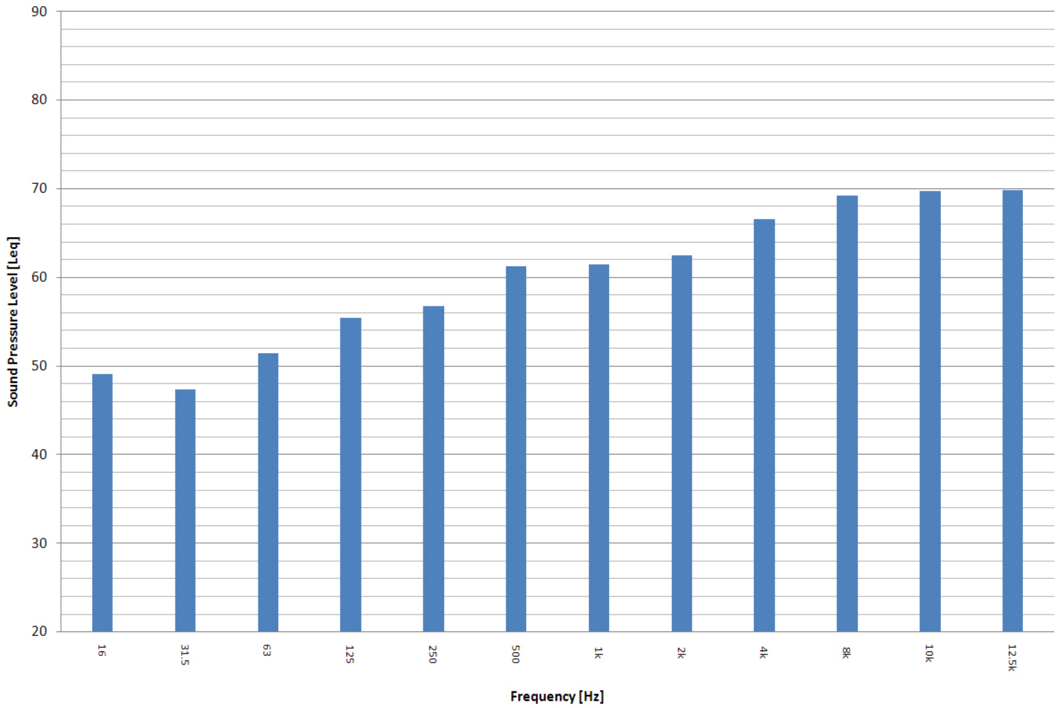


Figure 11: Octave band based on centre frequency band widths.

Figure 12 is a sample of measured sound pressure levels across the 1/3 octave band based on centre frequency band widths [note not all centre band shown on x axis of graph].

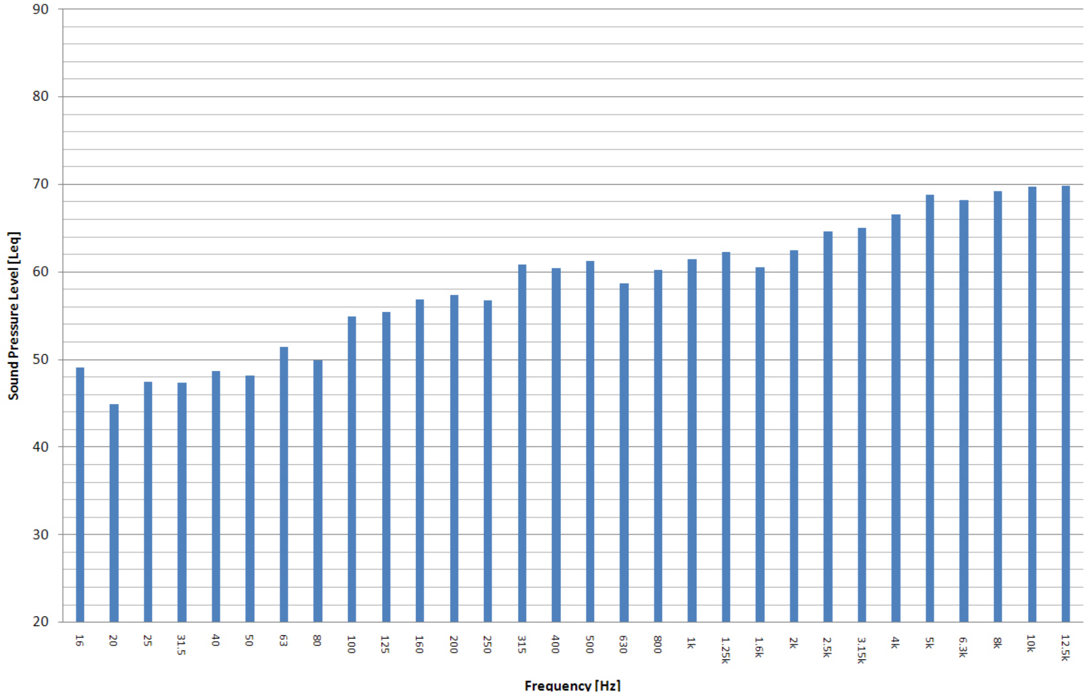


Figure 12: Third octave band based on centre frequency and widths.

Annoyance

Various studies [12][13] state the meaning of annoyance has roots in a complex set of responses which are moderated by personal and social characteristics of the complainant. Guski [14] proposes that noise annoyance is partly due to acoustic factors and partly due to personal and social moderating variables including sensitivity to noise, anxiety about the source, personal evaluation and coping capacity with respect to the noise. Guski states a number of social moderators also exist regarding annoyance including evaluation of the source and suspicion of those who control the source. **Figure 13** modified from Guski emphasises the central nature of personal factors moderating annoyance.

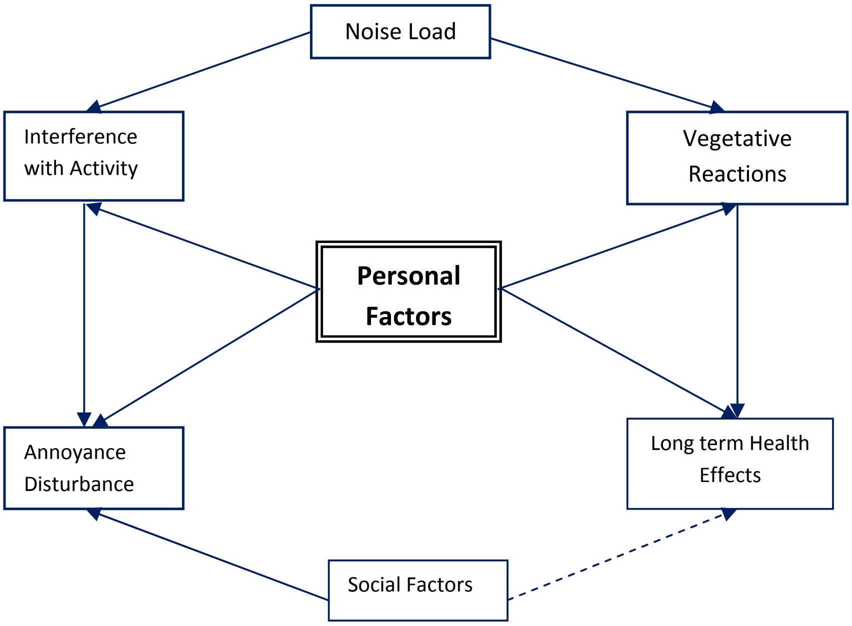


Figure 13: Factors moderating potential noise annoyance [14]

Guski proposes that noise annoyance is partly due to acoustic factors and partly due to *personal* and *social* moderating variables as shown in **Table 1**.

Personal Moderators	Social Moderators
Sensitivity to noise	Evaluation of the source
Anxiety about the source	Suspicion of source controllers
Personal evaluation of the source	History of noise exposure
Coping capacity with respect to noise	Expectations

Table 1: Noise annoyance moderators [15]

The Human Ear and Hearing

The human ear has two functions being hearing and balance. The human ear converts pressure fluctuations in the air into signals, which are transmitted by the auditory nerve to the brain where they are *perceived* as sound. The human ear consists of three main parts being the outer ear, middle ear and inner ear.

The outer ear is the visible part of the ear which collects airborne sound waves which then vibrate the ear drum which is the interface of the middle ear. The outer ear has two parts – the pinna and the ear canal. The pinna is made out of cartilage covered by normal skin. The pinna leads into the ear canal. The ear canal is an open tube with a skin lining. There is a small bend in the ear canal and it is sensitive to pain and can easily be injured. At the end of the ear canal is the ear drum.

The middle ear is a space that is filled with air which acts as an impedance device. Sound vibrations can only be conducted across the middle ear if the space is filled with air.

The inner ear has two parts being the cochlea which deals with sound vibrations and is responsible for hearing and the vestibular system which is responsible for balance. The cochlea is filled with fluid and contains tiny hair cells. The hair cells are all connected to the hearing nerve. The hair cells change the sound vibrations into tiny nerve signals. These nerve signals then travel along the auditory nerve to the brain. In the brain nerve signals are interpreted as the sounds we hear. The following **Figure 14** illustrates the basic schematic of the human ear structure and sound paths. **Figure 15** is a diagram of the human ear and components.

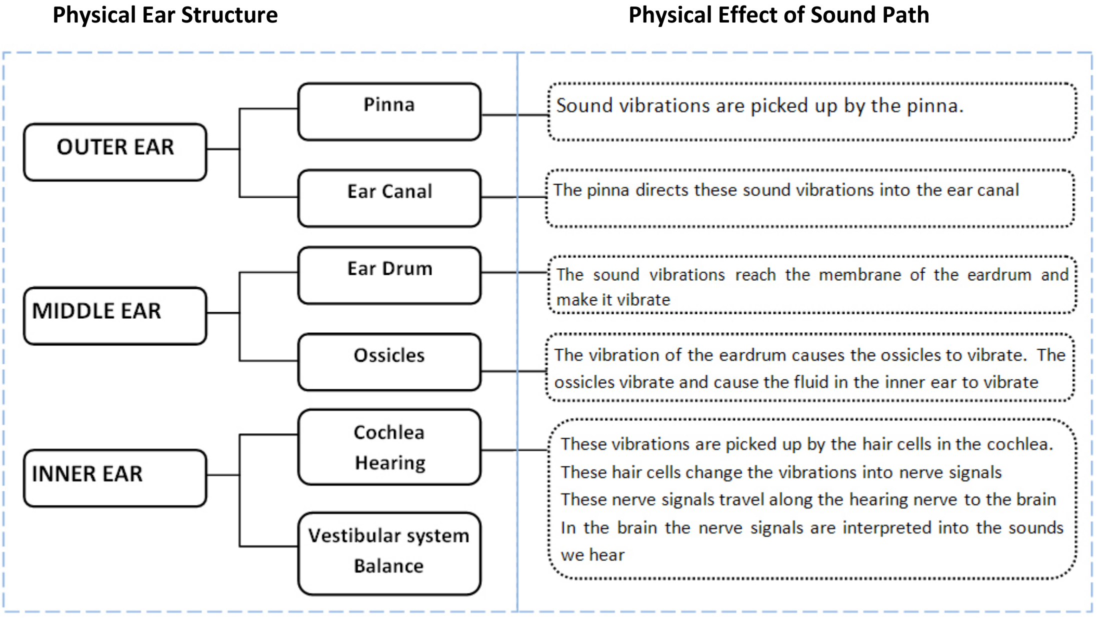


Figure 14: Schematic of human ear and sound paths.

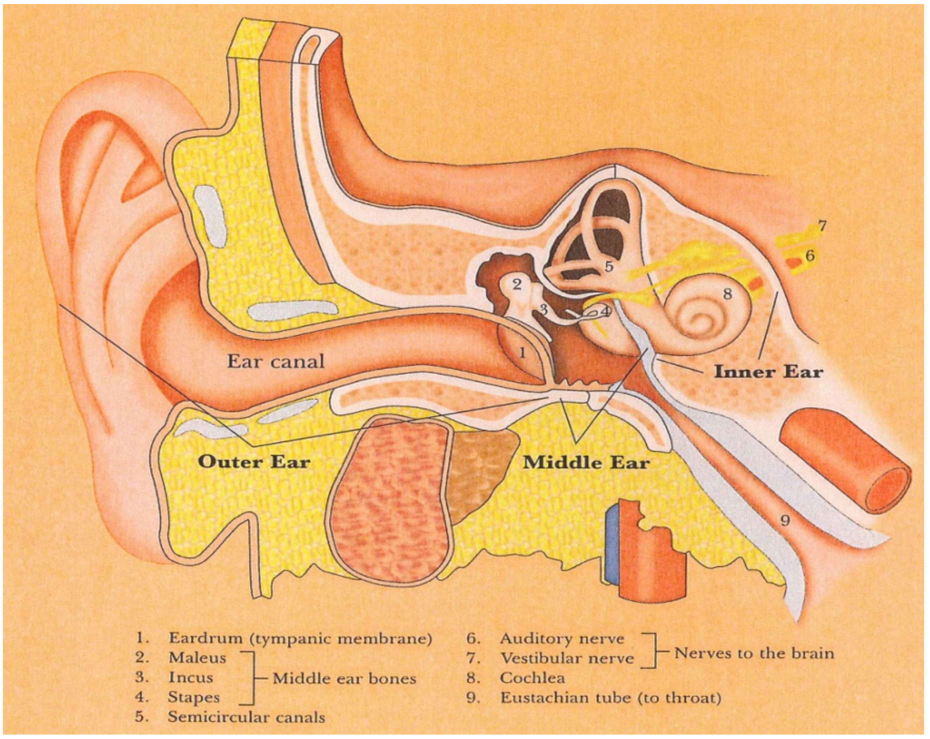


Figure 15: Basic structure of the human ear.

There are a number of key concepts in acoustics which relate to human hearing and how sound is perceived, these are discussed below.

Frequency

Frequency is the rate at which the sound source vibrates. It is measured in cycles per second referred to as Hertz [Hz]. One Hertz is one cycle per second. Frequency determines the pitch of the sound. The frequencies that the "normal" human ear may detect would be described as ranging from 16 Hz to 16 kHz [16,000 Hz] although individuals will vary greatly in terms of individual sensitivity, a person's health and age for example. Most sounds [apart from a pure sound] consist of varying frequencies.

Amplitude

The amplitude is the maximum excursion of the pressure difference of a sound wave. When sound is measured using a sound level meter an average value over time is required to provide a measurable indication of the amplitude. The signal is therefore passed to a root mean square detector and hence the root mean square [RMS] sound pressure is measured.

Loudness

Loudness is a "quasi-objective" measurement in the terms that it is free from emotional responses. Its determination depends on the subject's response which is measured against the loudness of a tone at 1,000 Hz. The subject adjusts the level of the sound under investigation until it sounds equally loud to the 1,000 Hz reference tone. This is the way in which the equal loudness contours of ISO 226:1987 Acoustics - *Normal equal-loudness level contours* are derived. These contours were developed by asking listeners to adjust the volume of a single tone [pure tone] of various frequencies so that they sounded as loud as at 1,000 Hz reference tone.

The subjective or perceived magnitude of sound is called loudness. Loudness depends upon frequency, intensity and duration. Binaural sound is perceived to be twice as loud as monaural sound. Typical "everyday" sound exposure is binaural [[16]]. The basic unit of loudness is the sone which is defined as the loudness of a 1,000 Hz pure tone heard at a sound pressure level of 40 dB with a reference of 20 Micropascals [20 µPa] under specified listening conditions [[17]]. Although an increase of approximately 6 dB represents a doubling of the sound pressure level an increase of around 10 dB is required before the sound subjectively appears to be twice as loud.

The perceived or subjective loudness is determined by complex factors, including that the ear is not sensitive at all frequencies. Generally the ear is most sensitive between 2 kHz and 5 kHz and less sensitive at very low and very high frequencies. This is illustrated by equal loudness contours in ISO 226:1987 Acoustics - *Normal equal-loudness level contours.* **Figure 16** illustrates sound at 100 Hz has to be around 20 dB louder than a sound at 1 kHz before it can be heard.

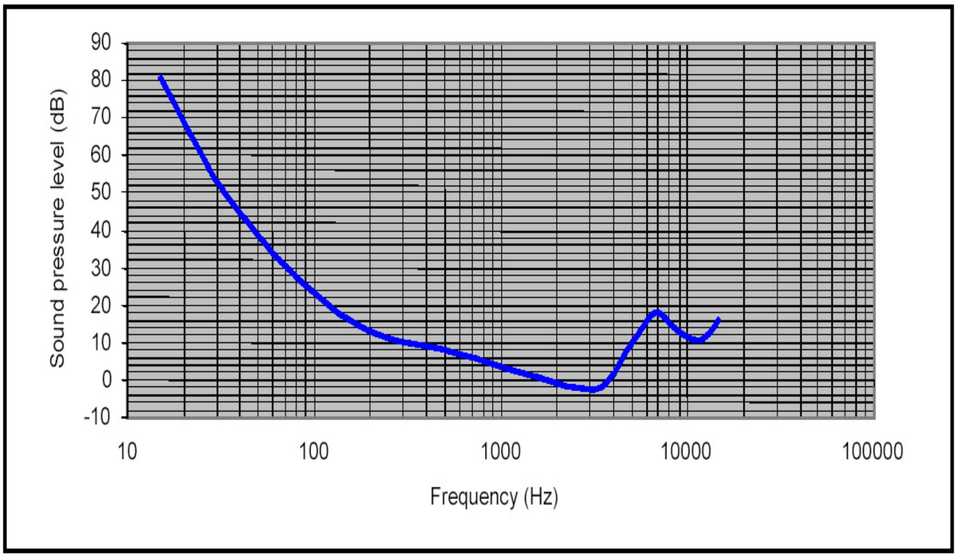


Figure 16: Example of threshold of hearing [audibility] for 18 to 25 year old age range [[18]]

It is commonly accepted that for the "*healthy*" young person a change of 1 dB is just subjectively perceptible under controlled conditions. A change of 3 dB is noticeable, 5 dB obvious and a change of 10 dB is significant. A 10 dB change corresponds approximately to subjectively halving or doubling the loudness of a sound for a pure tone. Just as a given sound is characterised by the way in which it varies over time, sound energy is usually made up of a wide range of different frequencies.

Pitch

Pitch is the subjective response to frequency. A low frequency may be defined as low pitched. A high frequency may be defined as high pitched.

Hearing Thresholds

The threshold of hearing is the minimum sound pressure level of a signal at a specified frequency that is capable of evoking an auditory sensation in a specified fraction of trials. In regards to environmental acoustics the threshold of hearing is generally reported as the Root Mean Square sound pressure of 20 Micropascals [20 µPa] which is equal to 2×10^{-5} Pascal [0.00002 Pa] being in theory '0 dB' i.e. the lowest sound a human with undamaged hearing can detect at 1,000 Hz.

At the opposite end of the scale is the maximum level for sound which can be experience before a person experiences discomfort, pain and even irreversible damage to their hearing system. It is generally accepted that at levels around 120 dB discomfort is experienced and around 140 to 150 dB pain occurs. Such maximum levels and effects they have will vary from person to person with children likely to experience discomfort or pain at much lower levels.

A-weighting Frequency Weighting Network

The ear is less efficient at low and high frequencies than at medium or speech-range frequencies. In order to be able respond to sound the same way or as close as possible to the human ear sound level meters have an A-weighting network for measuring A-weighted sound level.

Although each frequency is considered independently in terms of its weighting, the levels can be inversely logarithmically added to give an overall 'A'-weighted figure that best represents the response of the ear.

It is noted that the A-frequency weighting is internationally accepted to give an approximate best fit response which is similar to that of the ear. This concept is widely used in environmental measurement and acoustic engineering.

Sound Level Meter

A sound level meter is an instrument designed to respond to sound the same way the human ear does by adopting frequency weightings which provide an objective reproducible measurement of sound.

Generally the microphone of the sound level meter converts the sound signal to an electrical signal. This signal is small and hence is amplified by a pre-amplifier before being processed. The sound can be processed several ways with the signal being passed through a filter. The most commonly used filter is the 'A' weighting or A-frequency weighting. In addition to A-frequency weighting there are a number of other filters which include G-frequency weighting designed for infrasound.

Integrating-Averaging Sound Level Meter

In its "averaging" mode the sound level meter instrument provides a direct reading of the sample equivalent continuous sound level L_{Aeq} [s]. In its "integrating" mode, if provided, it reads Sound Exposure Level L_{EA} directly [[7]].

Calibration

The process of measuring to determine the accuracy of your measurement chain. This result can then be used to off-set measured values and take account of potential inaccuracy [[7]].

Calibrator

A device that produces a known sound pressure on a microphone in a sound level measurement system, or a known vibration [acceleration, velocity, or displacement] on an accelerometer in a vibration measurement system. It is used to adjust the system to standard specifications [[7]].

L_N or L%

The dB[A] level exceeded N % of the time, for example, L_{90}, the dB[A] level exceeded 90% of the time. [[7]].

Equivalent Continuous A-Weighted Sound Level [L_{Aeq}]

The constant sound level that, in a given time period, would convey the same sound energy as the actual time-varying A-weighted sound level [[7]].

Time Domain Factor and Statistics

Sound pressure levels are often the result of different sources of noise, each of which may be varying in strength from one instant to the next. Sound levels are usually quantified over a specified period. The time period will vary according to the nature of the sound source. The basic acoustic quantity to deal with variation over time is the equivalent continuous sound pressure level.

As an average energy level the equivalent continuous sound pressure level [L_{Aeq}] may conceal the pattern of variation over time which is important to determining human response. The L_{Aeq},T is derived from the following mathematical expression:

$$L_{Aeq[t_3]} = 10\log_{10}\left[\frac{1}{t_3}\int_{t1}^{t2} P_A{}^2\ [t]\ \mathrm{dt}/P_o{}^2\right] \qquad \textbf{[Eq 14]}$$

Where

t_3 is the measurement time interval between start and finish times t_1 and t_2
$L_{Aeq[t_3]}$ is the L_{Aeq} over time period t_3
$P_A{}^2[t]$ is the square of the A– frequency weighted sound presure as a function of time
P_o is the reference value, 20μPa

It is important to distinguish between very short-term fluctuations in sound pressure level occurring over periods of a second or less, medium term fluctuations occurring over periods of up to an hour, and daily and weekly fluctuations in sound level.

Very short term fluctuations are associated with impulsivity. Community noise exposure often varies significantly between day, evening and night-time periods. For obvious reasons, community sensitivity often varies considerably at these different times. Therefore, it is often desirable to set different criteria for acceptable noise exposure for each of these different time periods.

A number of time domain statistics can be used to describe the sample sequence as measured. Percentage of levels in excess such as the L_{A10} [the level exceeded for 10 % of the time] are used in New Zealand national standards to describe the average maximum levels of separate events within the time history sequence, and the L_{A90} [the level exceeded for 90 % of the time] to describe the mean minimum steady background noise level.

The L_{Amax} gives an indication of the maximum sound level recorded during the sample sequence. The standard deviation of the mean of the sample sequence gives an indication of the range of fluctuations in level from the maximum to the minimum. Other statistical descriptors can be used for special purposes such as L_{peak} for instantaneous noise from weapons [[6]].

Figure 17 represents a graph of various time varying acoustical sound level descriptors.

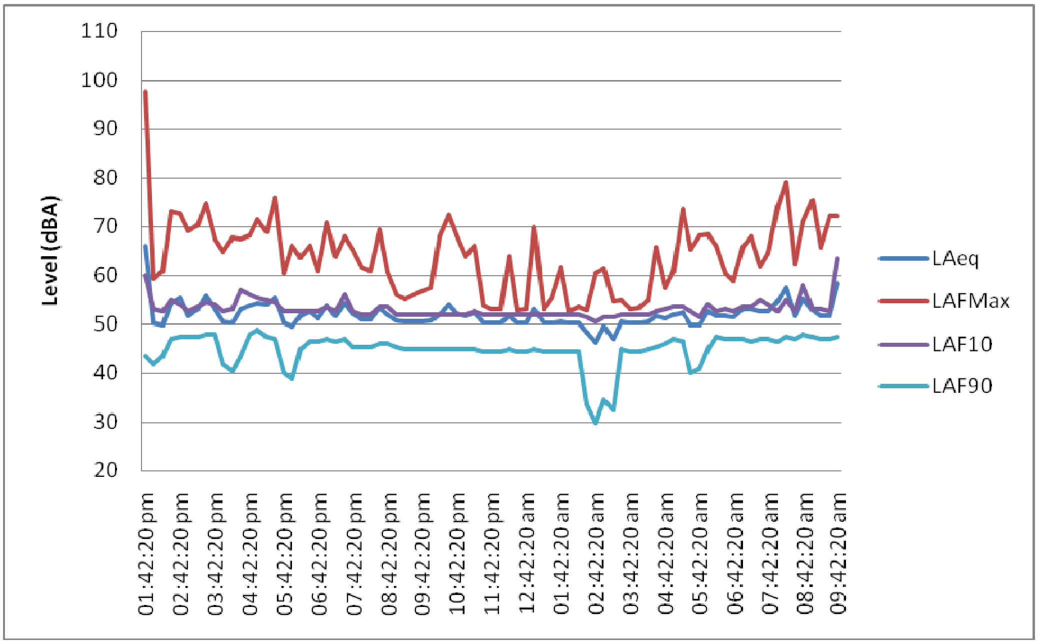


Figure 17: Example of various time varying acoustical sound level descriptors.

A-Weight Sound Expousre

Sound Expoure may be quantified using the A-weighted sound expousre L_{AE}, defined as the time intergral of the squared, instantaneous A-weighted sound pressure, $Pa^2[t]$ $[pa^2]$ over a particualr time period [T = t_2-t_1 [hours]]. The units are pascal-squared-hours [Pa^2.h] and may be defined as follows

$$L_{AE} = 10\log_{10}\left(\int_{t_1}^{t_2} p_A^2(t)dt / p_0^2\right)$$ **[Eq 15]**

Where

$p_A^2[t]$ = instantaneous A-frequency weighted sound pressure at time t

$t_2 - t_1$ = stated time period of interest of an event under investigation

p_o = reference sound pressure of 20 μPa

The relationship between the A weighted sound expousre and the A-weighted equivelent continuous sound level is

[Eq 16]

Far [Free] Field

The far field of a source begins where the near field ends and extends to infinity. The transition from near to far field is gradual in the transition region. In the far field, the direct field radiated by sound sources will generally decay at the rate of 6 dB per doubling of the distance from the source [for a point source]. The decay rate generally varies between 3 and 4 dB per doubling of distance for a line source [[7]].

The simplest form of a sound source would radiate sound equally in all directions from an apparent point, this sound energy emitted at a given time will spread in all directions and, one second later will be dispersed over the surface of a sphere of 340 m radius [7]. **Figure 18** is an example of the radiation of a simple sound source in the free field situation.

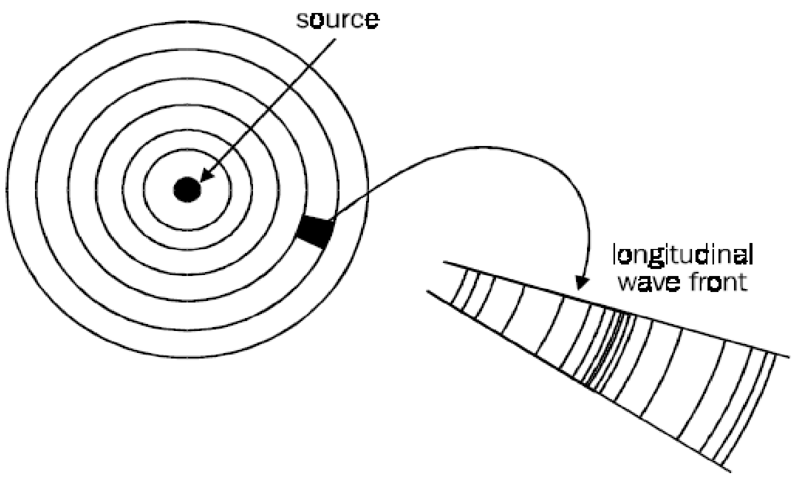


Figure 18: A representation of the radiation of sound from a simple source in free field [19]

Distance Double Law

In pure spherical divergence of sound from a point source in free space, the sound pressure level decreases 6 dB for each doubling of the distance. This condition is rarely encountered in practice, but it is a handy rule to remember in estimating sound changes with distance [7].

Sound Attenuation in Air

Figure 19 illustrates an example of approximate correction for air attenuation including the inverse square law for environmental acoustics.

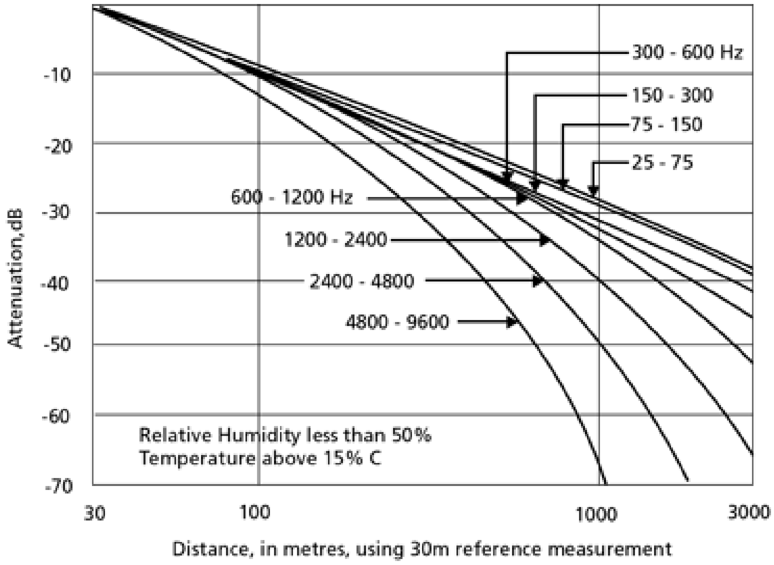


Figure 19: Correction for air attenuation including the inverse square law.
Attenuation [dB] versus distance [m] with relative Humidity [%] and temperate as ^{0}C [7].

Direct [Near] Field

The direct field of a sound source is defined as that part of the sound field which has not been subjected to any reflection from any surfaces or obstacles [7].

Reverberant Field

The reverberant field of a source is defined as that part of the sound field radiated by a source which has experienced at least one reflection from a boundary or enclosure containing the source [7].

Sound Fields

Figure 20 illustrates an example of typical sound fields in environmental acoustics.

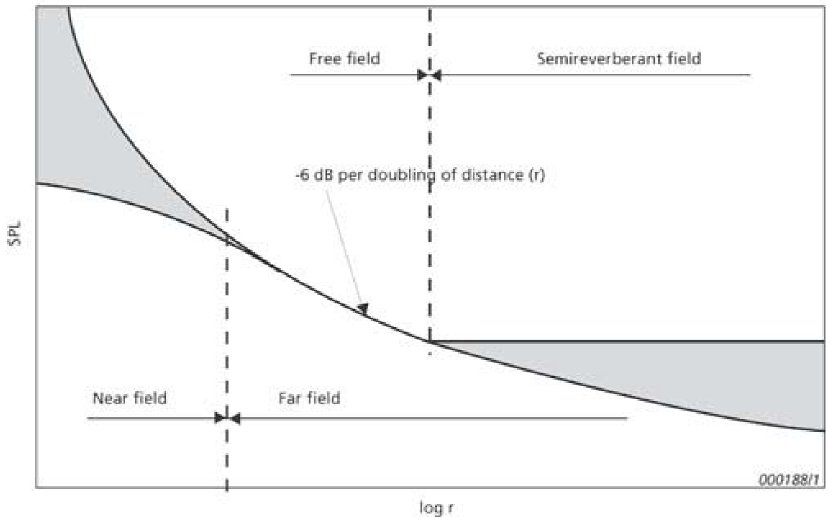


Figure 20: Approximation of sound fields [7].

In the near field, the shaded area shows that noise emission cannot be measured reliably. But further away in the far field, measurements are reliable and the level decreases 6 dB per doubling of distance [spherical spreading due to inverse square law] as long as the environment is effectively free field [7].

Objective Test

A sound test analysis that is carried out based on user selected descriptors. In the case of the study here the two selected sound level descriptors under investigation are the L_{Aeq} and L_{A90} sound level descriptors.

Point Source

A source whose dimensions are small compared to the propagation distances described in reference to it [7].

Line Source

A sound source composed of many point sources in a defined line, such as a train, flow of traffic on a motorway, or constant aircraft take-offs and landings [7]. A wind farm with multiple close wind turbine generators would not generally be considered representative of a line source.

Signal-to-Noise Ratio [SNR]

The difference between the nominal or maximum operating level and the noise floor in dB [[7]]. In the case of this study the 'signal' is defined as the 'sound' produced by the wind turbine generator, while the 'noise' is defined as all other sources including background noise.

Specific Noise

Noise from the source under investigation.

Ambient Noise Level

The total noise level in the acoustic environment, including the noise source[s] of interest [[7]].

Residual Noise

This is 'Ambient Noise' without Specific Noise. It is the noise remaining at a point under certain conditions when the noise from the specific noise is suppressed [[7]].

Masking Noise

A noise that is intense enough to render inaudible or unintelligible another sound that is also present [[7]].

Background Noise or Background Noise Level

Background noise is often used to mean the noise in the environment, *other* than the sound from the source of interest [in this case being the wind turbine generator]. For all intents and purposes of this study background noise is also referred to as unwanted noise or extraneous noise which describes all noise source[s] of interest *other* than wind turbine sounds.

Wind Turbine Generator Sound

For all intents and purposes of this study wind turbine generator sound is the source under investigation. In terms of the study the above two terms are used to provide clarity throughout the study.

Ultrasound and Infrasound

Ultrasound is sound at frequencies above the audible range, that is, above approx 20 kHz. Infrasound is sound at frequencies below the audible range, that is, below approx 20 Hz.

Chapter 4: L_{A90} and L_{Aeq} Sound Level Descriptors in Wind Turbine Acoustics – A Literature Review

Introduction

In this chapter, previous work and research carried out in the area of wind turbine generator acoustics is covered. This literature study provides a comprehensive review of the published work relating to wind turbine generator acoustics. The aim of the evaluation being to present what is viewed as the most significant points of current knowledge on the topic and provide a basis for investigative field work to be conducted.

It is noted that the literature review is only valid so far as literature present at the time of conducting the review as it is noted a number of newer papers have been published since. These papers do not however change any of the overall conclusions of the thesis.

A summary and explanation of key studies relevant to wind turbine generator acoustics and L_{Aeq}/L_{A90} noise descriptors is provided to include a qualitative review by authors as well as various systematic and quantitative procedures available on the topic, including an overview of both national and international wind turbine generator noise standards.

A chief area of environmental acoustics relates to how wind turbine generator sound is interpreted or perceived by people in their receiving environments. Wind turbine sound can be often described as tonal, impulsive or both and is often commented on as being annoying when subjectively described. However what may be *subjectively* described as annoying could *objectively* be assessed as complying with relevant standards or guidelines.

There are various methods for the measurement, perception and assessment of wind turbine generator sound. Key to the research question being carried out is an understanding of how sound is produced, the methods by which it is produced, the varying environment in which sound is received and ultimately interpreted by humans, which relates to a number of complex psychological and physiological factors. An understanding of both environmental acoustics and wind turbine generator sound is therefore significant as both topics are inter-related.

Several key questions have been identified as being comprehensive background information to this study to enable the primary research and field investigation to be undertaken. Key research questions viewed as important topics relating to this chapter are as follows:

- What does the literature currently state concerning the differences between measured or assessed sound level descriptors from modern commercial wind turbine generators?
- What are the key sources of sound related to wind turbine generators and how are they produced?
- What are the key types of sound produced by wind turbine generators?
- What are the key theories relating to sound production from wind turbine generators?
- What key guidelines and standards relate to the assessment and measurement of wind turbine sound?
- What factors influence sound propagation beyond the wind turbine?

Wind Turbine L_{A90} and L_{Aeq} Sound Level Descriptor Studies

The literature review into wind turbine acoustics illustrates that there are a variety of reports on various topics which discuss wind turbine acoustics and measured sound levels regarding sound descriptors relating to both wind turbine sound and background noise.

It is evident from the study that many people have used different parameters to identify the contribution from the wind turbine sound and attempt to separate them from background noise. In general most of the studies report fairly confident audible sound immission levels within 750 to 800 metre setback distance [but not necessarily in complex terrain].

Napoli [[20]] measured L_{Aeq} sound levels for a case study on wind turbine sound in a small and quiet community in Finland however no measurement intervals were specified. In a study by Ziliani [[21]] Ziliani measured L_{Aeq} and L_{A50} [at 10 minute intervals] from wind farm sound and then discarded points where L_{Aeq}- L_{A50}> 5dB.

Delaire [[22]] provided a comparison of background noise levels collected for an energy project in Melbourne [Australia] as L_{A95} [at 10 minute intervals] in a pre constructed noise study aimed at quantifying the background noise levels that would be subtracted from future measurements post wind farm construction.

Jiraska and Almgren [[23]] measured L_{Aeq} wind farm sound levels [at 1 minute intervals] in order to compare to the emission point. June [[24]] measured L_{A90} in 10 minute intervals to compare these levels to predictions while Bullmore [[25]] measured L_{Aeq} [at 1 hour intervals] for a study into background and operational sound level monitoring.

The common thread between the above reports has revealed that the data presented in these reports is not presented in a form directly relevant to the thesis topic i.e. L_{Aeq} or L_{A90} time varying sound level outputs from a wind turbine generator or the difference between the two sound level descriptors. These studies do not provide enough background data [such as simple measurement periods] or information to be actually very useful for this study. The thesis literature research has revealed that sound level data are presented in literature as correlated data i.e. wind speed [m/s] *versus* sound levels [L_{Aeq}] as opposed to any direct comparisons between sound level descriptors.

A handful of studies have however been sourced and reviewed as part of the literature review which do discuss directly L_{Aeq} or L_{A90}/L_{A95} sound level descriptors for wind turbine generator sound. The following discusses these studies in detail regarding only sound level descriptors in terms of wind turbine sound output.

Research of G.P Van den Berg

A study by Van den Berg [[26]] has been sourced which, although does not specifically relate to the topic being studied here, does present data sets as L_{Aeq} and L_{A95} time varying sound level outputs. The review by Van den Berg studied the effects of the wind profile at night on wind turbine sound. This study was carried out at the Rhede Wind Farm in north-western, Germany. This wind farm has seventeen 1.8 MW wind turbine generators each with a hub height of 98 m. Each turbine has 3 blades with 35 m long aerofoils [blades]. The turbines have a variable speed increasing with wind speed, starting with 10 revolutions per minute at a wind speed of 2.5 m/s at hub height up to 22 revolutions per minute at wind speeds of 12 m/s and over.

In this study Van den Berg reports that sound measurements were made over 1435 hours, of which 417 hours were at night, within four months at two consecutive locations [“A” and “B”] with an unmanned *Sound and Weather Measurement System* [SWMS] consisting of a Type 1 Sound Level Meter with a microphone at 4.5 m height with a 9 cm diameter foam wind shield, and a wind meter [anemometer] at 10 m as well as at 2 m height.

Figure 21 illustrates the site layout and measurement position “A” in the study. Van den Berg reports that sound levels were sampled every second, wind speed and wind direction [at 10 m and 2 m heights] and the A-weighted sound level were measured; the measured data was stored as statistical distributions over 5 minute intervals.

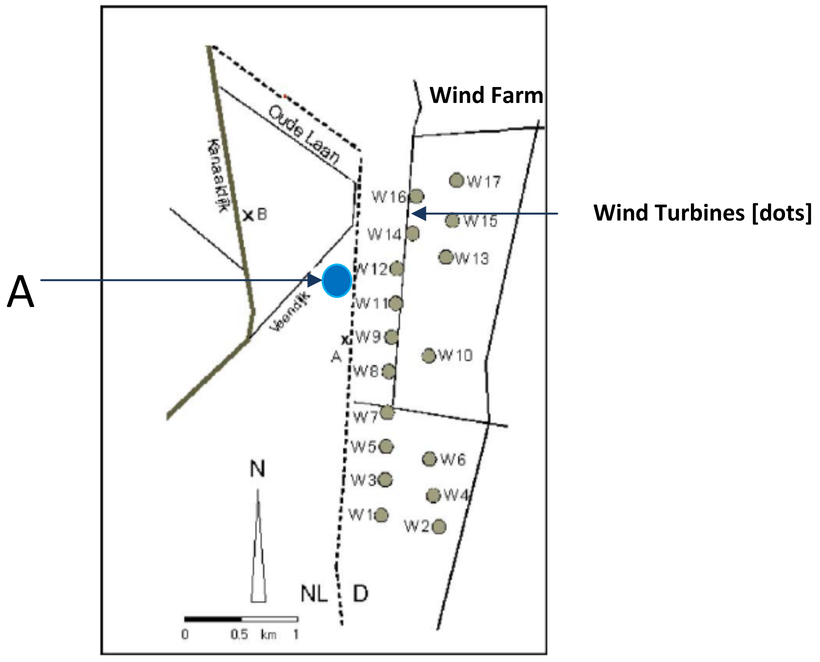
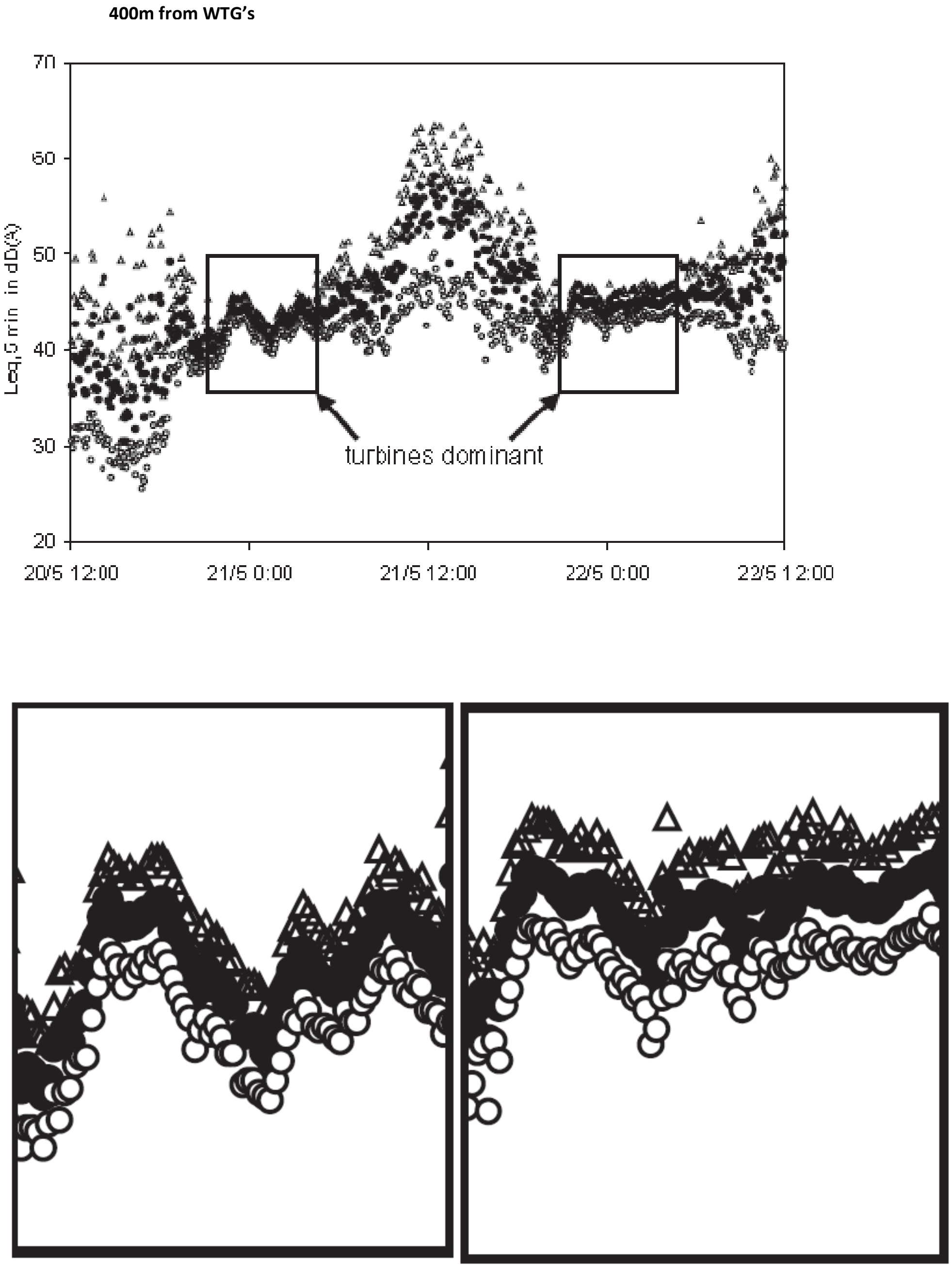


Figure 21: Location of wind turbines and measurement location [A] for Rhede wind farm near the Dutch/German border [26].

Although the study was not carried out specifically to look at L_{A95} and L_{Aeq} noise levels these descriptors are presented in some detail in graphical format. The study reports the sound levels were measured 400m west of the closest row of wind turbines [position “A”]. Van den Berg states that there were no reflections of turbine sound towards the microphone, except via the ground, and no objects [such as trees] between the turbines and the microphone.

The study provides background information regarding *dominant* wind turbine sound and a comparison between L_{A95} and L_{Aeq} sound pressure levels from wind turbine sound emissions only. Van den Berg reports that at times when the wind turbine sound is dominant, the sound level is relatively constant within 5 minute intervals. **Figure 22** demonstrates a sample of two nights [48 hours].

The measurement intervals with dominant turbine sound show very little difference and in some cases there appears to be no ‘level difference’ in L_{A95} and L_{Aeq} noise descriptors, however this would not be the case as even constant type environmental sounds would contain some form of variation between noise descriptors, even if very small. The actual levels are however not presented in tabulated format for review.



L_{Aeq} [solid black dot]

L_{A95} [black dot]

Figure 22: Comparison of 48 hour sound measurements levels [L_{Aeq} and L_{A95}]. Measurements presented at 5 min intervals at measurement location A [400m from wind farm]- turbines are considered the dominant sound source from site observations [[26]].

There are some key differences between the Van den Berg study carried out in Germany and the thesis study being carried out here. The key difference is the terrain for the Van den Berg study was flat; this is in contrast to New Zealand terrain where wind farms are situated which is usually undulating or steep and hilly. The fact that the terrain is flat for the Van den Berg study is significant in terms of the applicability of some wind shear effects, as what occurs in European countries with flat terrain may not apply for New

Zealand sites with low wind shear and / or are located within coastal environments with highly stable wind regimes. Wind shear and associated effects are discussed in **Chapter 5.**

The other key factor to note is the distance to turbine i.e. measurements for the Van den Berg study were at a relatively close proximity to the wind farm being 400m, the thesis question relates to providing a description of the relationship between L_{A90} and L_{Aeq} for wind turbine sound where people are located, this is generally almost always at distances greater than 400m from the turbine for sites in New Zealand. There are also issues with the data such as measurement being carried out at 10 m for wind as opposed to hub height. Regardless the study illustrates expected results being wind turbine noise is dominant when measured in the near field under favourable conditions. This is not unexpected in the near field.

Ramakrishnan Review

A very extended and detailed review of Van den Berg's Thesis has been carried out by Ramakrishnan [27]. As detailed in the Ramakrishnan Review, one of the main hypotheses of the Van den Berg work was atmospheric stability, particularly 'stable' and 'very stable' conditions occurring mostly at night time. The Van den Berg Thesis also states that hub height wind speeds can be higher than those predicted from the 10 m high wind speeds using standard methods, such as the logarithmic profiles of the IEC standards. This means that the wind turbine noise levels can be higher than expected. It was also conjectured by Van den Berg that these discrepancies are prevalent during summer months; and 'beat-sounds' can become very pronounced during stable and very stable conditions.

In terms of the Van den Berg results sound immission levels at Locations A and B discussed above in the Ramakrishnan report found that '*The data provided is very difficult to analyse and at times very confusing".* This appears to be a fair comment.

Ramakrishnan points out that the sound level meter monitors were un-manned and the differences in A-weighted sound levels between the 5^{th} and 95^{th} percentiles over 5-minute intervals were used to determine the dominance of turbine sound.

Ramakrishnan states that Van den Berg uses a value, $L_5 - L_{95} \leq 4$ dBA, to deduce the duration of high sound levels at night time and day time and there was no reason given as to the selection of the 4 dBA number. Ramakrishnan provides detailed comments and states regarding Van den Berg's findings that one would have expected a lower value, if the wind turbines were the main dominant sound sources. However as shown in the results the value is closer to 3 dB.

Ramakrishnan goes on to comment about the results that 'the criterion of $L_5 - L_{95} \leq 4$ dBA to determine the dominance of wind turbine noise is critical to the assessment. If the sound was steady during the 5 minute period, the above difference would be zero. Since outdoor sound levels are never steady, one expects some variability. However, it is the belief that 4 dBA range is too high. If one were to reduce the difference to 2 dBA or 3 dBA, the night time duration for dominant sound levels would reduce.'

In summary the Ramakrishnan assessment and findings take issue with the explanations and presentation of data presented by Van den Berg and hence does not accept the Van den Berg argument in its entirety. I agree.

Ramakrishnan states that the statistical analysis and associated results are limited with regard to wind turbine effects because of the paucity of the evidence obtained from at least one properly designed randomised controlled trial and evidence obtained from well designed controlled trials without randomisation.

The fundamental question regarding the results is - can the results relative to the study question and dominant wind turbine sound be relied upon? One of the major comments made by Ramakrishnan on the Van den Berg Thesis is the reliance on the wind farm sound levels at receptor locations from unmanned logging.

This analysis appears to be a significant issue for Ramakrishnan as the wind farm sound levels at receptors may not actually always be wind turbine sounds i.e. Ramakrishnan basically comments on the fact that how can one be 100% sure that the distribution of dominant wind turbine samples collected is actually wind turbine sound? Therefore he states that it cannot be concluded for sure that the data collected is in fact dominant wind turbine sound. This is a fair comment as it is not clear if any filtering of data has occurred.

The uncertainty of unmanned logging may have been able to have been avoided if simultaneous sound level measurements and real time audio recordings of wind turbine sound were undertaken. The practice of using data loggers is however a common practice for consultants to collect samples [especially if a large enough statistical set of data is to be collected]. Regardless one must be sure of the fact that the sampled sound is indeed wind turbine sound only.

In the author's experience it would be unpractical to attend the sound measurements at all times. In regards of say a short 12 hour sample it would not be unrealistic for simultaneous audio samples to be collected and the wind turbine sound pressure levels analysed concurrently, this way any audio recording could be reviewed in line with the sound pressure levels and any non turbine sound or noise with extraneous data removed from the sample set.

In terms of much longer samples i.e. days, weeks or months it would however be unrealistic to carry out analysis of audio recordings simultaneously for various reasons including the recording must be listened to and played back in 'real time'.

It is the author's experience from carrying out sample audio recordings for this study that download times, size and storage of audio files would also present potential issues for longer term studies. The 'quality' of audio recordings and being able to distinguish between non wind turbine sounds [background noise such as aircraft overfly, wind noise etc] and actual wind turbine sounds at receiver locations can also present a major challenge, even with the best audio recordings and systems in place. It is noted that audio recording in itself is a major undertaking to ensure quality clear recordings are available.

New Zealand Studies and Reviews

A third study [28] set in New Zealand conditions has been sourced regarding direct comparisons between L_{A95} and L_{Aeq} sound pressure levels from wind turbine sound emissions on a modern operating wind farm in the Lower North Island of New Zealand.

To the best of the author's knowledge, this is the only study which could be found where measurements were specifically carried out in order to investigate the perceived discrepancy of 2.5 dB between the L_{A95} and L_{Aeq} sound level descriptors under New Zealand Conditions.

This study was carried out as part of an assessment into a stake holder review of NZS6808:1998 *Acoustics - Assessment and Measurement Of Sound From Wind Turbine Generators*. The study was carried out by Malcolm Hunt Associates and one other consultant on behalf of the New Zealand Wind Energy Association. It is noted that the author of this thesis was part of the team of consultants that carried out the actual field measurements on the wind farm site for this study [and analysis].

Regarding the New Zealand Wind Energy Association field measurements these were carried out in the vicinity of wind turbines at the Te Apiti Wind Farm, Palmerston North [New Zealand]. This wind farm consists of 55, V72 Vestas wind turbine generators. The wind farm is a modern wind farm with horizontal three bladed turbines.

The study tells how that in order to investigate the relationship between the L_{A95} and L_{Aeq} sound levels a 'simulation' was prepared, using a sound level *recording* [audio recording] of a wind turbine at 100 m. The R_o location for these Te Apiti Vestas wind turbine generators is 105 m.

In addition to the above sound level measurement/audio recording several other measurements were also collected at the same time all being within close proximity of the subject wind turbine generator [Tap 35]. The greatest distance from the turbine was approx 900m [as the crow flies]. All surrounding wind turbine generators were switched into 'park' when the study was being conducted so that only sound level emissions from the subject turbine was measured.

The recording was essentially free from the influence of extraneous noise sources. This was because of the close proximity to the measurement location to the wind turbine generator which meant that the dominant sound source was wind turbine generator sound only. Furthermore, due to the dual audio recording, any extraneous noise was able to be removed after analysis was carried out. The recordings were also manned.

The method used allowed both the turbine sound level [L_{Aeq}] and the background noise level [L_{A95}] to be directly measured and the combined level to be separately analysed. The wind speed for the sample recordings was restricted to 14 metres per second, being the wind speed at hub height on the day the investigation was carried out.

The study states that for each ratio of turbine sound level to background noise level the L_{A95} of background noise level was subtracted from the L_{A95} of the combined level, and compared with the L_{Aeq} and L_{A95} of the directly measured wind turbine sound level. The study results are summarised in **Figure 23**.

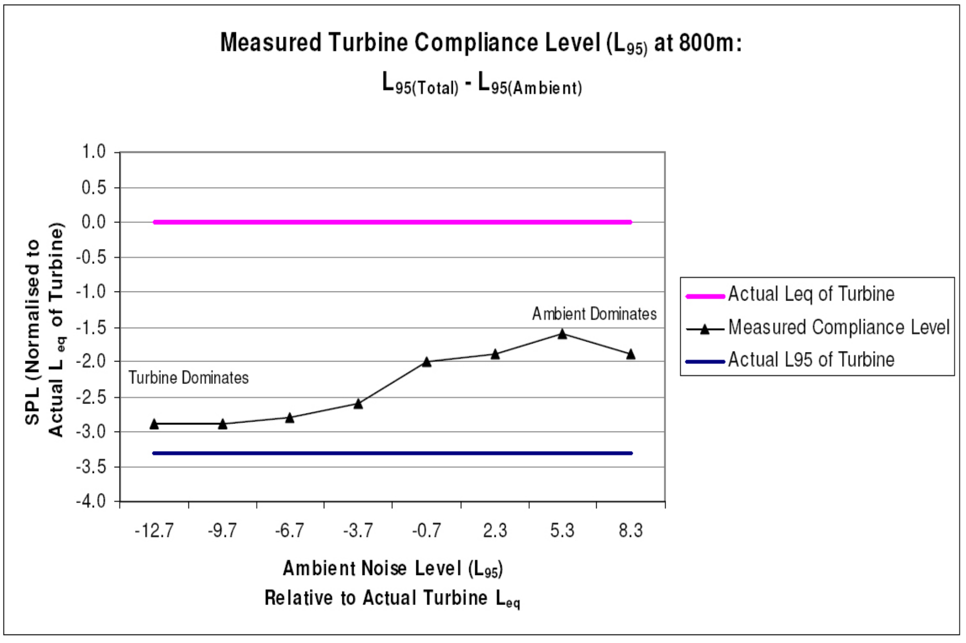


Figure 23: Comparison of turbine noise statistics [28].

As discussed in the study and shown in **Figure 23** the left most point on this graph represents the case where the measured sound is completely dominated by wind turbine sound. In regards to this scenario the *calculated* wind turbine sound level descriptor L_{A95} agrees well with the *predicted* level based on the L_{A95} of L_{Aeq}.

The right most point of the graph represents the case where the turbine sound is almost immeasurable. In regards to this scenario the calculated wind turbine generator sound level descriptor L_{A95} is under predicted but the L_{Aeq} sound level descriptor is over predicted.

Overall the New Zealand Wind Energy Association study concludes that the single measurement sample at one wind speed [14 m/s] on one single day is not sufficient to demonstrate the relationship between predicted and measured statistics.

The study does however provide a starting point in which it suggests that the L_{A95} and L_{Aeq} may in some cases under predict the measured sound pressure levels. Whether this discrepancy would occur in practice depends on the relative temporal variations of the turbine and the background noise environment at the receiving position. Regardless the study provides a key output that being there is a difference of around 3 dB between the actual measured L_{Aeq} of L_{A95} sound pressure levels at a distance of 800m from the turbine. The New Zealand Wind Energy Association study is the starting point for this thesis with the approach being to take the study off site to actual sound immission locations where people are located.

Wind Turbine Sound Sources

The sources of sounds emitted from operating wind turbine generators can be divided into two categories 1] mechanical sounds, from the interaction of moving turbine components, and 2] aerodynamic sounds, predominately produced by the flow of air on and around the rotor and rotor blades.

Mechanical sound arises from a number of sources including the gearbox, generator and pump systems. Aerodynamically produced sound [also referred to as aero-acoustics or aero-acoustic sound] arises chiefly from the interaction of the flow over the blade with the surrounding air flow.

It appears that the majority of research from reduction of aerodynamic sound from wind turbines focuses around the serrated trailing edges, different trailing edge and tip shapes. The profile of the rotor and aerofoil is also an area of common research. As mechanical sound is well understood in its concept and control there is limited coverage.

A summary of each of these sound generation mechanisms is discussed below.

Mechanical Sounds From Wind Turbine Generators

Pinder [29] identifies mechanical sounds from wind turbines as being generated by the movement of mechanical components and the active response among them. Five key sources of mechanical sounds identified by Pinder are:

1. Gearbox;
2. Generator;
3. Yaw Drives;
4. Cooling Fans;
5. Auxiliary equipment [i.e. hydraulics, oil coolers, pumps].

Mechanical sounds are largely viewed as “secondary” to aerodynamic sound. The extent to which audible sound is detected beyond the base of the wind turbine tower depends on the relative level of the mechanical sound to other sound types present and background noise level mainly due to wind noise. Aerodynamic sound would normally be the dominant of the two sound sources [30].

The emitted sound associated with the rotation of mechanical and electrical equipment tends to be tonal [of a common frequency] although it may have a broadband component. For example, pure tones can be emitted at the rotational frequencies of shafts and generators, and the meshing frequencies of the gears. In addition, the hub, rotor, and tower may act as ‘loudspeakers’, transmitting the mechanical sound and radiating it out into its surrounding environment. The transmission path of the sound can be air-borne or structure-borne. Air-borne means that the sound is directly propagated from the component surface or interior into the air. Structure-borne sound is transmitted along other structural components before it is radiated into the air. **Figure 24** shows transmission path and the sound power levels for the individual components [30].

It should be accepted that the numerical limits presented in **Figure 24** are indicative and would change depending upon the wind turbine generator model and operating modes at the time of measurement.

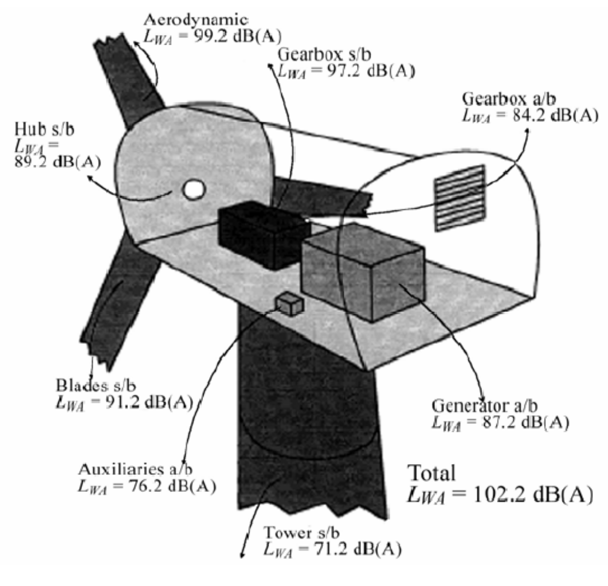


Figure 24: Components and total sound power level of a 2MW wind turbine, showing structure-borne [s/b] and airborne [a/b] transmission paths [30].

Figure 25 shows a measured sample of time varying sound pressure level of a modern wind turbine generator sound [under load] carried out at the base of a modern 3 bladed vertical wind turbine generator [with a 3MW electrical power output].

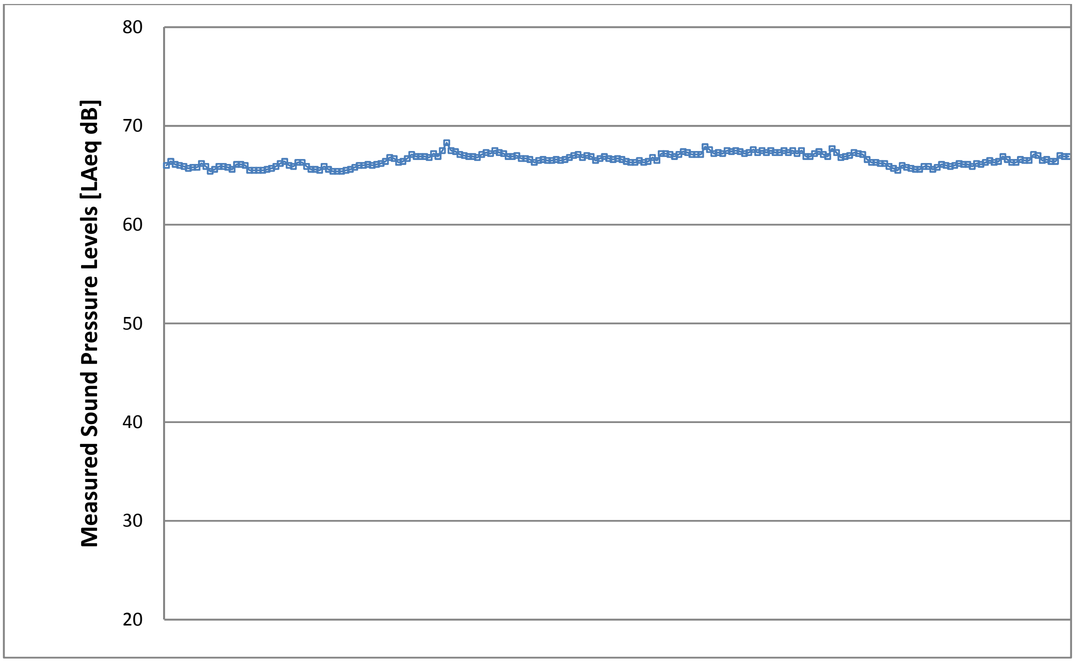


Figure 25: Sample of time varying wind turbine generator [under load] of a modern 3 MW wind turbine [measured at base approx 2 m from generator inside steel tubular base of tower with door closed [31].

Turbines can be designed or retrofitted to minimise mechanical sound and hence the total received sound output measured at surrounding locations. Such measures can include:

- Special finishing of gear teeth;
- Using low-speed cooling fans;
- Mounting components in the nacelle instead of at ground level;
- Adding baffles and acoustic insulation to the nacelle;
- Using vibration isolators and soft mounts for major components;
- Designing the turbine to prevent sounds from being transmitted into the overall structure.

Some of the key topics above are expanded in the following;

The dominant mechanical sound source would generally be gear box sound which could produce broadband sound with prominent tones [29]. An excess of mechanical sound in the sound output from a wind turbine may result in the presence of tones in the sound spectrum, sound in a band of frequencies called the 'critical' band surrounding the frequency of the tone [32].

Hau [33] states the noise emission from the gear box depends upon the quality and size, with a considerable range of sound power levels experienced. Hau provides the following expected sound pressure level values for three different types of gear boxes:

- Smaller parallel shaft gear boxes [up to ~100 kW] = L_{Aeq} 75 to 80 dB;
- Medium sized parallel shaft gear boxes [up to ~1000 kW] = L_{Aeq} 80 to 85 dB;
- Large planetary gear boxes [up to ~3000 kW] = L_{Aeq} 100 to 105 dB.

Although not reported by Hau it is expected the above levels relate to measurements inside the tower or nacelle and therefore it would be uncommon for a modern 3 MW commercial wind turbine generator to produce mechanical sound to levels above L_{Aeq} 50 to 60 dB at the base of the tower. Such levels at a distance of 50 or more metres from the base of the turbine would not likely be audible or even measurable [in the context of background noise].

Bevelled teeth are almost always used in 'normal' gear boxes in order to reduce the sound levels. When the teeth are set at an angle, the next tooth will start to engage and take up the load before the previous tooth has slipped contact. This results in a quieter, more harmonious operation. For interior gear wheels bevelled teeth can only be machined using special machine tools that up until now have solely been used for the machining of very large turbine gears for use in ships. Therefore planet gears have always had straight machined teeth resulting in a higher sound level. By combining a planet gear stage and two normal gear stages, one obtains an acceptable compromise of the advantages and disadvantages with the two different types of gear [[2]].

Current methods and literature indicates that in regards to the nacelle sound insulation is usually required to provide sound lagging against potential gear box sound emissions. In relation to the nacelle cladding choice is important in terms of sound insulation and the overall sound emission received beyond the base of the wind turbine tower.

Developmental field measurements carried out by Malcolm Hunt Associates have shown that removal of sound insulation within the tower can alter the sound spectrum and overall sound pressure levels from modern turbines. Regardless such field measurements would not likely be audible at key receiving locations off site.

The sound transmission loss is a measure of the effectiveness of a material i.e. external nacelle cladding, to prevent the transmission of sound from inside the wind turbine generator nacelle and tower reaching the external outside environment. The sound transmission loss [insertion loss] may be given as equal to Sound Power Level $_{\text{incident}}$ – Sound Power Level $_{\text{transmitted}}$.

Generally both the gear box and generator are mounted on supports by means of elastomeric bearings [flexible mounts] which helps ensure that no stresses are produced in the mechanical drive train. In the case of avoiding structure deformity this prevents potential structure borne sound from being transmitted. It is also noted that if the gear box was directly joined to the nacelle skin [cladding] it would be difficult to avoid unpleasant resonances. Hence the literature points out that such design is avoided in terms of minimising acoustic sound emissions from the wind turbine generator.

Aerodynamic Sound from Wind Turbine Generators

The literature review indicates aerodynamic sound is a highly complex field and while general principles are well understood there are vast amounts of unanswered questions, even in relation to modern wind turbine design. Aerodynamic sound is a chief area of sound production relating to the research question being investigated. Wagner [30] identifies three key areas of aerodynamic sound mechanics in relation to wind turbine generators:

- Low frequency sound;
- Inflow turbulence sound;
- Airflow self sound.

Wagner [30] describes the mechanism of these three areas and their importance as adapted in **Table 2.**

Type of Indication	Mechanism	Main Characteristic & Importance
1. Low-Frequency Sound		
Steady thickness sound; Steady loading sound	Rotation of blades or rotation of lifting surfaces	Frequency is related to blade passing frequency, not important at current rotational speeds
Unsteady loading sound	Passage of blades through tower velocity deficit or wake	Frequency is related to blade passing frequency, small in cases of upwind rotor, though possibly contributing in case of wind farms
2. Inflow Turbulence Sound	Interaction of blade with atmospheric turbulence	Contributing to broadband sound, not yet fully quantified
3. Airfoil-Self Sound		
Trailing edge-sound	Interaction of blades with atmospheric blade trailing edge	Broadband, main sound source of high frequency noise [<770Hz < f < 2 KHz]
Tip sound	Interaction of tip turbulence with blade tip surface	Broadband, not fully understood
Stall, separation sound	Interaction of turbulence with blade surface	Broadband
Laminar boundary layer sound	Non-linear layer instabilities interacting with the blade surface	Tonal, can be avoided
Blunt trailing edge sound	Vortex shedding at blunt trailing edge	Tonal, can be avoided
Sound from flow over holes, slits and intrusions	Unstable shear flows over holes, slits, vortex shedding from intrusions	Tonal, can be avoided

Table 2: Aero acoustic mechanisms of a wind turbine generator [[30]].

Wagner [30] states that all three key aerodynamic sound generation mechanisms should be considered both separately and cumulatively. It is generally unattainable to indentify all separate mechanisms when measuring sound levels from the wind turbine under investigation other than to identify the dominant sources and their related operating modes.

The literature review carried out by Wagner discusses the above three key areas as follows;

1. Low Frequency Sound: Low frequency is generated when the rotating blade encounters localised flow deficiencies due to the flow around a tower, wind speed changes, or wakes shed from other blades.

Hayes [32] states that low frequency sound between 20 Hz and 250 Hz, is said to be associated with inflow turbulence of air into the rotor disc. Increased inflow turbulence, for example due to high wind shear, yaw error [turbine rotor not correctly aligning to the correct wind direction or wind direction varying with height] or wake effects [turbines in the wake from other turbines on the site] have been noted in the literature to increase low frequency sound emissions.

In relation to low frequency sound Leventhall [34] states that there are three main noise sources in wind turbines.

1. Turbulence from the blade tip, which is the highest frequency produced by the turbine and may be in the range 500 Hz to 1,000 Hz;
2. Gear and other mechanical sound, which may be in the range 20 Hz to 100 Hz ;
3. Small pressure pulses caused when the blades interact with the wind flow at the tower. As these have a fundamental frequency of about 1 Hz, analysis of their sound gives frequencies in the infrasound region, but at a very low, inaudible and immeasurable sound pressure level.

2. Inflow Turbulence Sound: Generally depends on the amount of atmospheric turbulence. The atmospheric turbulence results in local force or local pressure fluctuations around the blade. At high electrical power levels or high wind speeds inflow turbulence is normally the largest contributor to the overall sound of the wind farm [35].

Turbulence in the natural wind causes unsteady pressure on the wind turbine blades, leading to the radiation of sound – however the exact mechanisms behind inflow turbulence sound are not yet fully understood [30].

3. Airfoil Self Sound: This large diverse group includes the sound generated by the air flow right along the surface of the airfoil. This type of sound is typically of a broadband nature, but tonal components may occur due to blunt trailing edges, or flow over slits and holes.

Aerodynamic sound increases with rotor speed such that sound generated by the blades increases at approximately the fifth power [5th] of the blade tip speed [36]. This theory suggests that sound levels produced by a rotor increases with blade speed proportional to this fifth power of the velocity. Other general theories studied suggest that the tip speed of the blade is by far the strongest indicator of the sound a rotor blade may produce; therefore, it is recognised that theoretically it is most effective to reduce the tip speed by lowering the rotational speed.

Van den Berg [26] states that a blade radiates sound when the forces on the blade change because of a local variation in wind velocity. This happens every time the blade passes the tower because there the wind is slowed down by the tower. Because the tip has the highest speed the sound of a wind turbine mainly comes from the blade tips. The frequency content of the sound may also vary with speed or may remain unchanged depending upon the mechanism of sound generation present and the flow conditions.

Figure 26 is an example of an "acoustic photograph" showing the high speed tips of a wind turbine radiating - the greatest sound pressure levels are shown as purple and red colours.

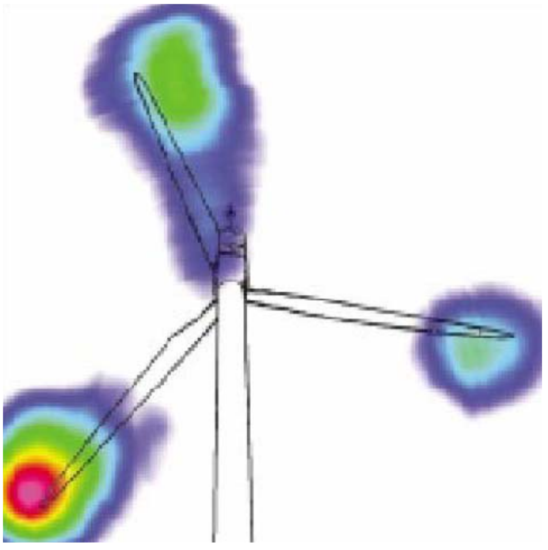


Figure 26: Acoustic photograph showing the high speed tips of a wind turbine [37]

Wind turbine blade sound is typically described as broadband sound and is characteristically the chief component of wind turbine sound emissions. Aerodynamic sounds originate from the flow of moving air around the blades. There are a large number of complex factors which occur to generate aerodynamic sound [30] – these issues have been reviewed further below with an analysis into the main areas of aerodynamic sound related to wind turbine rotor and wind turbine rotor blades.

These areas relate to the research in that alongside the operating environment which 'drives' the wind turbine it is the aerodynamic sound which is recognised as the main noise interpreted or perceived by people in the receiving environment.

Figure 27 illustrates a sectional elevation through a typical wind turbine rotor blade and key components.

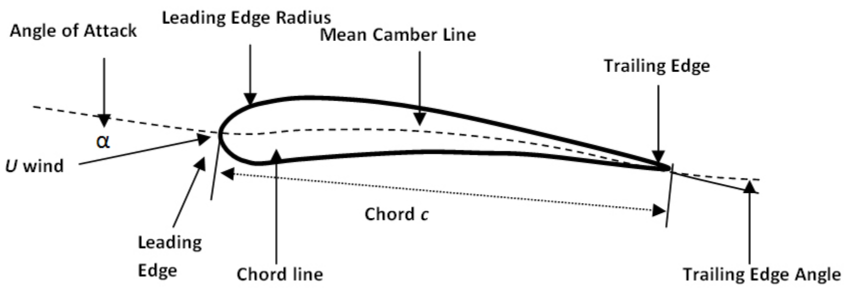


Figure 27: Sectional elevation through of a typical wind turbine rotor blade and key components. Two dimension sectional view.

Figure 28 illustrates a three dimensional view of flow around a wind turbine rotor blade [30] discussed further below.

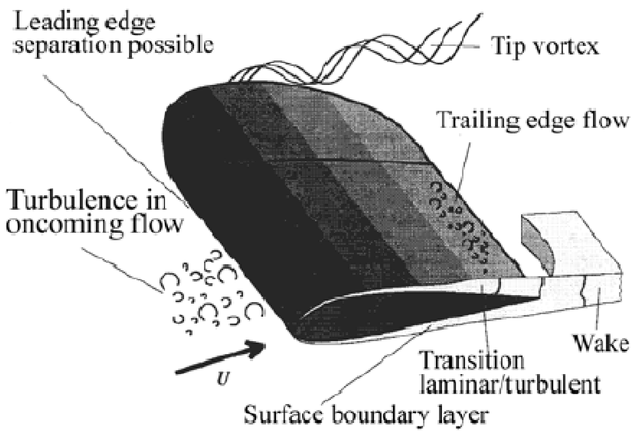


Figure 28: Flow around a wind turbine rotor blade – three dimension view [30].

Figure 29 illustrates six areas of flow around a wind turbine generator rotor blade leading to aerodynamic sounds.

Further to the above categories for aero acoustic sound from a wind turbine generator Migliore [38] describes six chief areas of aero-acoustic sounds [**Table 3** and **Figure 29**] as follows:

- Turbulent boundary layer trailing edge sound;
- Leading edge inflow turbulence sound;
- Blunt trailing edge sound;
- Separation sound;
- Blade tip sound;
- Laminar boundary layer vortex- shedding sound.

Migliore illustrates the above six categories as follows:

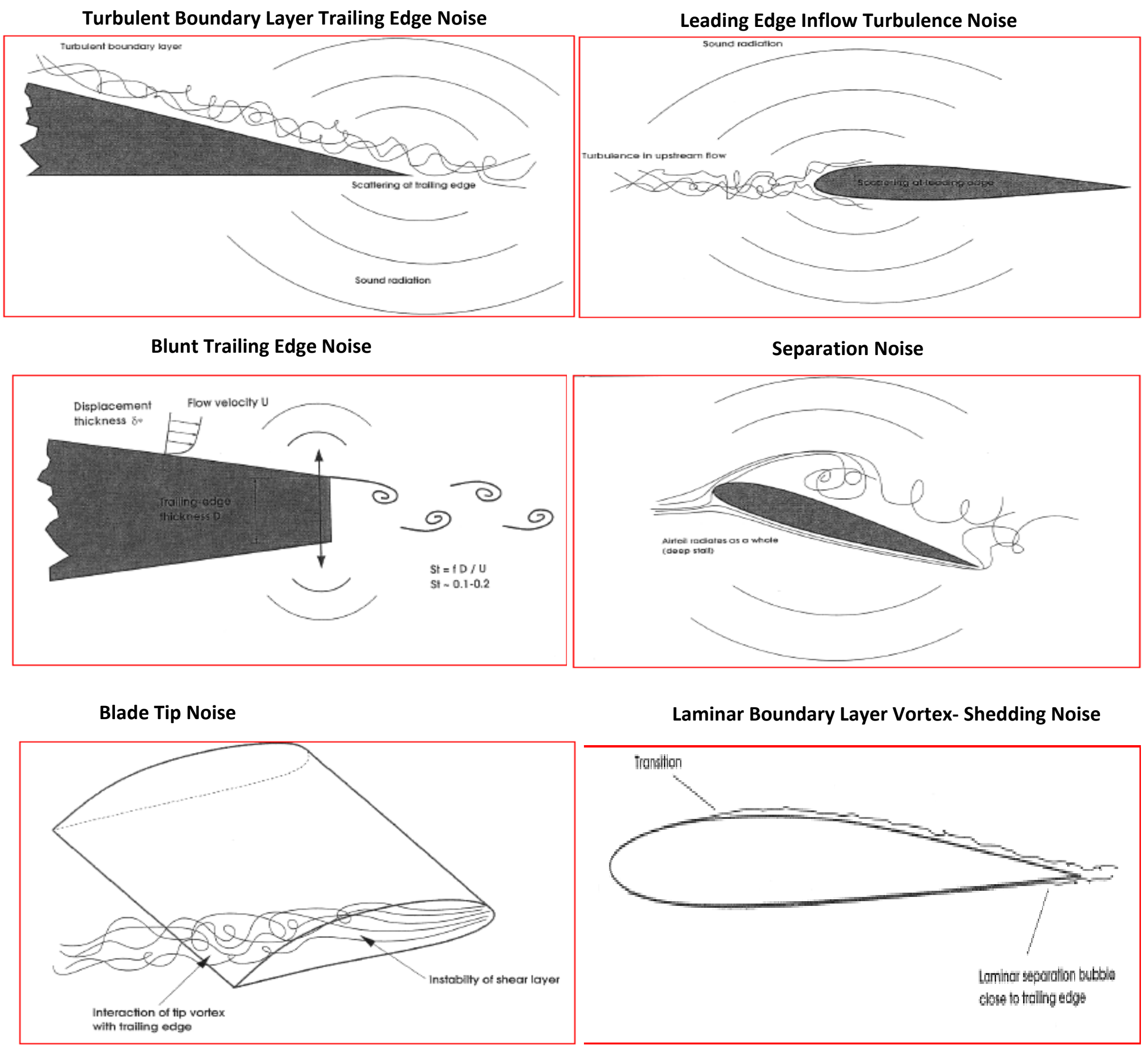


Figure 29: Six mechanisms of aero-acoustic sound[38]

In relation to the key aerodynamic mechanisms of a wind turbine generator Van den Berg [26] states that the sound of modern wind turbines is generated mainly by the flow of the wind along the blades.

In this process a turbulent boundary layer develops at the rear side of the blade where trailing edge sound of relatively high frequencies originates and which is radiated into the environment. This turbulent boundary layer becomes thicker and produces more sound when the wind flows in at a greater angle. The inflowing wind is turbulent itself. The blade cuts through these turbulent movements and as a result sound is generated; in-flow turbulence sound. Here lower frequencies dominate [26].

The peak in the frequency spectrum and the intensity of this source of aerodynamic sound is determined by the thickness of the trailing edge and the velocity of the blade through the air. In particular, the sharpness of the trailing edge can have significant effects upon the overall 'A-weighted' sound pressure levels [such as L_{Aeq}] generated by a turbine. This is due to the peak in the sound spectrum being around the most sensitive region of the A-weighting network, used by sound level meters to replicate the frequency response of the human ear, between 500 Hz – 2 kHz [26].

Tip sound is associated with the pressure difference between the lower and upper surfaces of the blade around the tip area which leads to an outflow of air from the underside of the blade to the low pressure upper surface. As the angle of attack increases, this outflow will increase leading to the development of a vortex above the blade, as occurs on the wings of large aircraft on landing. Sound associated with the tip is centred in the 2 to 3 kHz region, depending upon the angle of attack and tip speed. Blade tip noise can be minimised through detailed design of the tip shape and through control of the rate of change of pitch angle [26].

Other sources of aerodynamic sound that are tonal in character may occur. These are associated with nonlinear boundary layer instabilities, vortex shedding at blunt trailing edges, and unstable shear flows over holes and slits. Where they have occurred, solutions such as change in the pitch angle of the blade or boundary layer tips have improved reduced or removed these sources of sound. Such sound is generally of high frequency and is therefore attenuated very quickly, as distance from the turbine increases [32].

Patrick [39] states that the two dominant sources of aero-acoustic sound for wind turbines are thought to be sound due to the interaction of atmospheric turbulence with the leading edge of the blades and turbulent boundary layer sound from the trailing edges of the blades. Hayes [32] states that trailing edge sound associated with the interaction of the boundary layer turbulence with the blade trailing edge is one of the more dominant characteristics.

These six important topics of aerodynamic sound are examined further from current literature as follows:

Turbulent Boundary Layer Trailing Edge Sound: Turbulent boundary layer trailing edge sound occurs when the 'attached' boundary layer converts into the wake of the aerofoil resulting in turbulence referred to as boundary layer trailing edge sound production.

Fuglsang [40] states that turbulent boundary layer trailing edge sound is broadband and its contribution is minor to the overall sound pressure level produced by the wind turbine generator at Reynolds numbers. Fuglsang [40] using the work of Williams and Hall produced the following formula for predicting the sound pressure level from turbulent boundary layer trailing edge sound [TBL-TE].

$$[L_p]_{TBL-TE} = 10\log_{10}\left[10^{[L_p]_\alpha/10} + 10^{[L_p]_s/10} + 10^{[L_p]_p/10}\right] \qquad \textbf{[Eq 17]}$$

Where

$Lp_{\text{TB-LTE}}$ = Sound pressure level produced by the turbulent boundary layer trailing edge

$[L_p]_\alpha$ = Sound pressure level due to angle of attack [not equal to zero]

$[L_p]_s$ and $[L_p]_p$ = Sound pressure level from the suction and pressure sides of the aerofoil at an angle of attack equal to zero.

In the area of aerodynamics the Reynolds number is a ratio of inertial forces to viscous forces for a given flow condition. The Reynolds number is dimensionless. In relation to wind turbine generators the Reynolds number is used to identify and predict different flow regimes, such as laminar or turbulent flow. Laminar flow occurs at low Reynolds numbers. Turbulent flow occurs at high Reynolds numbers. The Reynolds number of an aerofoil can be given as

$$Re = \frac{\nu\, l}{\upsilon} \qquad \textbf{[Eq 18]}$$

Where

ν = flow velocity [m/s]

l = chord length [m]

υ = kinematic air viscosity $[m^2/s]$ at m.s.l.: $\upsilon = 1.5 \cdot 10^{-5}\ m^2/s$

Howe [41] further sets out a theory which illustrates that the use of a serrated trailing edge would lead to reduction of sound emissions from the wind turbine generator blades, accordingly Howe believes the reductions are obtained independently on the aspect ratio of the serrations and their related lengths along the trailing edge.

Braun [42] found in his studies that sound reductions could be achieved due to straight, bent or curved serrations. However the study pointed out that sound reductions occurred below 1250 Hz while above 2000 Hz sound levels increased. Nevertheless the literature agrees that overall total sound level reductions of around 2 dB could be achieved across the frequency spectrum. **Figure 30** illustrates a laboratory model rotor within a wind tunnel with trailing-edge serrations, including projection of sound sources on rotating blades. Note the majority of acoustic energy is produced at the blade tips [coloured red in photo].

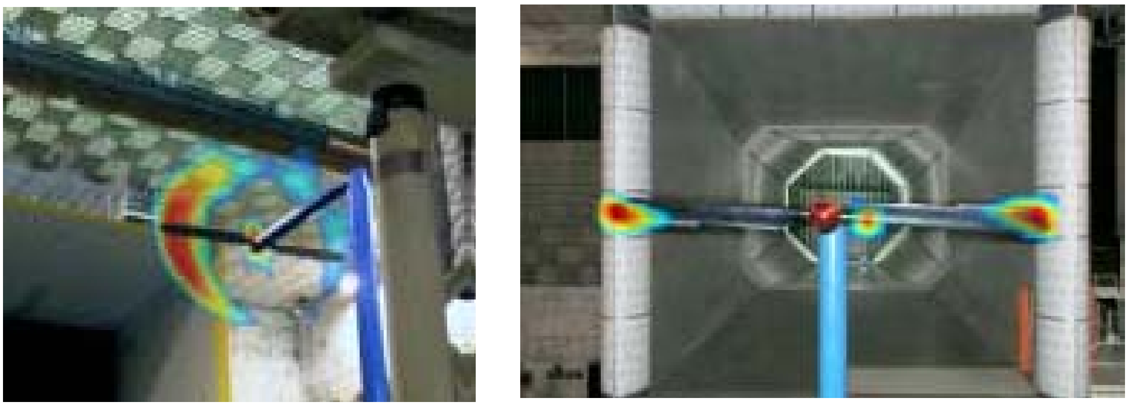


Figure 30: Rotor with trailing-edge serrations, including noise sources on rotating blades [[43]].

In a study by Oerlemans [[43]] it was found that trailing edge sound reduction by an optimised airfoil shape is possible with the average sound reduction achieved for varying conditions being about 4 dB. A reduction of 4 dB at the source should be viewed as noteworthy.

Inflow Turbulence Sound: Wagner [[30]] states that the exact mechanisms behind inflow turbulence sound are not yet fully understood with the turbulence in the natural wind causing unsteady pressure on the wind turbine blades leading to sound emissions.

Separated Inflow Sound: Separated flow sound is produced from unsteady flow caused from the separation which originates from the shedding of vortices from the aerofoil trailing edge into the wake. Wagner [[30]] states such sound can only be avoided by limiting the angle of attack of the aerofoil so as to avoid stalled flow.

Lowson [[44]] considers at high power levels or high wind speeds inflow turbulence is the largest contributor to the overall sound emission levels of the wind turbine.

Laminar Boundary Layer Vortex- Shedding Sound: Trailing edge sound may exist on either side of the aerofoil for a rotor blade operating at Reynolds numbers less than 10^6. However as modern wind turbine generators operate at much higher numbers the Laminar Boundary Layer Vortex-Shedding Sound is not viewed as a major contributor to the overall aerodynamic sound emissions. Wagner [[30]] states solutions to the issue include leading edge serrations and tripping of the boundary layer upstream of the trailing edge.

Rotor Blade Tip Sound: Brooks et al [45] states that the tip vortex interacts with a trailing edge in the same way the boundary layer turbulence would for trailing edge sound. Blade tip sound is dependent upon blade tip speeds, with tip sound from modern wind turbine generators usually being classed as higher frequency sound and broadband in nature.

Brook et al [45] provide the following formula for sound pressure levels produced from a tip vortex sound:

$$[L_p]_{TIP} = 10\,\lg\left[\frac{M^2 M_{\max}^5\, l^2\, \bar{D}_h}{r_e^2}\right] - 30.5[\lg St'' + 0.3]^2 + 126 \qquad \textbf{[Eq 19]}$$

Where:

$[L_p]_{TIP}$ is the sound pressure level due to tip vortex formation noise
$M = U/c$ is the Mach number
Where U is the free stream velocity, c is the speed of sound
$M_{max} = M_{max}[\alpha_{tip}]$ is the maximum Mach number in the vicinity of the tip vortex
Where α_{tip} is the angle of attack of the tip
D_h is the directivity
r_e is the retarded observer distance
$l = l[\alpha_{tip}]$ is the spanwise extent of the separation zone and depends on what is rounded or the sharp
$St'' = fl/U_{max}$ is the Strouhal number
Where U_{max} is the maximum velocity − in the vicinity of the tip vortex
f is the frequency

The literature reveals that blade tip shape is one key area associated with blade tip sound. Klug et al. [46] performed sound level field measurements on full scale outdoor wind turbines with different rotor blade tip shapes and showed that the geometry of the blade tip has a considerable effect on the overall broadband sound level. Klug reported that modifying the blade tip shape with respect to aerodynamic optimisation can lead to a substantial reduction of the sound emission at higher frequencies and reduce the overall sound level by up to 4 dB. The reduction of sound radiation at frequencies between 800 Hz and 7000 Hz can be clearly seen in **Figure 31**. It would be likely that future wind turbines will have increased rotors and increased tip speed ratios thus tip speeds can be expected to increase, potentially causing a problem of sound emitted from the blade tip if not addressed sufficiently.

Figure 31 illustrates the influence blade tips have on sound power levels. Note the presence of low frequency noise for both LM14.2 and LM14.4 tip designs.

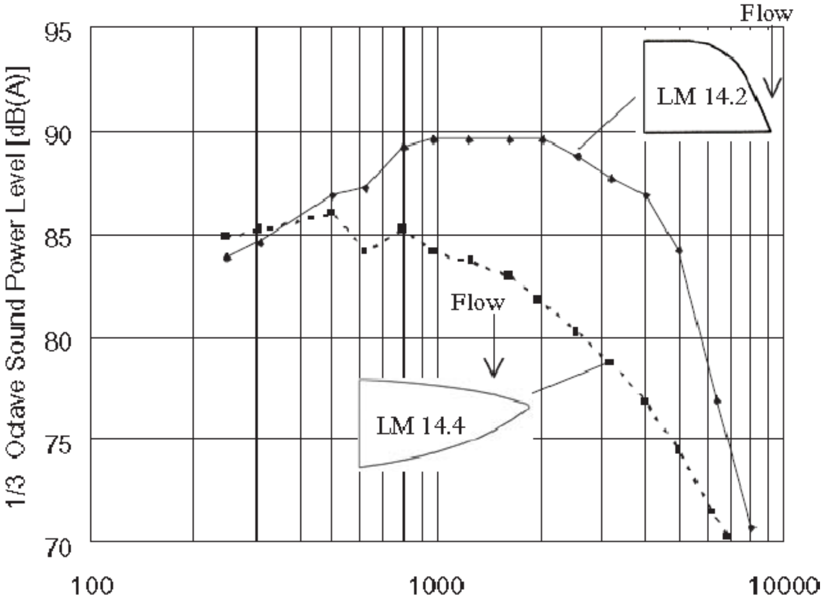


Figure 31: Blade tip shape influence on wind turbine sound radiation [46].

In a topical study by Arakawa [47] a computational model for aerodynamic sound prediction took into account the true shape of the wind turbine blade geometry being developed. This is viewed as an important step towards wind turbine blade design with respect to aerodynamic sound reduction in the receiving environment.

Through the analysis [**Figure 32**] Arakawa found it was the vortical structures that contribute most to the generation of the far-field sound which could be identified. The primary source of aerodynamic sound being unsteady motion of vortices in regions close to the blade. Regarding the actual tip shape, a concentration of high value sound source could be identified immediately downstream of the trailing edge at the tip. These sound sources near the blade surface can be expected to contribute strongly to the far-field sound pressure levels [47].

Figure 32 shows a sound source intensity map being used to detect dominant sound origins. The map shows that the most relevant sound sources are vortex generated aerodynamic sound for low-speed flows [47].

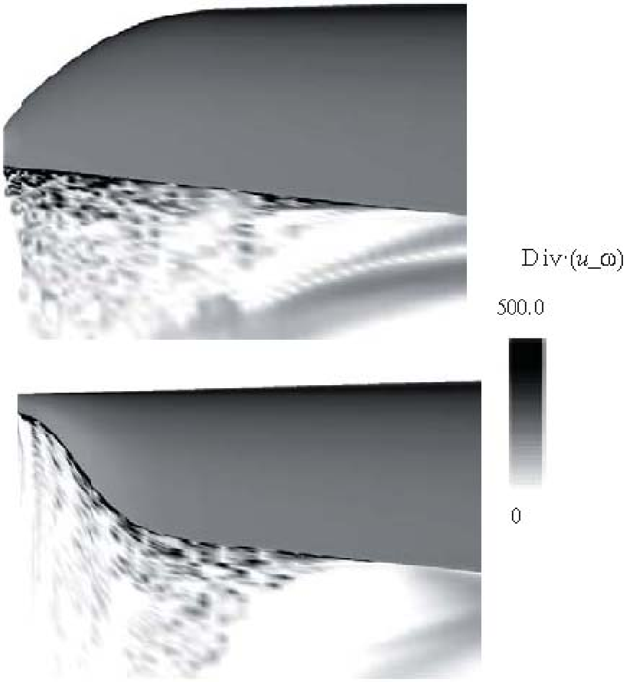


Figure 32: Distribution of instantaneous values of Powell's sound source term Div·[u×] on face *S1* [47].

Modulation of Aerodynamic Sound

Modulation of aerodynamic sound refers to sound with a greater than normal degree of fluctuation at approximately once per second which makes it more noticeable and potentially more annoying at distant receiving locations.

The broadband noise emitted by a wind turbine generator is modulated by the blade passage frequency giving rise to a characteristic "swishing" or "whooshing" sound.

The International Standard IEC 61400-11: *Wind Turbine Generator Systems Part 11: Acoustic noise measurement techniques,* states that modulation can be displayed by recording the measured A-weighted sound pressure level with time weighting [Fast] for at least ten blade passes by the turbine [48].

A common description of wind turbine sound is that of 'swishing' from the blades. This is generally only in evidence close to a single wind turbine and is an effect caused by the change in level and spectral shape with angular position of the blade relative to the listener. As the blade travels towards the ground, the sound associated with the trailing edge rises to a maximum, the mid to high 'sw' of the swish [32].

As the blade reaches vertical in the six o'clock position, directivity effects will then reduce the blade noise from the trailing edge and tip. However, tip sounds associated with the upper pair of blades will become more dominant providing the high frequency 'ish' of the swish. When standing directly underneath a wind turbine, it is clear that as the lower tip passes overhead, high frequency sound all but disappears whilst the upper blades become more audible [[32]].

The swish, swish, swish sound, which is associated with wind turbines, is a modulation of a higher frequency, the blade tip turbulence, and does not contain a vast amount of low frequency sound. For example, compare an amplitude modulated radio signal, which contains only the carrier and sidebands. It is understood that some people may be inaccurately referring to the low frequency modulation as low frequency sound [[34]].

The spectrograph shown in **Figure 33** illustrates the 'swish' measured adjacent to two separate wind turbine generators. The various colours represent the A-weighted magnitude of the sound as a function of time, along the horizontal axis, and frequency, along the vertical axis.

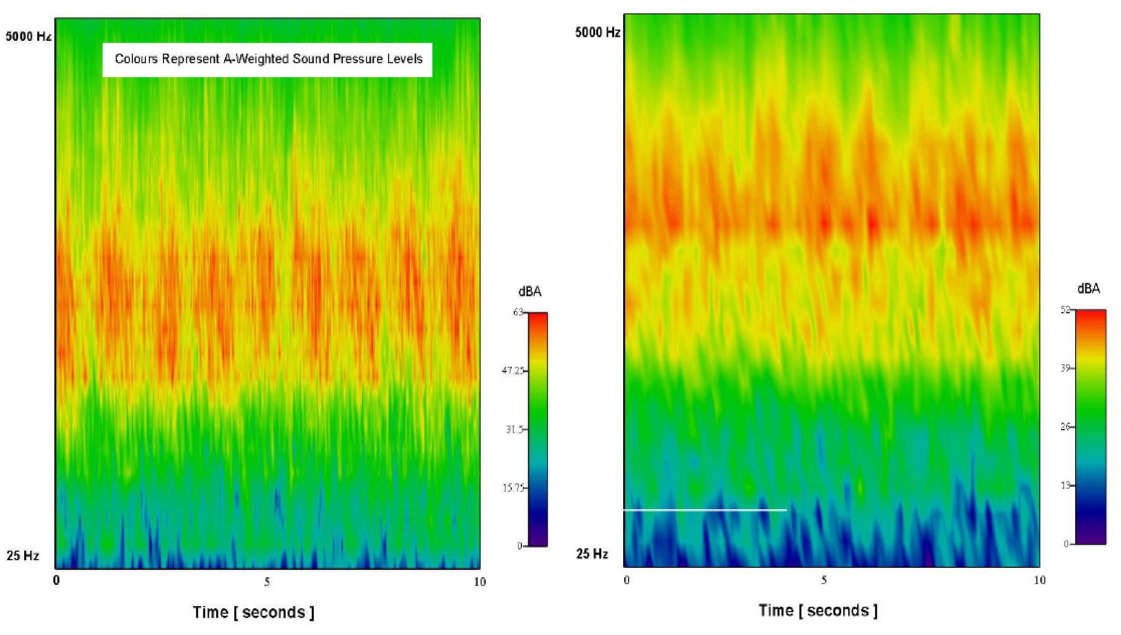


Figure 33: [left] Spectrogram of sound pressure levels measured near a GE 1.5 MW wind turbine generator. [Right]: Spectrogram of sound pressure levels measured near a Vestas 1.8 MW wind turbine generator [[41]].

A study was carried out by Stanford University on a report by the Hayes McKenzie Partnership [[49]] of low frequency sound emission from wind farms and sound complaints. The Hayes McKenzie report concluded that the complaints were not caused by low frequency sound, but by amplitude modulation of aerodynamic sound from the wind turbines.

The study was carried out in four parts, a survey of local authorities with wind farms in their areas, further investigation of sites for which amplitude modulation was identified as a factor, a literature review and a survey of wind turbine manufacturers.

The outcome of the study was that the incidence of amplitude modulation and the number of people affected is probably too small to make a compelling case for further research funding in preference to other types of sound which affect many more people. On the other hand, since amplitude modulation cannot be fully predicted at present, and its causes are not understood the study stated that it would be prudent to carry out further research to improve understanding in this area [[50]].

Navier Stokes Equations

The theory of the generation of sound by aerodynamic flows has been established whereby the central equations of motion of fluid are coerced into a form of the wave equation of linear acoustics. The Lighthill Theory is that aerodynamic sound is generated from fluid flow governed by the mass conservation and Navier-Stokes momentum equations.

The Navier Stokes equations [Claude Louis Navier and George Gabriel Stokes] describe the motion of fluids. The equations establish the change in momentum in volumes of fluid are the sum of dissipative viscous forces, changes in pressure and gravity acting inside the fluid - an application of Newton's Second Law relating to acceleration being that the rate of change of momentum of a body is proportional to the resultant force acting on the body and is in the same direction.

In terms of wind turbine acoustics the equations are important as they are used in the design and modelling of flow around an aerofoil [i.e. wind turbine blade]. There are various studies which discuss the topic including computer simulation for wind turbine generator noise modelling and design. One such study [[51]] discusses the advances in computing technology that have made computer simulation a relatively inexpensive avenue for modelling and design. Computational fluid dynamics has been increasingly used in the design of fluid interactive systems including wind turbine airfoils [used to analyse flow over wind turbine optimisation airfoils].

Lighthill Theory

In aero-acoustics both theoretical and computational efforts are made to solve for the acoustic source terms in Lighthill's equation in order to make statements regarding the relevant aerodynamic sound generation mechanisms present.

The Lighthill Theory rearranged the Navier-Stokes equations which govern the flow of a compressible viscous fluid into an inhomogeneous wave equation so as to make an analogy between fluid mechanics and acoustics.

The Lighthill equation [52] can be written as:

$$\left[\frac{1}{c_0^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right]p' = s_1 + s_2 + s_3 \qquad \textbf{[Eq 20]}$$

Where

$$s_1 = \frac{\partial}{\partial t}\left[m + \frac{1}{c_0{}^2}\frac{\partial}{\partial t}\left[p' - c_0^2\rho'\right]\right]$$

$$s_2 = \frac{\partial f_i}{\partial x_i}$$

$$s_3 = \frac{\partial^2 \rho u_i u_j}{\partial x_i \partial x_j}$$

The classical interpretation of the **Equation 20** consists of regarding the aerodynamic sound as a solution of a wave equation in a fictitious medium at rest.

Low Frequency Sound and Infrasound

A review of low frequency sound was completed by Leventhall [53]. In this review low frequency sound was defined as from 10 Hz to 200 Hz, whilst infrasound was defined from 20 Hz down to a very low frequency of around 1 Hz. The human ear is generally most sensitive between 500 Hz and 4000 Hz where speech signals are mostly contained, noting that the human hearing range is generally quoted as being between 20 Hz to 20,000 Hz and that Leventhall described infrasound as generally being 20 Hz and downward.

It is important to note that albeit any statement or reference to low frequency sound or infrasound is insignificant without reference to sound pressure levels of the sound itself i.e. below 20 Hz sound is usually normally inaudible, but may be experienced as being in a region of very high sound pressure levels. Combinations of the characteristics of, for example, the level, variability in the level, duration, frequency content and apparent loudness determine how each type of how sound may affect people. Leventhall in his low frequency sound study states that the information available concerning infrasound frequency emission from wind turbine generators indicates that the level of emission at frequencies below 20 Hz is little more or no more than at frequencies in the octave above 20 Hz. Typical sound power levels at infrasound frequencies are no higher than between

100 dB and 105 dB. The experts state that this level of infrasound emission is so low that it would be *inaudible* even at reasonably close distances to a wind turbine generator [34].

The aim of most studies on the low frequency threshold has been to determine the lowest levels which are audible to an average person, often a young 'healthy' person, with normal hearing. Thus, the threshold is a "quasi-objective" measurement in the sense that it is free from emotional responses and stimuli.

A literature review by Yeowart [54] has found that threshold studies have been carried out on relatively small groups, typically about 10 to 20 subjects, so that differences between experimenters are to be expected. However, the different studies follow the same trend, and the threshold region at low frequencies is now well established. Yeowart [54] presents the following results from studies into the threshold levels [**Table 3**].

Tester[s]	Test Frequency Range	Description of Test
Corso	5 Hz to 200 Hz	Monaural headphone
Whittle et al	3.15 Hz to 50 Hz	Pressure chamber
Yeowart and Evans	1.5 Hz to 100 Hz	Monaural headphone
	5 Hz to 100 Hz	Binaural headphone
	2 Hz to 50 Hz	Pressure chamber
Moller and Andresen	2 Hz to 50 Hz	Pressure chamber
Watanabe and Moller [a]	25 Hz to 1 kHz	Free Field
Watanabe and Moller [B]	4 Hz to 125 Hz	Pressure chamber
Ludolf and Moller [a]	20 Hz to 1 kHz	Pressure chamber/free field

Table 3: Frequency ranges covered and method of exposure from seven studies [54].

Different measurement methods i.e. monaural/binaural headphones, pressure chamber, free field potentially produce different results. Free field levels are often taken in the absence of the subject, whilst pressure chamber measurements are taken in the presence of the subject.

In a separate study by Watanabe and Møller [55] it was found no significant difference between their two measurements in the frequency range of overlap.

Sound sources associated with infrasound frequencies are generated by unsteady loading of the wind turbine blade. Such effects were noted by Hubbard & Shepherd [56] following measurements on 'downwind' turbines, i.e. turbines with blades downwind of the tower or other turbine support structure. The result of such a wind turbine configuration is that the blade passes through the wake caused by the presence of the tower in the airstream, generating high levels of acoustic energy at the blade passing frequency and associated harmonics - with the development of upwind turbines, operating at lower rotational speeds, this source of sound has all but been eliminated.

The World Health Organization Guidelines for Community Noise [6] discusses the subject of low frequency sound, however there appears to be no particular reference to wind turbines in the section dealing with industrial sound. The report guidelines discuss low frequency sound in general terms stating under ***Section 7.1.4*** Infrasound and Ultrasound:

Frequencies below 16 Hz [or 20 Hz] are referred to as infrasonic frequencies. Infrasound is audible. However, the human hearing has a very narrow dynamic range at infrasonic frequencies; the range from the first soft perception to pain is only 30 - 40 dB. Perception of sound from 100 Hz down to about 2 Hz is a mixture of auditory and tactile sensations. For example, frequencies around 10 Hz, can cause discomfort through a modulation of the vocal cords. But the main sensitive organ for sound at frequencies below 20 Hz is within the ear and not in the breast or stomach. There is no reliable evidence that infrasound below the hearing threshold produce physiological or psychological effects[6].

Annoyance from Wind Turbine Generator Sound

Annoyance measurements are generally an attempt to relate annoyance ratings directly to measured sound levels. There have been a large number of laboratory determinations of annoyance of low frequency sounds, mainly measurements using either 'normal' or 'sensitive' subjects. Stimuli have included tones, bands of sound or specially developed spectra.

Kalveram [57] points out that much psycho-acoustical sound research has limitations, because it is based upon the correlation between annoyance ratings and physical measurements of sound energy, with subsequent correlation of annoyance and sound level.

Determinations have also been aimed at relating the A-weighted level of the low frequency sound to its annoyance. A comparison of a band of sound peaking at 250 Hz with a band peaking at 100 Hz, whilst both were adjusted to the same A-weighted level, showed that the annoyance from the low frequency sound was greater than that from the higher frequency sound at the same A-weighted level [58].

Conclusions drawn from reviewed studies are: 1] there is a large variability between subjects and 2] The dB [A-frequency weighted] underestimates annoyance for frequencies below about 200 Hz. For broadband low frequency sound, the underestimation was found to be 3 dB for levels around 65 dB [Linear] and 6 dB for levels around 70 dB [Linear]. Similar results had been obtained in earlier work [59].

Broner [60] measured individual annoyance functions for 20 subjects using ten low power frequency sound stimuli. The psychophysical function was assumed to be a simple power function as follows:

$$\Psi = k\varepsilon.^{\beta} \qquad \text{[Eq 21]}$$

Where

$\Psi =$ estimation of psychological magnitude

$\varepsilon =$ stimulus intensity

$\beta =$ subject − specific exponent

It was shown that there was a wide range of individual exponents, *β* from a low of 0.045 to a high of 0.4 and three groupings of individual differences were identified. Previous work at higher frequencies had also shown individual loudness functions [61] and had posed the question of whether one set of regulations should be applied to all people [62]. This question appears to still remain unanswered within current literature today.

Low Frequency Sound and Health Effects from Wind Turbine Generators

G Frequency Weighting

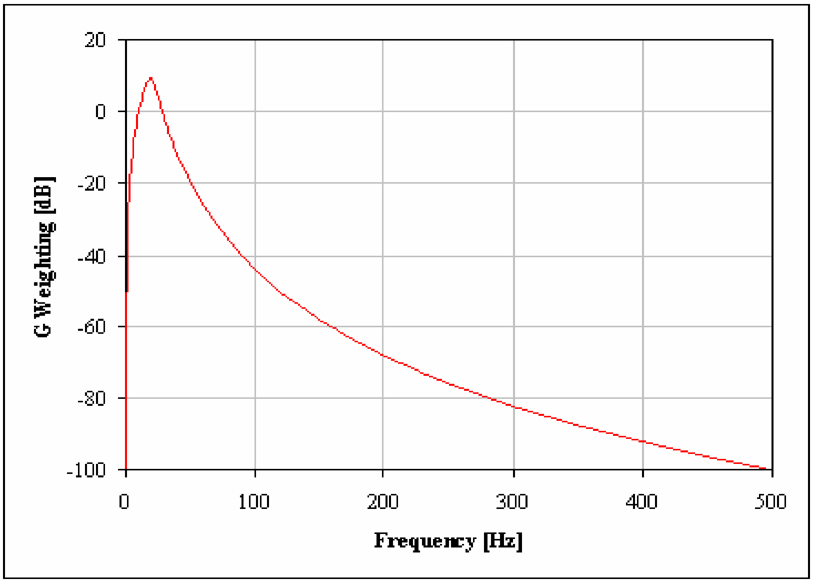
A study prepared for the Canadian Wind Energy Association [41] states that infrasound, at a certain level, is prevalent everywhere in the natural environment; people are continually subjected to sound at infrasonic frequencies. Natural sources of infrasound include wind and breaking waves, and there are a wide range of man-made sources such as industrial processes, vehicles and HVAC systems in buildings.

The study reports that there are a variety of ways to define the magnitude of infrasound, one of which is the G-weighting network [dBG], designated by ISO specifically to deal with infrasound. G-weighted sound levels of 85 dBG and lower are not sufficient to create human perception. Infrasonic levels created by wind turbine generators are often similar to the background sound levels prevalent in the natural environment due to wind, typically 85 dBG or lower, and there is no evidence of adverse health effects caused by this infrasound. Infrasound near modern wind turbines is generally not perceptible to humans, either through auditory or non-auditory mechanisms [41].

There is often an audible ‘swish’ created by wind turbines, which is essentially broadband sound whose amplitude is modulated at a low frequency, but this should not be mistakenly confused with infrasound. All in all, based on Canadian and international studies, infrasound generated by wind turbines should not be considered a concern to the health of nearby residences [41].

G weighting purportedly reflects human subjective response to infrasound. The curve is defined to have a gain of zero dB at 10 Hz. Between 1 Hz and 20 Hz the slope is approximately 12 dB per octave. The cut-off below 1 Hz has a slope of 24 dB per octave, and above 20 Hz the slope is -24 dB per octave [63].

The threshold for human perception of infrasound, for the most sensitive 5 to 10% of the population is generally acknowledged to be around 85 dBG such that a sound with a frequency of 2 Hz would need to have an amplitude of 115 dB for it to be perceptible. **Figure 34** illustrates the ISO 7196: *frequency weighting characteristic for Infrasound measurements*.



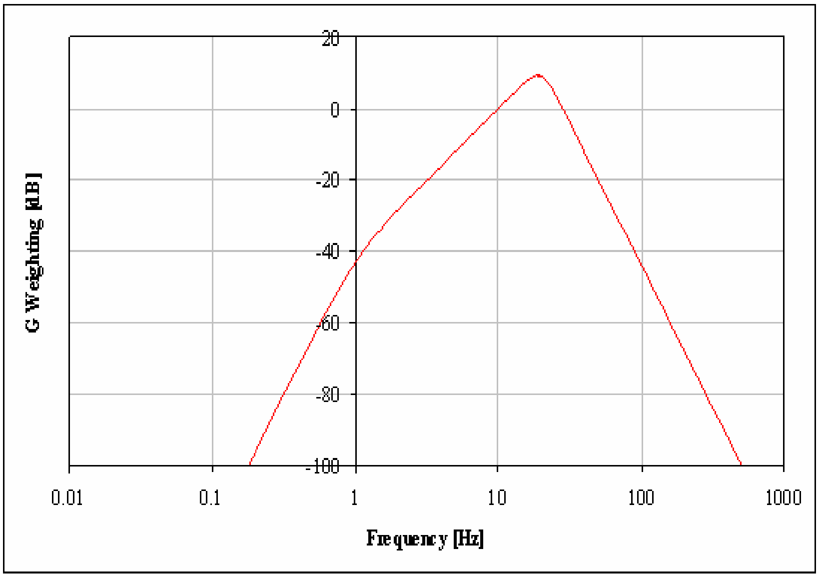


Figure 34: ISO 7196: 1995 Acoustics – Frequency Weighting Characteristic for Infrasound Measurements G weighting scales [63].

Where guidance exists for the assessment of low frequency sound, a 'rule of thumb' comparison of the level difference between the measured C-weighted and A-weighted levels provides an indication of the low frequency content of a sound. DIN 45680: 1997 *Measurement and Evaluation of low-frequency noise emissions in the neighbourhood* suggests that a level difference of 20 dB warrants further investigation of the low frequency content of the sound.

Studies undertaken by KjellBerg [[64]] indicate that for level differences of 15 dB and more, an appropriate correction to the A-weighted sound pressure level is the addition of 6 dB. It is not untypical for wind turbine sound spectra, in the absence of any masking from background noise to provide a C to A level difference of 11 to 16 dB when the separation distance between turbines and receptors are 400 to 1500 metres, respectively.

Moorhouse [[50]] provides a graph of the typical *perception* threshold of the human ear for low frequency sound as a function of pressure. **Figure 35** shows that lower frequencies must be of a higher magnitude [dB] to be perceived, e.g. the threshold of hearing at 10 Hz is approx 100 dB [an incredibly high level of noise at any frequency, never mind at 10 Hz].

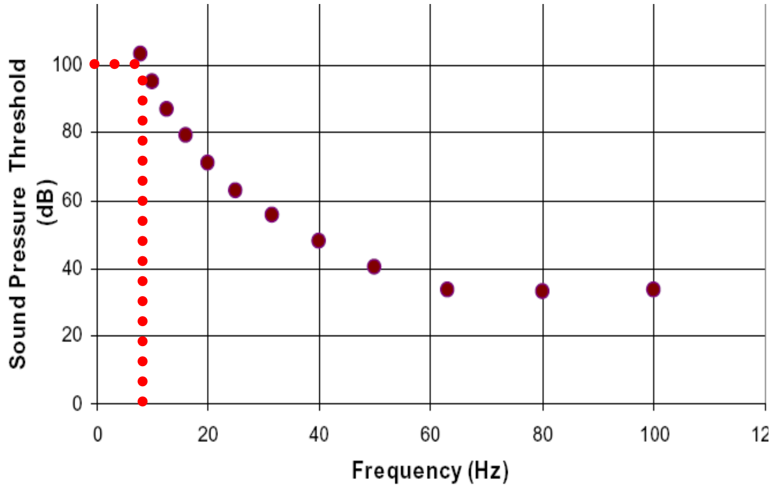


Figure 35: Perception threshold of human ear - low frequency sound as a function of pressure [[50]].

The literature review has studied measurements of infrasound sound emission from modern upwind, wind turbine generators. Certain studies indicated that at distances of 200 metres infrasound is between 25 and 40 dB below recognised perception thresholds [[32]] that being below the threshold shown in **Figure 35** i.e. sounds received would need to be an additional 25 to 40 dB to be perceived by human threshold for healthy hearing.

Measurements presented by Hayes [[49]] of internal infrasound measurements [inside the wind turbine tower] and external measurements at a distance of 420 m from the closest wind turbine with rated output of greater than 1 MW but less than 2 MW yielded a sound pressure level less than 50 dB [between the 0 Hz and 2 Hz range] as shown in **Figure 36**. These measured levels were well below threshold 85 [G weighted].

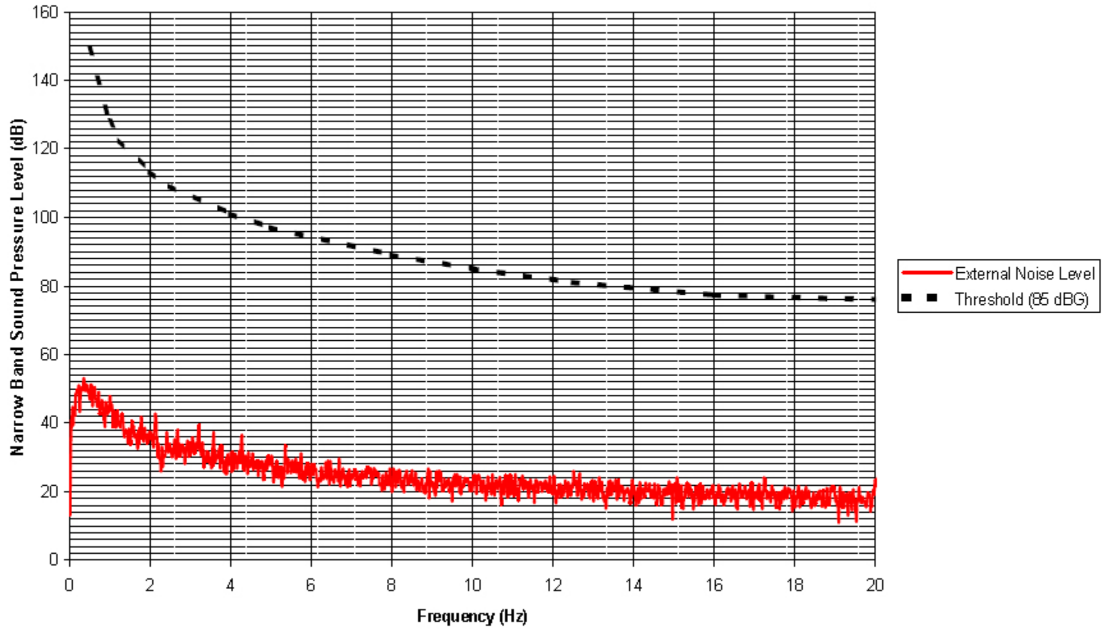


Figure 36: External sound pressure level at distance of 420 m from closet turbine versus 85 dBG threshold.

Further a document prepared for the World Health Organization [6] states that 'there is no reliable evidence that infrasound below the hearing threshold produce physiological or psychological effects'. Rogers [65] also states that there is no reliable evidence that infrasound below the perception threshold produces physiological or psychological effects.

Measurements up to 1 km away in a wide range of wind speeds and direction were reported within ETSU W/13/00392/REP [66]. This report details levels of low frequency acoustic energy which fall below recognised perception thresholds for such a sound source. Despite the reference to ground borne sound, the conclusions apply equally to airborne sound.

It is reported that the perception of sound differs from person to person. As such, what one person hears as an unacceptable sound may not even be audible to another. This may be due to a hearing deficiency of one listener, i.e. hearing damage for example, or that the hearing thresholds for the persons may just be different [66].

It is not unheard of for thresholds of audibility in the low frequency region of hearing to differ by as much as 20 dB at specific frequencies. Furthermore, with increasing age, the effects of presbyacusis will result in the reduction of high frequency acuity and lead to a biasing of the hearing towards the lower end of the spectrum. Based upon this general degrading of the hearing mechanism with age it is not unsurprising to discover that a majority of 'low frequency noise complaints' originate from the more elderly members of the population [66].

The literature study reveals that as a general rule, sound which is more than 20 dB below the average threshold of ISO226:2003 *Acoustics: Normal equal-loudness-level contours* are unlikely to be a problem as from the statistics of the threshold determination, this is below the threshold of the most sensitive person [[67]].

Vibro-Acoustic Disease [VAD]

Vibro-Acoustic Disease [VAD] is described as a multi-systemic entity caused by occupational or chronic exposure to large pressure amplitude low frequency [LPALF] noise [greater than 90 dB SPL at frequencies under 500 Hz]. The clinical picture described for this controversial disorder involves extra-auditory pathology, such as neurological disturbances, respiratory disorders and cardiovascular problems [[68]].

VAD is undergoing a great deal of examination by both experts and lay persons. Further at present VAD is an emerging area related to the consequence of sound exposure and low frequency sound. Dose-responses for LFN exposure have not yet however been established [[69]]. The question which relates to the disease is how does it relate to wind turbine generator acoustics?

There appears to be a lot of anecdotal evidence [newspaper accounts, personal communications], conjectural, based on unpublished research which refers to sound pressure levels well above those associated with wind turbine generator operations. It also appears from the literature study that there is no peer reviewed studies on the topic and no data presented by researchers.

As illustrated in this literature study a sound pressure level of 90 dB or above from modern wind turbine generators at receiving locations at frequencies below 500 Hz would be exceptionally uncommon.

Many different pieces of literature illustrate how low frequency sound to levels above 85 dB and above can be an integral part of many work related and leisure activities. A study by Branco et al. [[69]] discusses the topic of VAD and low frequency sound. It is noted that this paper largely deals with VAD in aircraft technicians and crews and establishes no connection to wind turbine generators.

Nevertheless the Branco study illustrates some important issues relating to measured low frequency sound levels for a number of activities including the cockpit of an A340 Airbus, dance club, commuter train and common automobile. As reviewed in the Canadian Wind Energy Association Study [[41]] low frequency sound is part of everyday life.

The Branco study describes these environments as “low frequency noise rich environments”. Levels presented are in some cases above 100 dBA. **Table 4** illustrates the weighted [dBA] and un-weighted [dB Lin] levels presented in the study.

Location	dBA	dB_{Lin}
Cockpit A340	72.1	87.3
Bar	98.4	104.4
Dance Club	110.3	127.5
Commuter Train	65.2	92.1
Subway	70.9	93.6
Common Automobile	71.2	100.8

Table 4: Comparison of dBA and dB_{Lin} values in several low Frequency environments [69].

In the study by Branco et al. [69] comparison is made with the A340 aircraft cockpit and the other environments, as shown in **Table 4**. **Figure 37** illustrates the results from the study for the cockpit versus commuter train. The results show typical leisure activity and the elevated amounts of low frequency sound. Note a level of approx 80 dB at 1.6 Hz for the commuter train. Similar high levels for low frequency noise were also presented in the study from leisure activities such as dance clubs and bars.

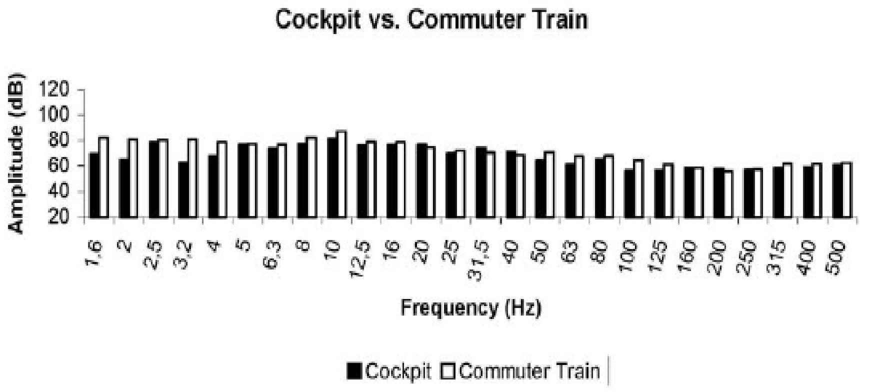


Figure 37: Frequency distributions within the 1.6 – 500 Hz range, of the A340 cockpit in cruise flight and of a commuter train [69]

From the current literature available and subsequent data presented on documented health impacts from low-frequency sound, it is concluded that there is no connection between VAD and wind turbine generators other than anecdotal evidence.

Wind Turbine Syndrome

Wind turbine syndrome is a name specified by some researchers in regards to people living near wind turbines with certain medical symptoms. The literature study concludes that all evidence to date is only anecdotal.

Impacts of Low Frequency Sound Perceptions and Investigations

To date it appears from credible literature there is no amount of scientific evidence which links the levels of low frequency sound emitted by wind turbine generators with impacts on human health. It is acknowledged that early wind turbine designs in the 1980s had problems associated with low frequency sound. However careful design and technological advance of modern wind turbine generators have overcome many such problems. The literature reveals that a number of issues relate to down wind turbines which are rarely used today.

Two key bodies and related published literature [[70]] on low frequency sound by Department for Environment, Food and Rural Affairs [DEFRA] and the World Health Organization [WHO] confirm that the primary effect of low frequency sound to humans is annoyance. Other studies also illustrate that no links have yet been shown to biological health effects [[71]].

Noise annoyance can only be defined subjectively and is influenced by numerous non-acoustic attitudinal and situational factors in addition to the amount of sound. Sometimes a sound is heard by a complainant, but cannot be measured. In these situations a mechanism other than airborne sound can be responsible, known as false perception of building resonance sound.

Investigations by Vasudevan and Gordon [[72]] of persons who complained of low frequency sound from various sources, not including wind turbine farms indicated a number of common factors which include the following:

- The problems arose in quiet rural or suburban environments;
- The noise was often inaudible or just above thresholds of inaudibility and heard by a minority of people;
- The noise was typically audible indoors and not outdoors;
- The noise was more audible at night than day;
- The noise had a throbbing and rumbly characteristic;
- The main complaints came from the 55-70 years age group;
- The complainants had normal hearing.

Rogers [65] states that although sound levels can be measured similarly to other environmental concerns, the public's perception of the acoustic impact of wind turbine generators is, in part, a subjective determination. Whether a sound is objectionable will depend on the type of sound [tonal, broadband, low frequency, or impulsive] and the circumstances and sensitivity of the person [or receptor] who hears it. Because of the wide variation in the levels of individual tolerance for sound, there is no completely satisfactory way to measure the subjective effects of sound or of the corresponding reactions of annoyance and dissatisfaction.

Van den Berg also makes the comment [73] that although wind turbine generators produce low frequency sounds it has not been shown that this is a major factor contributing to annoyance.

Studies into the topic of low frequency sound show that one such established area with wind turbine generators is Denmark. This country has a long history of wind energy and both the Danish Wind Industry Association and the Danish Environmental Agency confirm that low frequency sound from wind turbines has not been an issue and there have been very few complaints from the general public in the past 20 years.

Further studies carried out by the German Wind Energy Association has confirmed that no impacts to human health have been proven from low frequency sound from wind turbine generators. Studies conducted in Germany found that wind turbines emit sound at extremely low levels in the infrasound range [below 20 Hz] [67]. However, this sound is far below detection threshold and far below levels which can cause any impact [74].

Tonal Sound for Wind Turbine Generators

A review into sound produced from wind turbine generators found that tonal sound may also be present from working wind turbine generators.

The tonal noise could potentially have both mechanical and aerodynamic origins. Tonal sound due to mechanical sources is typically associated with the rotation of mechanical equipment, and pure tones tend to be related to the rotational frequencies of shafts and generators and the meshing frequencies of the gears [34]. Tonality differs between wind turbine generators and may also vary between tests of the same turbine model.

Impulsiveness of Wind Turbine Generator Sound

Wind turbine generator sound is not usually considered to be impulsive, as it has a more or less constant level due to the essentially random nature of the sound production mechanisms. Although there are periodic audible swishes, these are not equal to ‘real energy impulses’ like hammering or gun shots [73].

General Spectrum of Wind Turbine Generator Sound

Many wind turbine generators, although from different manufacturers, have similar sound spectra because modern wind turbine generators are of similar construction. A study by Snow [75] reports detailed measurements using 1/24th octave band analysis in the range from 0.36 Hz to 60 Hz of sound from a wind farm consisting of eleven 450 kW wind turbine generators. The wind turbine generators make, model or hub height are not stated in the Snow Report. Snow states that the measurement distance was 100 m from the turbines.

It was shown by Snow that harmonics of the 1.5 Hz blade frequency could be detected up to the tenth harmonic and possibly higher. The levels of the lower harmonics were generally below 70 dB and fell rapidly in sound pressure levels above 4 Hz [**Figure 38**]. All were reported to be below the infrasound hearing threshold at their frequencies. The Snow report states that G-weighted sound levels [as per ISO 7196:1995. Acoustics Frequency weighting characteristic for infrasound] were carried out and were shown to be within the 60 dB to 70 dB range. These reported levels are below the level expected to cause complaints of infrasound [75].

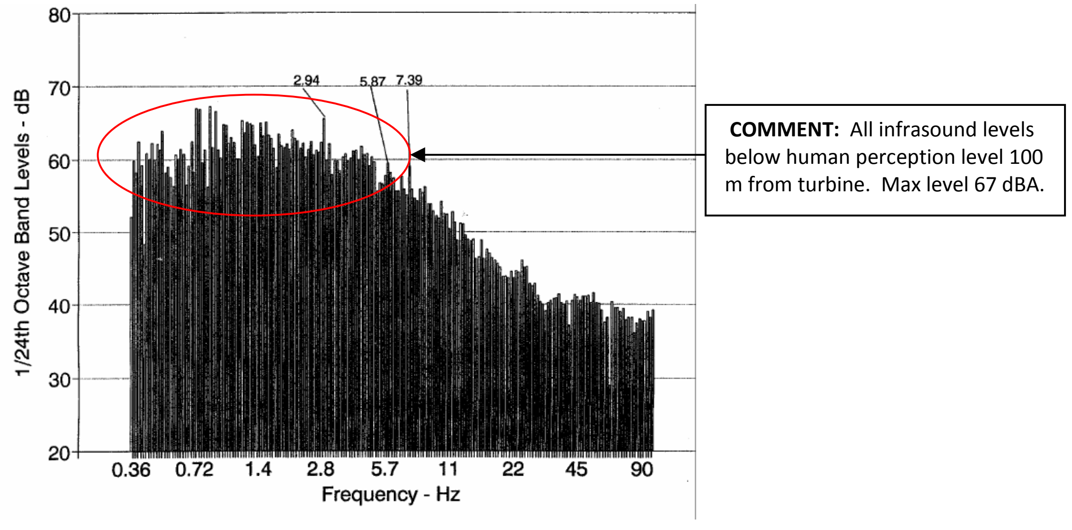


Figure 38: Low frequency sound from a wind turbine. 1/24 octave band analysis [75].

Further testing by Vestas on their V52: 850 kW wind turbine gives spectra under different operating conditions. The test conditions for the Vestas testing was an analysis bandwidth of 0 Hz to 2 Hz. **Figure 39** shows a spectrum from the test results which rises up into the lower frequencies, reaching a maximum of about 70 dB. There are peaks superimposed on the spectrum as several peaks below 100 Hz, a peak at nearly 200 Hz and a peak at 600 Hz.

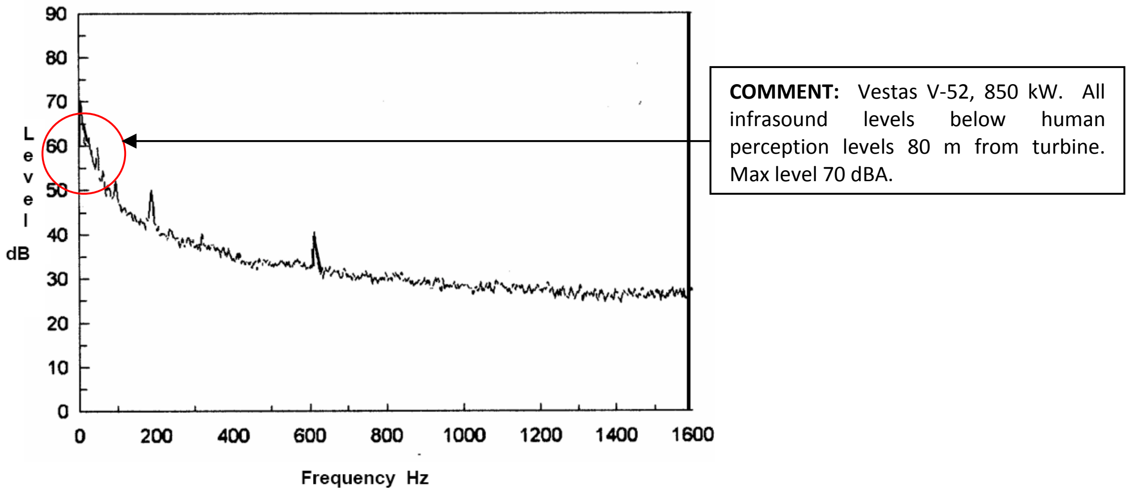


Figure 39: Vestas V52 – 850 kW wind turbine. Typical noise at 10 m/s wind speed [[76]]

A DELTA acoustic report to Bonus Wind turbine manufacturers [[77]] on the Bonus 1.3 MW wind turbine generator gave spectrum details and digital audio recording of the wind turbine sound [**Figure 40**]. Leventhall reports [[34]] on the findings of the DELTA Acoustic report stating that a detailed low frequency analysis was performed in addition to the range up to about 200 Hz. The waveform of the sound was also investigated using a digital oscilloscope and the tape listened to by playing through a low frequency loudspeaker.

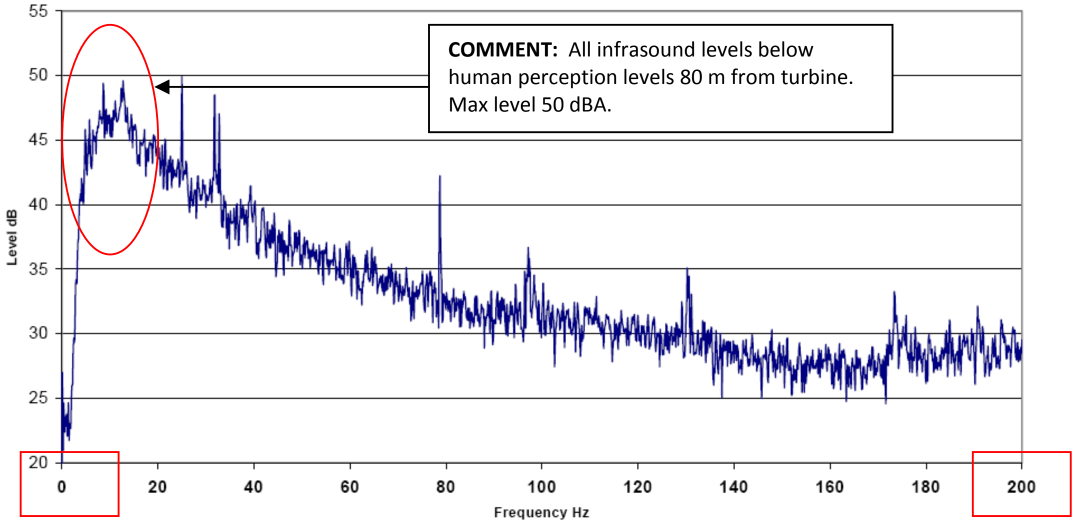


Figure 40: Low frequency sound from the DAT tape - Bonus 1.3 MW wind turbine to 200 Hz [[77]].

It was found that there was some variation in the detail of the spectrum through the 1.5 hour length of the recording on the tape, although the main characteristics were constant. Similarly, the waveform of the sound was variable, being controlled by large, very low frequency swings, presumably from gusts of wind. Listening to the tape revealed the swish, swish, swish pulsations, which are typical of turbines, at about one per second. These are related to the turbine blades passing the tower and are not low frequencies, but a modulation of higher frequencies These pulsations tend to diminish with distance and to blur when there are multiple turbines [34].

Vibration

In terms of vibration *from* wind turbine generators there are two key areas of study, these relate to ground-borne vibration and loading on the wind turbines themselves chiefly from wind loading and earthquakes, which is clearly important in New Zealand. This area of design and analysis is based on treating the wind turbine structure and seismic loading similar to loads acting on a building or tower.

The second area of study related to vibration produced from the wind turbine generator as received in the surrounding environment. A modern wind turbine is generally a large steel cyclical tower strongly coupled to the ground by a massive reinforced concrete foundation. Vibrations may be transmitted to the surroundings and with rotating turbine blades generating low frequency acoustic signals which may couple acoustically into the ground. Ways in which the signal may couple into the ground include [78]:

- As a cantilever carrying the nacelle/blade mass, with frequencies typically less than 1 Hz [depending upon tower height];
- As a tensional oscillator at low frequencies;
- As a complete distributed system at high frequencies.

Gasch [79] states that vibrations are derived from complex interaction of mechanical factors associated with machinery including electricity generator; rotation bearings; blade adjustment, blade braking mechanisms; effects of wind; moments of force on the blades and tower.

Snow [75] undertook measurements on a wind farm in the UK, which consisted of eleven 450 kilowatt [kW] wind turbine generators. Sound and vibration measurements were taken at increasingly distant points up to 1 Km from the wind farm. Low frequency vibrations were determined down to 0.1 Hz, taking into consideration variation with distance, wind speed and on/off load levels.

During the experiment a wide range of wind speeds and directions were recorded. The research found that the absolute level of the vibration signals measured at any frequency at 100 m from the nearest wind turbine generator were significantly below criteria for 'critical working areas' given by British Standard *BS6472:1992 Evaluation of human exposure to vibration in buildings [1 Hz to 80 Hz]* [75], and were even lower than limits specified for residential premises [75].

Recent research confirms that ground vibrations from wind farms are not a significant issue being at levels of vibration significantly below human threshold of perception. A detailed study [80] conducted in the United Kingdom into the effects of large wind turbine generators on ground vibration levels found that no significant vibration effects for people, animals or structures exist beyond wind farm boundaries.

Seismic Monitoring

Seismic monitoring has recently become a potential issue in wind energy development in countries such as southern Scotland and northern England. This is because seismic monitoring stations such as those located in Scotland are used to monitor international compliance with the Comprehensive Test Ban Treaty [CTBT].

It is noted that there were concerns over the potential to generate seismic vibration from wind turbines which can mask the seismic signals from nuclear weapons testing. The aim being with seismic monitoring stations to be placed in an area free of all vibration. To address the vibration problem research into the issues was commissioned by the British Ministry of Defence, in partnership with the British Wind Energy Association. It was concluded that wind turbines of current design could interfere with the operation of the station, but a way forward has been agreed by setting a 'noise limit' [0.336 nm rms], which is effectively double the existing noise level at the site. The 'noise limit' extends to 50 km around the site, and proposals for wind farm schemes beyond the 50 km zone will be assessed against any remaining noise allocation budget. In principle the further a project is away from the seismic recording station the less the potential interference [[81]].

Wind Turbine Generator Acoustic Standards

International Standard IEC 61400-11: Wind Turbine Generator Systems Part 11: Acoustic Noise Measurement Techniques - Wind Turbine Sound Power Measurement Standards.

The internationally accepted standard to ensure consistent and comparable measurements of utility-scale wind turbine sound power levels is the International Electrotechnical Commission IEC 61400-11 Standard: Wind turbine generator systems – Part 11: Acoustic noise measurement techniques.

The standard requires measurements of broadband sound, sound pressure levels in one-third octave bands and tonality. These measurements are all used to determine the sound power level of the wind turbine at the nacelle, and the existence of any specific dominant sound frequencies.

The sound power level is calculated by measurement of the sound pressure level in the field. Manufacturers of IEC-compliant wind turbines can provide sound power level measurements at required wind speeds as measured by certified testing agencies.

NZS6808:1998, Acoustics – The Assessment and Measurement of Sound from Wind Turbine Generators and NZS6808:2010 Acoustics Wind Farm Noise

NZS6808 was developed specifically for the measurement and assessment of sound from wind turbine generators and wind farms in New Zealand conditions.

At the commencement of preparing this study the current New Zealand wind turbine acoustic standard in use was NZS6808:1998 Acoustics – *The Assessment and Measurement of Sound from Wind Turbine Generators.* During the conclusion of the field work for this study the 1998 version was superseded by NZS6808:2010 Acoustics– *Wind Farm Noise.*

NZS6808 provides details on prediction, measurement and assessment in one document. The stated purpose of NZS6808 is to aid both wind farm development and Territorial Local Authority planning procedures by providing a suitable method for the measurement and assessment of sound from wind turbine generators. NZS6808 provides specific guidance on limits of acceptability for sound received at residential and noise sensitive locations emitted from both wind farms and single wind turbine generators.

NZS6808 requires ambient background noise levels to be measured at relevant receiving locations; the noise level data is measured concurrently with wind speed and direction. A direct correlation of wind speed versus background noise level is then made for each receiving location by using a regression curve which describes this relationship [taking account of day and night and different wind directions etc if required]. This data is then used to provide the allowable recommended design limits of 40 dBA or 5 dB above the measured background sound level [the greater of the two].

The new 2010 version of the standard also includes a new provision for a lower, more stringent limit to allow for a higher degree of protection of acoustic amenity in a particular area. The new limits are referred to as the 'High Amenity Area' noise limits. The relationship between the background noise levels and recommended noise limits set out in NZS6808:2010 are shown in **Figure 41.**

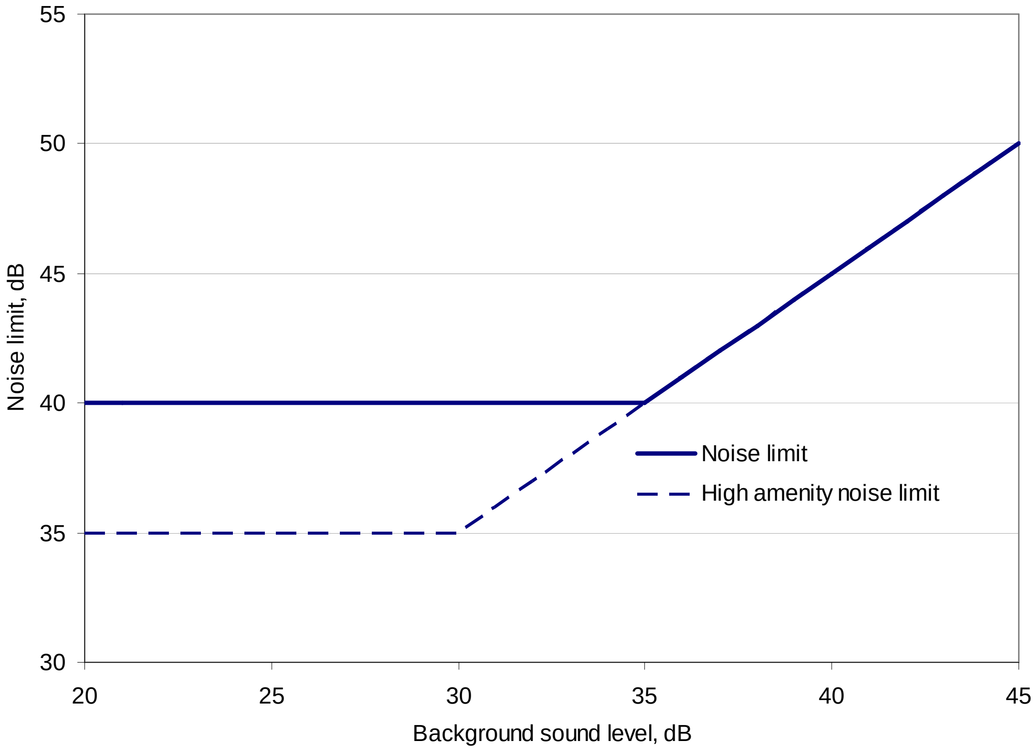


Figure 41: The relationship between the background noise levels and recommended noise limits set out in NZS6808:2010.

Once the known limits are set they can then be directly compared to the predicted wind turbine or wind farm sound pressure level at the relevant receiving site from the wind turbine[s] to allow for a statement regarding compliance with the recommended limits to be made. A number of technical changes were introduced into the contemporary 2010 Standard. In terms of all changes two key changes are viewed as relevant to this thesis. The first change relevant to this study was a change from the use of the L_{A95} to L_{A90} sound level descriptor. This change was introduced so as to bring the 2010 Standard into line with the L_{A90} descriptor used in other updated New Zealand Standards. In terms of the change from L_{A95} to L_{A90}, the 2010 standard states there is no significant difference between the L_{A90} and L_{A95} values of *typical* environmental sound. Research examining the difference between L_{A90} and L_{A95} generally shows a sound level difference of less than 1 dB [at most].

A further key change relevant to this study was an alteration from L_{Aeq} to L_{A90} for the prediction of wind turbine sound i.e. assuming for the purpose of the new 2010 standard that L_{Aeq} was equal to L_{A90}. In terms of assuming L_{Aeq} is equal to L_{A90} for wind turbine sound, this was to allow a direct comparison of measured background noise levels at receiver sites [collected as L_{A90}] and predicted wind farm sound levels [measured as L_{Aeq}] consequently deeming L_{Aeq} equal to L_{A90} for predicted wind farm sound and permitted site specific limits [set as L_{A90} sound levels].

Evaluation of NZS6808:2010 Noise Limits versus Noise Limits in Other Countries

NZS6808:2010 recommends the cumulative wind turbine sound level for each assessment location should not exceed L_{A90} 40 dB or the average L_{A90} background sound level + 5 dB, whichever is the greater. This was the same method adopted under NZS6808:2010 predecessor NZS6808:1998 however background sound levels were assessed under the 1998 version using the L_{A95} dB noise descriptor.

NZS6808 recommends wind farm sound limits be set at a level 40 dB or 5 dB above the background L_{A90} level [whichever the greater of the two] noting as above that at some noise sensitive locations a more stringent noise limit may apply for 'High Amenity Areas'.

The relationship between the background sound levels and recommended noise limits set out in NZS6808:2010 are shown in **Table 5.**

<table>
<tr><th>Background sound level</th><th>Noise limit [$L_{A90[10\ min]}$]</th><th>High amenity noise limit [$L_{A90[10\ min]}$]</th></tr>
<tr><td>> 35 dB</td><td>Background + 5 dB</td><td rowspan="2">background + 5 dB</td></tr>
<tr><td>30 – 35 dB</td><td rowspan="2">40 dB</td></tr>
<tr><td>< 30 dB</td><td>35 dB</td></tr>
</table>

Table 5: Relationship between the background sound levels and recommended noise limits set out in NZS6808:2010.

New Zealand NZS6808:2010 equals or exceeds the standards of protection in most countries except France. Also South Australia appears to have the strictest standards in the world with a level set at 35 dBA or 5 dBA above the background sound level [whichever is the greater] which is measured using L_{90}. The state of Victoria in Australia has the same standards as New Zealand.

Table 6 illustrates the limits set in other countries. It is important to note that New Zealand is one of countries that set limits in terms L_{A90}, as some countries set limits also using L_{Aeq}.

Sample Country	Limit	Wind Speed 10 m AGL	Comment/ Comparison
United Kingdom	L_{eq} 40 dBA day L_{eq} 43 dBA night Or L_{90} + 5 dBA	All Speeds	Less stringent than New Zealand Standard. Uses separate night measurements but night limit is higher by 3 dB.
Denmark	L_{eq} 40 dBA residents L_{eq} 45 dBA night Or L_{90} + 5 dBA	8m/s	Less stringent than New Zealand Standard under if Low L_{90} at high wind speeds. Only one reference wind speed
Holland	L_{eq} 40 dBA [rural] Recommendation only	8m/s	Similar to New Zealand. Each authority may apply own levels.
Germany	L_{eq} 40/45 dBA [rural]	-	Less stringent than New Zealand Standard
USA [Illinois]	L_{eq} 55 dBA [day] L_{eq} 51 dBA [night]	8m/s	Less stringent than New Zealand Standard has 340m min distant standard
France	L_{90} + 3 dBA [night] L_{90} + 5 dBA [day]	All Speeds	More stringent than New Zealand Standard. Limit for all industrial noise

Table 6: Wind farm noise limits set in other countries [82].

Chapter 5: Wind Power Generation

Introduction

This chapter reviews the wind resource, specifically a short review and outline of the development and evolution of wind energy.

An understanding of the wind resource, chief operating environment and modes for which the wind turbine generator functions is a key topic to sound generation at the wind turbine generator itself and propagation of sound from the wind turbine generator in the receiving environment [both on and off the wind farm site]. Parts of the work in this chapter have been adapted from the work of Hau, Gardner, Manwell and others [as referenced].

Although each site will have a different layout and surroundings which determine wind conditions, obtaining reliable wind data is key to planning and best use of the wind turbine generators on any site. Long term detailed site monitoring is normally carried out followed by the use of sophisticated wind modelling methods. The use of large scale wind maps are not sufficient for the task of modelling the wind resource at an exacting site. An understanding of the wind resource and chief laws governing wind energy conversion and wind turbine generator performance with respect to operating modes and acoustic 'outputs' is thus fundamental to the research.

Several key questions have been identified as being comprehensive background information to this study to enable the primary research and field investigation to be undertaken. Key research question viewed as important topics relating to this chapter are as follows:

- What are the basic sources and systems of wind energy in relation to wind turbine generators and how are they produced?
- What are the key theories relating to wind energy and how do they relate to the sound produced from wind turbine generators?
- What are the basic operating modes of a modern wind turbine generator and how do these factors influence sound propagation from the wind turbine?

Appendix A contains further detailed information on wind energy conversion and the science of wind power from wind turbine generators in relation to acoustics.

Fundamentals of Wind Power Generation

The wind has kinetic energy. The sun heats the Earth and its elements such as water, land and air. The heating process occurs at different rates. This imbalance in heating causes the air to move – this air flow is known as wind.

In regard to wind turbine generators the thermal energy in the sun is transformed into kinetic energy in the wind, with the wind turbine generator designed to transfer this kinetic energy into mechanical energy and then in to electrical energy.

Based on first principles the energy of the wind is transferred to the blades, the blades turn the rotor which transfers this mechanical energy to the low speed shaft. This mechanical energy is then sent through the gear box to a high speed shaft before being transferred to the generator. As the generator turns there is a magnetic winding which creates electricity. This electrical energy is then sent to the grid for use by consumers.

The World Wide Development and Evolution of Wind Energy

Wind power technology dates back many centuries. There are historical claims that wind machines which harness the power of the wind date back beyond the time of the ancient Egyptians. Hero of Alexandria used a simple windmill to power an organ whilst the Babylonian emperor, Hammurabi, used windmills for an ambitious irrigation project as early as the 17th Century B.C. The Persians built windmills in the 7th Century A.D. for milling and irrigation and rustic mills similar to these early vertical axis designs can still be found in the region today. In Europe the first windmills were seen much later, probably having been introduced by the English on their return from the crusades in the Middle East or possibly transferred to Southern Europe by the Muslims after their conquest of the Iberian Peninsula. It was in Europe that much of the subsequent technical 'modern' development took place. By the late part of the 13th Century the typical 'European Windmill' had been developed and this became the norm until further developments were introduced during the 18th Century. At the end of the 19th Century there were more than 30,000 windmills in Europe, used primarily for the milling of grain and water pumping [[83]].

It is acknowledged that there are a number of relevant "land marks" in the history of wind energy pre the 1970's these included an early attempt at large-scale commercial generation of power from wind including the 1.25 megawatts [1.25 MW] 53 m rotor diameter, Smith Putnam wind turbine generator erected at Grandpa's Knob in Vermont, USA in 1939. This design brought together some of the finest scientists and engineers of the time. The wind turbine operated successfully for longer than some multi-MW machines of the 1980s. It was a landmark in technological development and provided valuable information about quality input to design, machine dynamics, fatigue, and siting sensitivity [[83]].

Garrad [84] reported that modern commercial wind energy started in earnest in the early 1980s following the oil crises of the 1970s when issues of security and diversity of energy supply and, to a lesser extent, long-term sustainability, generated interest in renewable energy sources. Steel rotors were tried but rejected as too heavy, aluminium was deemed too uncertain in the context of fatigue endurance, and the wood-epoxy systems were employed and tested in a number of small and large turbines. The modern blade manufacturing industry has, however, been dominated by fibreglass polyester construction. During this time wind power sceptics raised questions in relation to a number of key issues such as noise, reliability, efficiency and cost. It is acknowledged by Gardner [84] that initially, none of these issues could be dismissed lightly, but gradually all have been addressed such that some of the early turbines were noisy, both aerodynamically and mechanically, and noise was a major problem. However today, mechanical noise is practically eliminated and aerodynamic noise has been vastly reduced.

In terms of historic noise issues one of the most well known “modern” historic periods was the wind turbines known as the M.O.D or MOD series. These wind turbine generators were well known for producing ‘inexplicable’ noises which it is understood that at the time were much talked about. Complaints from MOD-1 [version 1] were associated with noise from the turbine lattice tower which reportedly created considerable tower shadow from the downwind rotor mounted at a close distance. Low frequency noise described as infrasound also added to complaints believed to be caused by oscillation of low frequency range which caused resonances in houses which were “lightly built” or had light weight timber or glazed window facades.

The MOD series developed in the United States of America from 1975 to 1987 were experimental turbines designed by General Electric [GE]. These turbines were ambitious at the time having a rated power of 7300 w [7.3 kW] and rotor diameters of up to 122 m. It is the MOD wind turbine series regarding noise issues which started the various scientific investigations into modern wind turbine generators and their noise emission.

Following various periods including that of the experimental turbines wind energy experienced its greatest surge of activity in California during the 1980’s, nurtured by a combination of state and federal energy and investment tax credits. However the growth of wind energy in California was not sustained, but there was striking development in European markets with an installation rate in Germany of around 200 MW per annum in the early 1990s. From a technological standpoint, the significant outcome was the appearance of new German manufacturers and development of new concepts, with the introduction of innovative direct drive generator technology being particularly noteworthy. During the 1980's installed capacity costs dropped considerably and wind power has become an economically attractive option for commercial electricity generation. Large wind farms or wind power stations have become a common sight in many western countries [85].

Subsequently, a huge expansion of the Spanish market occurred, including wind farm development, new designs and new manufacturers. As recently as 2003, 80% of the wind turbines sold worldwide was by European companies. The largest manufacturers of complete wind turbines are based in the three largest country markets being Denmark, Germany and Spain [86].

Today's leading nations in wind energy are Germany, Spain and Denmark, which account for 84% of the total European wind capacity. Emerging markets include Austria, Italy, the Netherlands, Sweden and the UK. Other regions of the world which are developing important wind power industries include the United States, India, China and Japan. Over 50 countries around the world now contribute to the global total, including New Zealand. At the time of preparing this chapter there were currently seven operating wind farms in New Zealand as shown in **Figure 42.**

Wind Farm	Operator	Region	Capacity (MW)
Tararua	TrustPower	Manawatu	161
West Wind	Meridian	Wellington	142.6
Te Apiti	Meridian	Manawatu	90.8
White Hill	Meridian	Southland	58
Te Rere Hau	NZ Windfarms	Manawatu	32.5
Hau Nui	Genesis	Wairarapa	8.7
Horseshoe Bend	Pioneer Generation	Cental Otago	2.25

Figure 42: 'Current' wind farms development in New Zealand [87].

These wind farms have a combined installed capacity of over 400 MW. These farms supply about 3% of New Zealand's annual electricity generation, which is about the same amount of electricity as approx 145,000 New Zealand homes use in a year. Developers are exploring sites throughout New Zealand for new wind farms all the time [88].

Modern wind technology is available for a range of sites with low and high wind speeds and for various climates. Wind turbine size at the centre of commercial production has increased year on year. The wind rotor diameter, which basically dictates how much energy, can be harnessed from the wind as a function of time is illustrated in **Figure 43**.

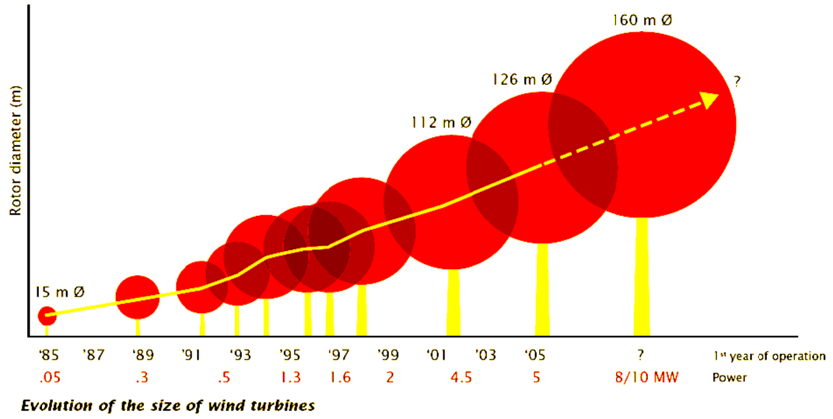


Figure 43: Sample of wind turbine rotor diameter size versus time [1985 to 2007] [87].

Measured sound power levels for a sample of wind turbine generators is presented in **Figure 44** as a function of rated electrical power. The data illustrates that sound emissions from wind turbine generators generally increases with turbine size. The graph also shows that wind turbine designers' efforts to address noise issues in the 1990s and later have resulted in significantly quieter wind turbines than the initial designs of the 1980s.

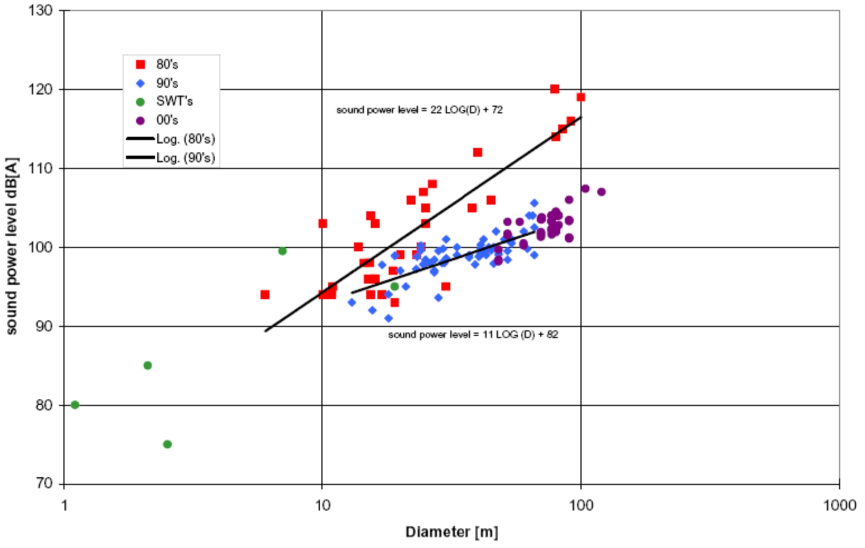


Figure 44: Sample of wind turbine rotor diameter versus sound power level [65].

While it is useful to see in **Figure 44** how sound power levels for wind turbine generators change with rotor diameter it is also constructive to consider how sound power levels have changed with turbine power capacity over time. Generally the relationship between sound power level for fixed capacity turbines [when normalised] shows that wind turbines have generally become quieter as turbine size have become bigger, the result being that a modern single wind turbine now has a similar production output [in terms of MW] of approx 8 to 10 smaller wind turbines.

At present wind energy is a subject receiving a significant amount of attention around the world and much has been published on the topic, including in New Zealand. The wind turbine industry is also growing at a rapid rate and continually developing and marketing new technology. The globally installed wind capacity increased from 2,500 MW in 1992 to over 40,000 MW in 2003 [[89]]. This represents annual growth of almost 30%.

In the early 1980's, wind turbines were typically around 50 kW [0.05 MW] with rotor diameters of 20 m, but today wind turbines of up to 5 MW [+] and 200 m [+] rotor diameters are being tested for operation in off-shore wind farms. The rapid growth in the sector has provided manufacturers with opportunities for research and development leading to lower cost per MW of installed wind turbines capacity, significant gains in the efficiency of conversion of wind energy to electricity and the addition of safety and grid support features which are considered normal in conventional generators [[89]].

Wind energy is a classic case of technology driving demand. The growth of wind energy in Europe and the United States has taken wind turbine generators from being an alternative energy source to being mainstream requiring manufacturers and the supply industry to tackle integration issues head on. The latest technology trends are driven by economics and also by the need for wind turbine generators to directly support grid security. There is currently a trend towards wind turbine generators that have variable speed rotors which is achieved using pitch control of the turbine blades, particularly for the increasingly common megawatt class wind turbine generators. The pitch of the blades is constantly adjusted to achieve the required operating point in the most efficient manner and to limit the output of the wind turbine generator to its safe operating range [[89]].

The European Wind Energy Association [[89]] states that the preferred generator technology for variable speed operation is the DFIG in which the stator windings are directly connected to the grid and supply about two thirds of the power output while the rotor windings are connected to the grid via an AC-DC-AC converter and supply the balance of the output power.

Limits on the Wind Capacity

The capacity of an electricity system to absorb wind generation is determined more by economics than by absolute technical or practical constraints. As the percentage of wind generating capacity rises in New Zealand and around the world so do the technical and network issues that will require resolution. All of these are to some degree influenced by the technologies available at the time, and future technological innovations make the determination of long-term absolute limits unreliable[[1]].

The most obvious practical constraint on wind capacity occurs when peak wind output exceeds the lowest period of demand on the grid system [i.e. a windy warm summer night], allowing for the requirement for some base load plant to continue operating. At this point excess wind capacity will need to be shortened, and this has an economic cost for wind plant [[1]].

Technical constraints include the ability of wind turbine generator to respond to system faults, and this is related both to the type of wind turbine technology used and to the dispersal of wind generation on the network. Improvements in turbine technology and network reinforcement are both possible solutions, again with possible cost implications [[1]].

Chapter 6: Aeroacoustics – Wind Turbine Generator Aerodynamics

Introduction

Wind turbine generator aerodynamics is a multifaceted subject. The study of aerodynamics in terms of sound and acoustics is referred to as 'aero-acoustics'. Wind turbine generator aerodynamics is not only concerned with sound production but the study of the motion of air [wind] and the interactions with the moving components of the wind turbine generator used to produce electrical energy. A wind turbine generator transforms the kinetic energy in the wind to mechanical energy in the shaft and finally into electrical energy in a generator. It is the interaction of the wind's energy with the rotor blades of the turbine which are of the greatest interest in wind turbine generator aerodynamics including acoustics as both electrical and acoustical output of the wind turbine generator are functions of wind speed and the winds interaction with the rotor blades.

This chapter reviews some basic fundamental aerodynamics of a wind turbine generator specifically a basic overview of rotor and blade aerodynamics. One key question has been identified as follows:

- What are some of the basic theories and fundamentals relating to aerodynamics of a wind turbine generator and how do they influence sound produced from the wind turbine?

Appendix B contains further detailed information on the science of aerodynamics and acoustics from wind turbine generators.

Rotor and Blade Aerodynamics

The aerodynamics of *wind turbine generators* is essential to how a *wind turbine* will perform. Key to the research question being carried out is an understanding of how sound is produced and the methods by which it is produced i.e. aerodynamics deserves attention as the physical mechanics for the generation of sound.

The aerodynamics of a wind turbine generator is a function of the 'physical' wind turbine itself and how the individual components interact with their surrounding environment. The chief aerodynamic function of the wind turbine generator is to convert the maximum amount of variable wind energy moving through the turbines swept rotor area, and turn this fluctuating wind energy into mechanical energy. This in turn, with the use of the wind

turbine ‘power plant’ produces electrical energy. Wind turbine generators, like any machine with moving parts, do not operate without producing some form of sound.
The aerodynamic properties of a wind turbine generator are a function of the rotor, rotor blades and tower. These are the three decisive elements with respect to sound received in the surrounding environs. It is the ‘mode’ of operation and related wind turbine generator aerodynamic design which ultimately dictates the acoustic parameters of any wind turbine.

Rotor blade aerodynamics is the largest driving factor in relation to corresponding sound intensity, frequency and nature of sound generated at source from any wind turbine.

It would not be possible to achieve an understanding of a wind turbine generator and associated acoustic measurement outputs without knowledge of the key aerodynamics and related characteristics. These key elements are discussed further below.

The branch of physics that deals with the motion of a solid body through gases is aerodynamics [air in the case of a wind turbine generator]. The aerodynamic design of wind turbine rotors require an understanding of various issues namely the shape of the rotor, the number of rotor blades and aerodynamic properties. Key to all of these properties and related sound produced is the aerofoil [sometimes referred to as airfoil] shape.

The wind may be considered to be a combination of the mean wind and turbulent fluctuation about the mean flow. Experience has shown that the major aspects of wind turbine performance [mean power output and mean loads] are determined by the aerodynamic forces generated by the mean wind]. Periodic aerodynamic forces caused by wind shear, off axis wind and rotor rotation and randomly fluctuating forces induced by turbulence and dynamic effects are the source of fatigue loads and are a factor in the peak loads experienced by a wind turbine. These are of course important but can only be understood once the aerodynamics of steady state operation has been understood [[90]].

When discussing the features of the rotor, the actual design is taken as known, however modern wind turbine rotor designs obtain their fundamental technologies from aircraft and helicopter design with alterations specific to wind turbines made as wind turbine rotors are required to work under a different environment, that being shifting wind direction and changing speeds. Nevertheless the basic rotor blade of a wind turbine was developed from that of an aircraft wing.

The front and rear sides of a wind turbine rotor blade have a shape roughly similar to that of a long rectangle, with the edges bounded by the leading edge, the trailing edge, the blade tip and the blade root. The blade root is bolted to the hub. The radius of the blade is the distance from the rotor shaft to the outer edge of the blade tip.

Figure 45 illustrates the key components of the wind turbine rotor blade in 2d dimension. **Figure 46** illustrates the final configuration of three rotor blades joined to the rotor hub in 3d dimension [as seen on the turbine itself].

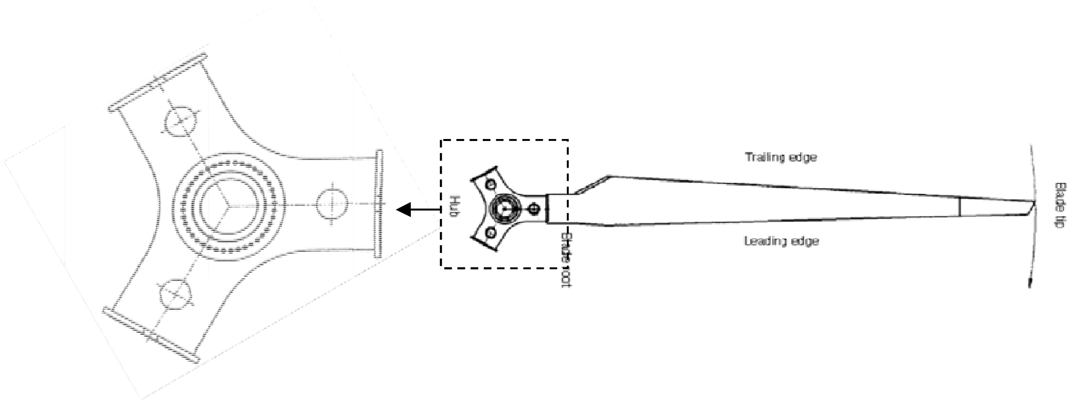


Figure 45: Basic components of a wind turbine rotor blade and aerofoil cross section.

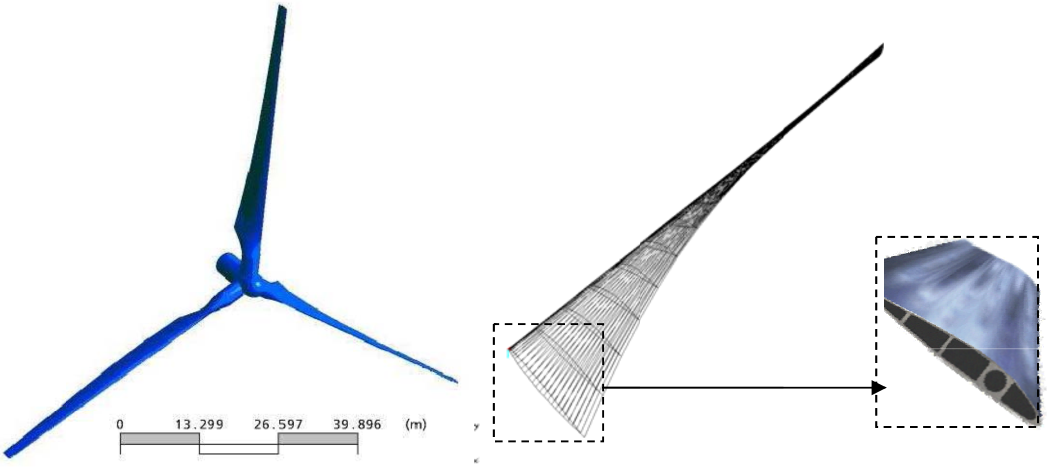


Figure 46: Basic components of a wind turbine rotor and blades [3d].

Figure 47 illustrates the rotor and rotor blades from the Te Apiti wind farm V72/NM72 wind turbine generator.

Figure 47: V72/NM72 wind turbine rotor and blades at Te Apiti Wind Farm.

In summary aerodynamically produced sound arises from the interaction of the flow over the blade with the surrounding air flow. In relation to the key aerodynamic functions of a wind turbine generator sound is produced chiefly by the flow of the wind along the blades.

The two dominant sound sources are thought to be due to the interaction of atmospheric turbulence with the leading edge of the blades and turbulent boundary layer sound from the trailing edges of the blades. Low frequency sound is also produced when the rotating blade encounters localised flow around the tower, wind speed changes, or wakes shed from other blades.

Chapter 7: A Field Investigation into the Relationship between L_{A90} and L_{Aeq} Wind Turbine Sound Level Descriptors in New Zealand

Introduction and Overview

The principle of the study is to examine the relationship between L_{A90} and L_{Aeq} sound level descriptors for commercial three bladed horizontal modern wind turbine generators in New Zealand. The study has been based on two test locations being adjacent to a dwelling in the 'far field' and at the R_o measurement location [1] on a wind farm. Key to the study has been to provide the maximum percentage of time and resources to the typical dwelling location [primary location].

The dwelling location was chosen as this is a receiving location outside the wind farm boundary where people reside i.e. not on the wind farm itself which is uninhabited. It is noted that NZS6808:2010 places priority on received sound levels at locations remote from turbines rather than emission at the turbines.

In order to carry out the study a dwelling in close proximity to a Meridian Energy Limited wind farm was sourced. The specific wind farm chosen for the study was located in Makara, Wellington, New Zealand [refer **Figures 49 and 50** for Makara Wind Farm]. The wind farm is known as 'Project West Wind, Wind Farm' [also known as the 'Makara Wind Farm'].

In this case a dwelling at number 403 Makara Road, Wellington was selected. Full permission was given by the dwelling occupants to carry out acoustic measurements and with their full co-operation access to their site was granted. A common trust resided where communications were given to the occupants' before entering the site to ask permission each time and advise of a planned site visit. This was very important for night time and early morning site visits where gates and access needed to be organised beforehand. It was also important to advise the occupants of visits as they were not always on site.

The 403 Makara Road dwelling was selected not only because of access [although this was a very important element] but the site has one of the shortest distances between the

[1] The R_o location as defined in IEC 61400 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques. The Ro location is a standard location where acoustic measurements are made close to the turbine in order to minimise the influence of terrain effects, atmospheric conditions or wind-induced noise.

dwelling and closest wind turbine generator [wind turbine generator - D12] located on the wind farm site. The site was also selected as it had close proximity to Wellington City CBD [approx 45 minute drive] and comparatively trouble-free access for a rural area of this type having well formed and constructed metal roads in most parts.

Discussions with the owners of the site were also conducted on occasion to try and get an understanding of the audible sounds and different types of sound characteristics which occur at the site during different weather conditions. The wind farm owners [Meridian Energy Limited] also agreed to assist with providing wind data.

A second site location being on an actual wind farm was selected. This secondary site was the Te Apiti Wind Farm [refer **Figures 51 and 52** for Te Apiti Wind Farm]. The Te Apiti Wind Farm is located north-east of Palmerston North, New Zealand.

Te Apiti Wind Farm was selected as the wind farm owner Meridian Energy Limited and wind farm operators Vestas [New Zealand Division] both provided permission for site access and measurements to be conducted. The Te Apiti Wind Farm was selected not only because of admittance but also because the author has carried out work on this site before and viewed it as a suitable test location which represented a modern commercial wind farm.

The two sites were also selected based on the fact that they are home to vertical three bladed, upwind, wind turbine generators which are typical of current wind farm developments in New Zealand. As stated above resources and time were divided between the two sites, hence only limited time was given to measurements carried out on the secondary Te Apiti Wind Farm site due various limitations [as discussed further below].

The premise to carrying out measurements on the Te Apiti Wind Farm site itself was to test the statement by the UK Working Group on Noise documented in ETSU-R-97 which showed that the L_{Aeq} sound level descriptor for wind turbine noise is generally 1.5 to 2.5 dB higher than the L_{A95}.

Site visits allowed not only measurements but many hours of observations of various types of weather conditions to take place on site. These were carried out at different times of day and under varying weather conditions and operating modes of the wind turbine generators i.e. on and off, up and down wind, with and without line of sight.

Different site visits times also allowed for study and understanding of the surrounding environments and related changes in varying seasons. Due to site access restrictions no measurements or site visits were able to be carried out on the Te Apiti Wind Farm during night time periods. Visits after dusk or before dawn were also never conducted due to a number of safety issues. In regards to the 403 Makara Road dwelling measurements were able to be conducted during almost any period of day or night.

Structure of Study

The following sets out a discussion and background information relating to the field work and investigations carried out for this study. The study is structured as set out below.

Background Information

- Description test sites;
- Site location maps;
- Position of selected test wind turbine generators and sound assessment location;
- Technical specifications of test wind turbine generators;
- Assumed published sound power levels of test wind turbine generators;
- Measurement personnel and equipment;
- Surrounding environs;
- Climatic conditions.

Method of investigation and test procedure

- Limitations and key issues to repeating the study;
- Data analysis methods.

Results

- Results [Primary Site];
- Results [Secondary Site];
- Summary of Results [Primary Site];
- Summary of Results [Secondary Site].

Background Information

Verbal Description of Test Sites

Project West Wind [Makara] Wind Farm

Project West Wind is located west of Wellington City in Makara at the bottom of the North Island of New Zealand. The funnelling effect of Cook Strait and fact that the site lies off the west coast means the site generally has high and consistent wind speeds. Project West Wind is owned and operated by Meridian Energy Limited.

Te Apiti Wind Farm

Te Apiti Wind Farm is located north of the Manawatu Gorge in the North Island of New Zealand. The Manawatu Gorge is approx 10 km from the City of Palmerton North. The Manawatu Gorge is viewed as a positive location for wind farm developments with the Tararua and Ruahine ranges providing a barrier to the predominantly westerly winds that flow across New Zealand. Between the two ranges lies a lower range of hills that serve to funnel the wind. Te Apiti Wind Farm is owned and operated by Meridian Energy Limited.

Geographic Location and Mapping of Test Sites

Wind Farm Site Location Map

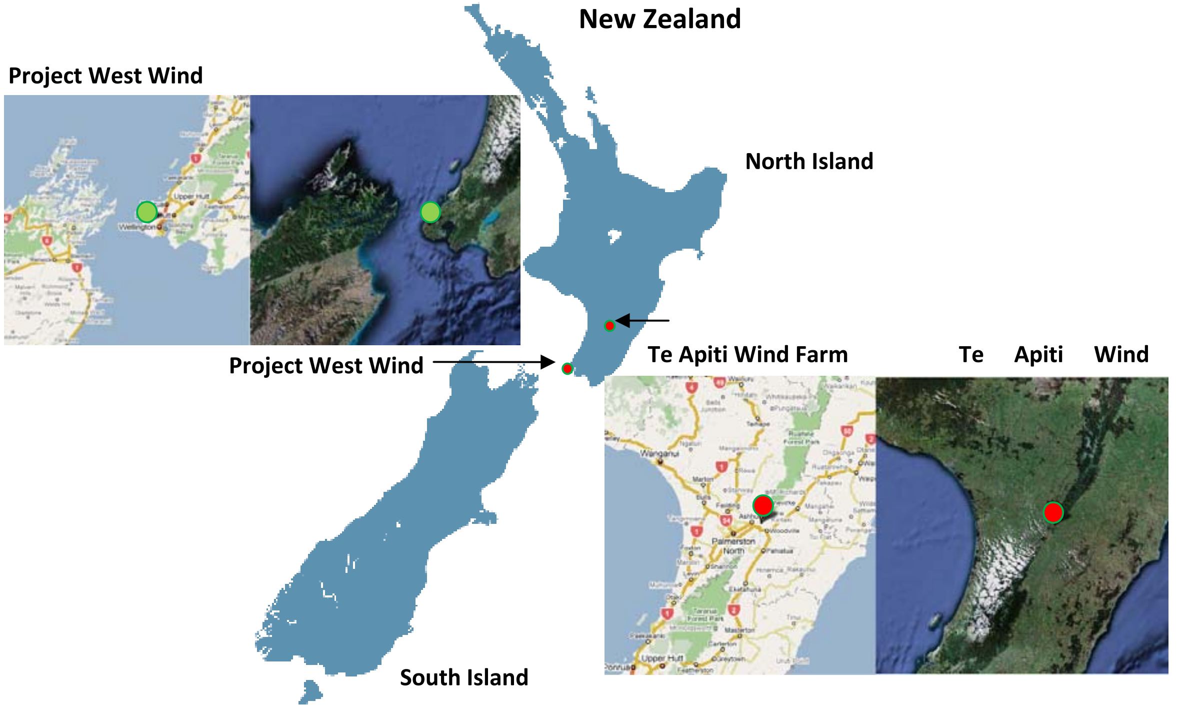


Figure 48: Site location map for Te Apiti and West Wind [Makara] Wind Farms, Lower North Island, New Zealand.

Wind Turbine Generator Locations

Project West Wind [Makara] Wind Farm

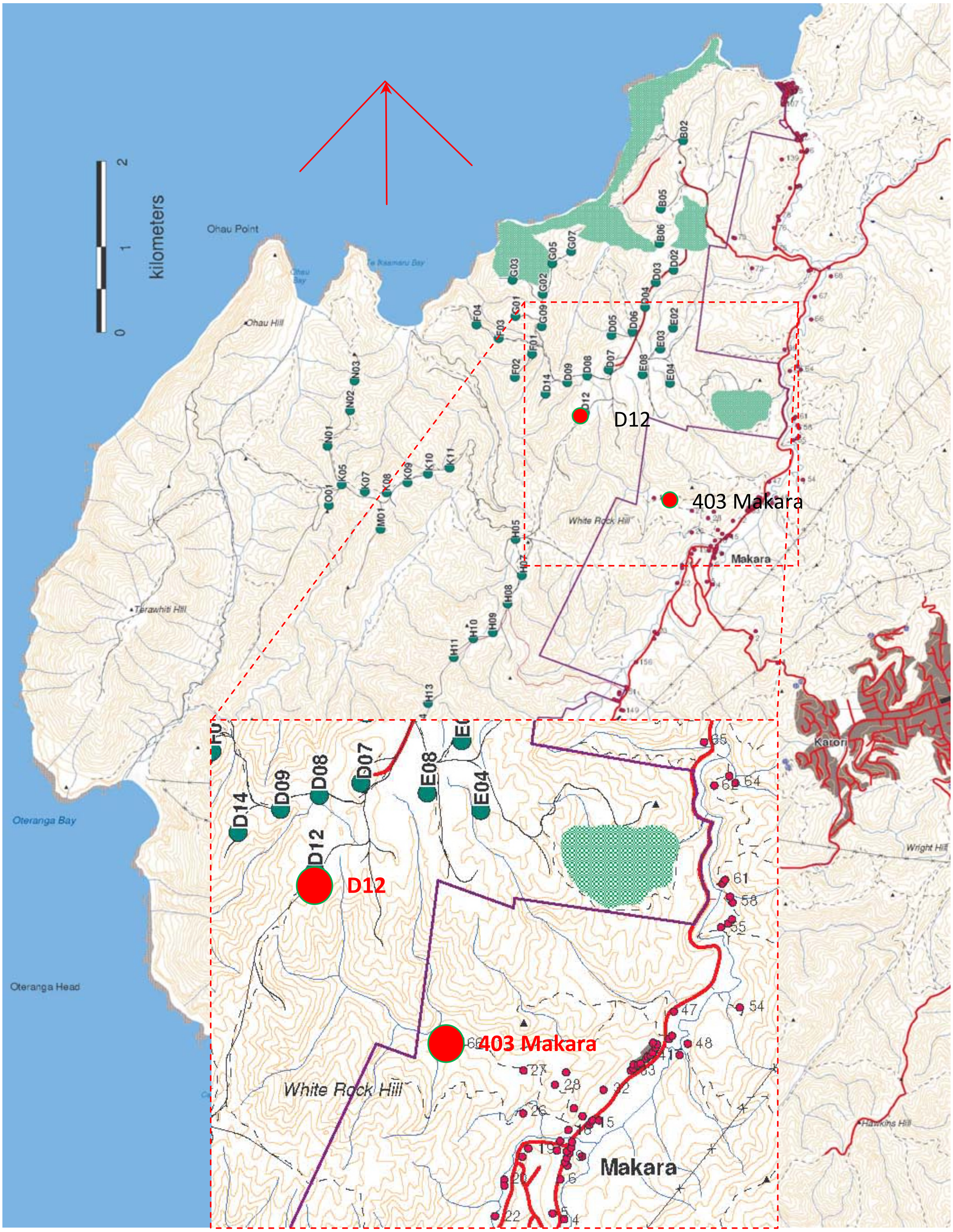


Figure 49: 2D contour map of Project West Wind [Makara] Wind Farm, 403 Makara Road and D12 Wind Turbine Generator.

Project West Wind [Makara] Wind Farm

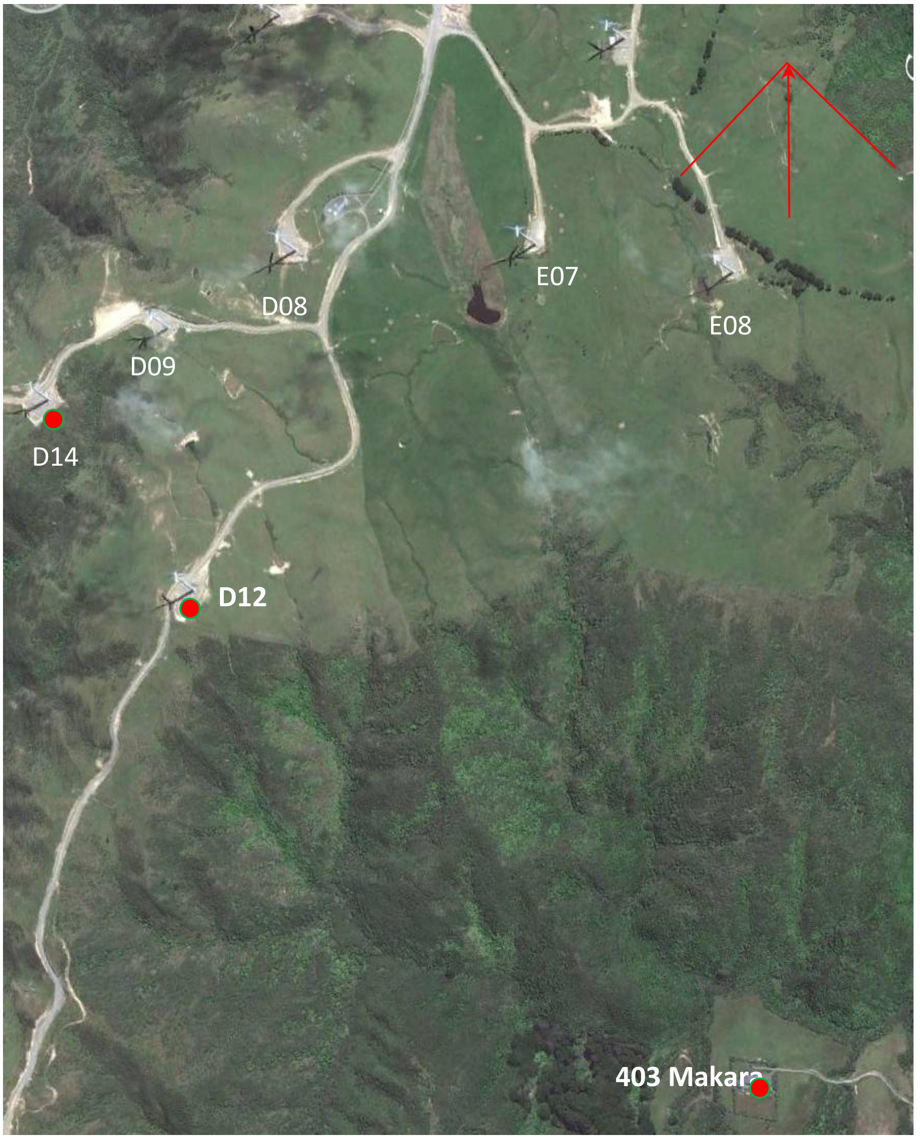


Figure 50: 2D aerial photo of Project West Wind [Makara] Wind Farm, showing 403 Makara Road and closest wind turbine generators with access tracks. Drawing adapted from Google Earth to include turbines.

Te Apiti Wind Farm

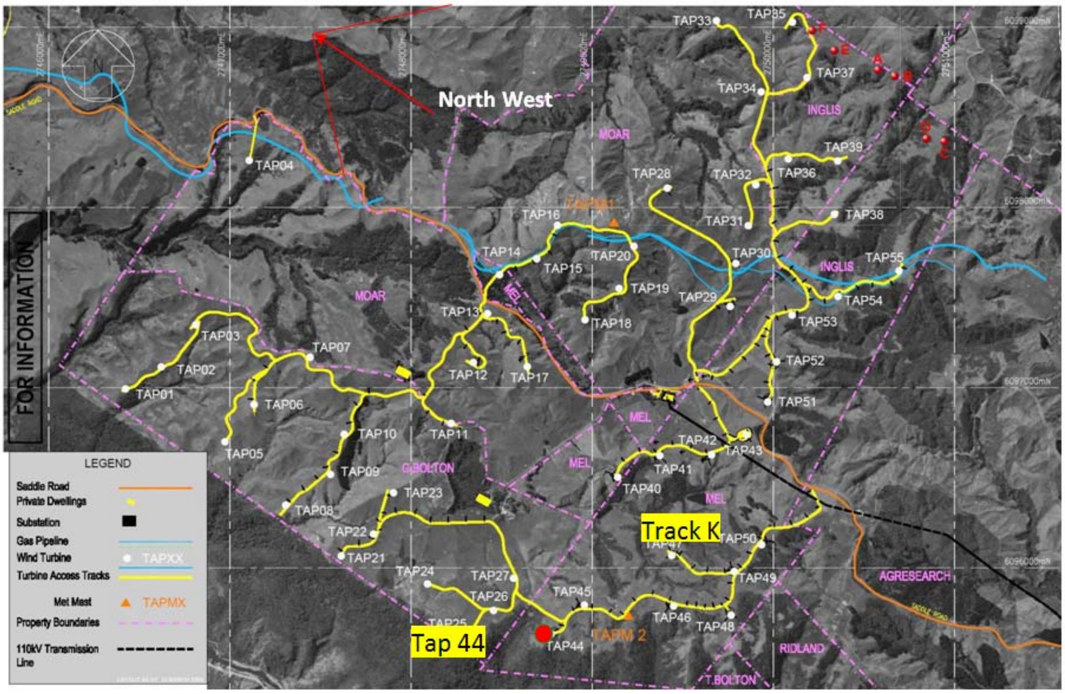


Figure 51: Black and white 2D aerial photo with Te Apiti Wind Farm, including Tap 44 wind turbine generator and tracks.

Figure 52: 3D aerial representation with Te Apiti Wind Farm overlay, including Tap 44 wind turbine generator & R_o measurement location. Note undulating terrain. Drawing adapted from Google Earth to include turbines.

Position of Selected Test Turbines and Sound Assessment Locations

Te Apiti Wind Farm

In relation to Te Apiti Wind Farm the wind turbine generator used for testing was Tap 44. This turbine is located on Track K. Track K is accessed via Saddle Road [public road]. This road links the town of Ashhurst [west of the farm] to Woodville [east of the farm].

Tap 44 was not the first choice for testing by the author but was elected as the test turbine by the wind farm site manager. This was because Tap 44 is located on Meridian Energy land [as opposed to a turbines on private stakeholders land].

Tap 44 is located adjacent to the most southern boundary of the wind farm site and overlooks the Manawatu Gorge and Manawatu River to the south. Road noise can be heard under certain conditions [namely southerlies when wind turbine generators on site are not operating].

Measurements were undertaken at the R_o location [downwind]. The R_o is based on a standard formula set out ISO 61400 being based on the hub height [H] and turbine diameter [D]. The formula in specific is R_o = [D/2]. As stated above the R_o location is a standard location where acoustic sound power measurements are prepared i.e. close to the turbine in order to minimise the influence of extraneous noise effects such as terrain effects, atmospheric conditions or wind induced noise. **Figure 53** illustrates definitions of R_0 and slant distance R_1.

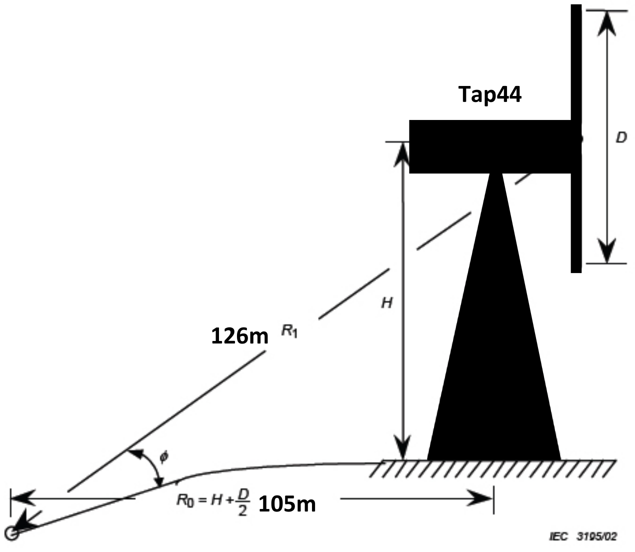


Figure 53: Illustration of the definitions of R_o and slant distance R_{1} [[48]].

In this case the resulting R_o is approx 105 m, this results in a slant distance between the hub and measurement location of 126 m. The following graphic illustrates a plan view and three dimensional view of the Tap 44 and the R_o location [shown as downwind for a north-east wind direction].

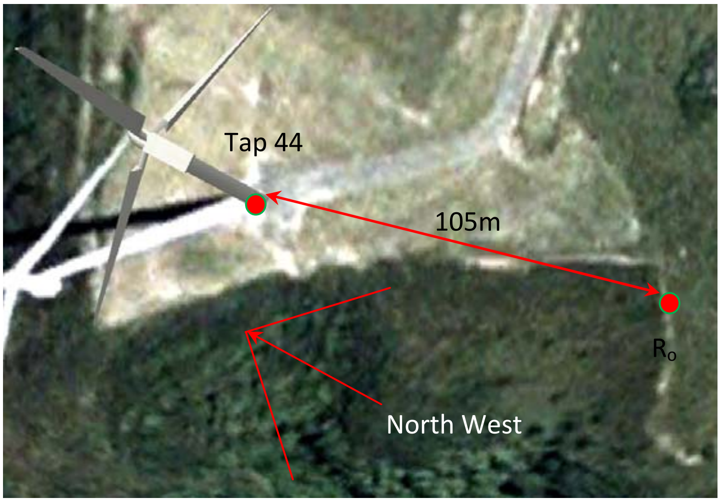


Figure 54: 2D base aerial photo with Te Apiti Wind Farm Tap 44 wind turbine generator [protruding 3D] and R_o measurement location. Drawing adapted from Google Earth to include Tap44.

Figure 55: [left] 3D aerial photo with Te Apiti Wind Farm Tap 44 wind turbine generator and R_o measurement location. Note sudden drop of terrain west of turbine. Drawing adapted from Google Earth to include Tap 44. [Centre]: Photo of Tap 44 and GPS being used to work out Ro location in terms of angle and distance. [Right]: Photo of Tap 44 from ground level.

As shown in the graphics above other turbines are within close proximity to Tap 44 and hence contribution from these turbines was unavoidable as they could not be turned off for testing purposes as part of this study. The likely influence from other turbines is discussed in detail further below.

The New Zealand Map Grid Co-ordinates for the R_o measurement location and Tap 44 wind turbine generator is shown in **Table 7**. The New Zealand Map Grid Co-ordinates have been used to calculate the distances between the wind turbine generator and R_o measurement location.

	Easting **New Zealand Map Grid**	**Northing** **New Zealand Map Grid**	**Height** **Above Ordnance Datum [AOD= Sea level] [m]**	**Distance [m]**
R_o [Assessment Location]	2748783	6095638	330 m	-
Tap44 Wind Turbine Generator	2748886	6095622	330 m	-
Tap44 to R_o	2748886	6095622	-	105 m

Table 7: Te Apiti Wind Farm, Tap 44 Wind Turbine Generator New Zealand Map Grid Northing and Easting co-ordinates, R_o assessment location heights and distances.

Project West Wind [Makara] Wind Farm

In relation to West Wind the sound assessment location was 403 Makara Road, Makara, Wellington. The closest visible turbine to 403 Makara Road is wind turbine generator D12. Access to number 403 is via Makara Road. Entry to the dwelling is via a shared access way which is approximately 1 km from Makara Road.

Sound level measurements were carried out approximately 15 to 20 m south of the dwelling with direct line of sight with D12. The measurement location is located approximately 2 m above the dwelling.

The New Zealand Map Grid Co-ordinates for the measurement location and closest wind turbine generator [D12] is shown in **Table 8**. The New Zealand Map Grid Co-ordinate has been used to calculate the distance between D12 wind turbine generator and measurement location.

	Easting New Zealand Map Grid	Northing New Zealand Map Grid	Height Above Ordnance Datum [AOD= Sea level] [m]	Distance [m]
403 Makara Road [Assessment Location]	2652179	5992265	98 m	-
D12 Wind Turbine Generator	2651421	5993247	269 m	-
403 Makara Road to D12 [as the crow flies]	-	-	-	1240.5 m
403 Makara Road to D12 [Slant Distance]	-	-	-	1252.3 m

Table 8: Project West Wind, Wind Farm, D12 Wind Turbine Generator and 403 Makara Road New Zealand Map Grid Northing and Easting co-ordinates, heights and distances.

The following graphic in **Figure 56** illustrates a three dimensional view of the D12 wind turbine generator in relation to 403 Makara Road.

Figure 56: 3D schematic of 403 Makara Road location relevant to D12 wind turbine generator. Note steep surrounding terrain and hills. Drawing adapted from Google Earth to include 403 Makara Road and D12.

The following graphic [**Figure 57**] illustrates a further three dimensional view of the wind turbine generator D12 in relation to 403 Makara Road. The graphic has had the valleys shaded to illustrate the complex terrain. It is noted the distance from wind turbine generator D12 to the edge of the hill is approx 500 m at which point the terrain starts to fall off toward 403 Makara Road. The approx vertical distance between 403 Makara Road and the edge of the wind farm site is approx 200 m in vertical elevation.

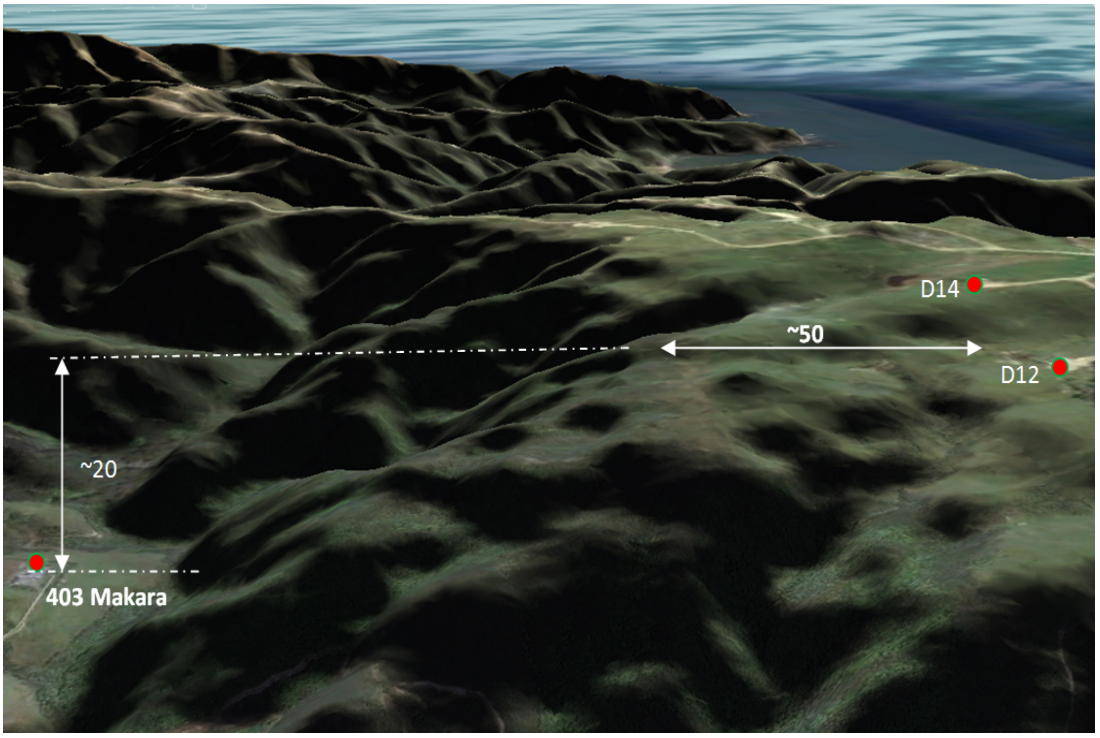


Figure 57: 3D aerial photo of Project West Wind [Makara] Wind Farm, showing 403 Makara Road and closest wind turbine generators with access tracks. Drawing adapted from Google Earth to include 403 Makara Road and D12

The distance between the turbine and noise receiver location has a slight barrier effect from the terrain between [as discussed further below]. Only two of the three blades are ever visual at any one time. The following three dimensional visualisation in **Figure 58** shows this concept.

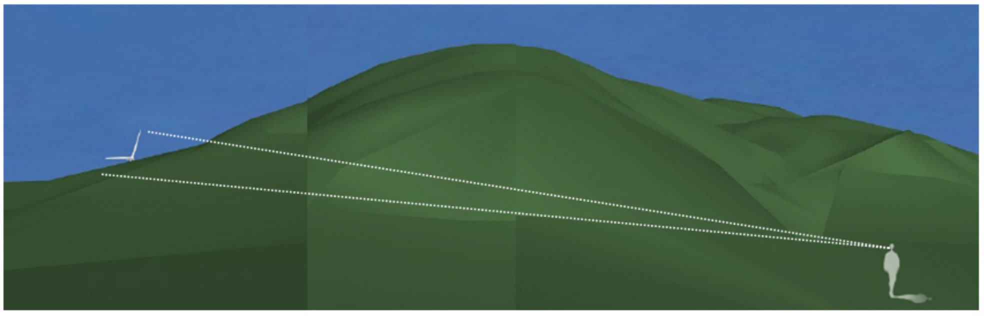


Figure 58: Visualization of D12 wind turbine blades as viewed from 403 Makara Road [[32]]. Note visualisation is based on Vestas V90 using rotor diameter of 90m and hub height of 80m rather than the final Makara turbines installed which has 82m rotor diameter and 67m hub height.

Photo of Test Sites and Wind Turbine Generators

Te Apiti Wind Farm

Figure 59: Te Apiti Wind farm as viewed from off the wind farm site, looking east-ward towards farm.

Figure 60: Photo simulation as viewed from base of Tap 44 looking through 360 degree view.

Figure 61: Photo viewed from base of Tap 44 looking approx north-west towards turbine Tap 26 in foreground.

Figure 62: Photo viewed from base of Tap 44 looking approx north towards turbine Tap 45 in foreground.

Figure 63: Photo viewed from base of Tap 44 looking approx south. Note fence line represents wind farm site boundary with steep drop off terrain towards Manawatu Gorge below.

Figure 64: Photo viewed from base of Tap 44 looking approx west, turbines in far background from Tauraua Wind Farm [along ridge line].

Figure 65: Photo viewed from approx north-west looking towards base of Tap 44.

Figure 66: Photo viewed from approx south west looking towards base of Tap 44. Tap 45 in foreground.

Figure 67: Photo viewed from approx south east looking towards base of Tap 44. Tap 26 in foreground.

Project West Wind [Makara] Wind Farm

Figure 68: Photo viewed from aircraft of West Wind, Wind Farm.

Description of Test Wind Turbine Generators

Project West Wind [Makara] Wind Farm

West Wind [Makara] Wind Farm has 62 'Siemens 2.3 MW' [SWT-2.3-82VS] Model Wind Turbine Generators. The Siemens wind turbine generator is a horizontal axis wind turbine with a hub height of approx 67 metres. The turbine has three blades each 40 m in length. The Siemens turbine has a rated power output of 2.3 MW. The maximum power output of 2.3 MW per wind turbine generator equates to a total wind farm output of 142.6 MW.

Te Apiti Wind Farm

Te Apiti Wind Farm has 55 'Vestas V72' Model Wind Turbine Generators. The V72 turbine is a horizontal axis wind turbine with a hub height of approx 70 metres. The V72 has three blades each 35 m in length. The V72 rated power output is 1.65 MW. The NM72 [Neg Micon NM72] was renamed the Vestas V72.

The V72 was the first commercial 'mega-watt' class wind turbine generator used in New Zealand.

Technical Specifications of Test Wind Turbine Generators

Main Data	Description Vestas V72 Te Apiti	Description Siemens SWT2.3-82V Project West Wind
Type/Position	3-bladed, horizontal axis/Upwind	3-bladed, horizontal axis/Upwind
Nominal Power	1650 kW or 1.65 MW	2300 kW or 2.3 MW
Rotor Diameter	72m [= 35m Blade +2m rotor]	82m [= 40m Blade +2m rotor]
Swept Area	4072 m^2	5300 m^2
Hub Height	70m	67m
Rotational Speed	17.3 rpm [fixed speed]	6-18 rpm [variable speed]
Rotor		
Number of Blades	3 Pieces	3 Pieces
Rotor Shaft Tilt	5 degrees	6 degrees
Power Generation	Active Stall	Pitch regulation
Rotor Orientation	Upwind	Upwind
Blades Length	35m	40m
Type	AL 35	Self supporting
Blade Length	35m	40m
Material	Fibre glass/Carbon Fibre/Epoxy Wood	GRE
Blade Profile	FFA W32-xx NACA 63.4	NACA 63.xxx, FFAxxx
Blade Twist	10 degrees	8 degrees
Hub		
Type	Spherical	Nodular
Main Shaft		
Type	Forged shaft and flange	Flange shaft
Gearbox		
Type	1 step planet. 2. step helical	3-stage planetary-helical
Generator		
Type	1 Speed generator, water cooled	Asynchronous
Rated Power	1650kW	2300 kW
Yaw System		
Type	Ball bearing, internal gearing	Active
Tower		
Type	Vertical Cylindrical Steel	Vertical Cylindrical Steel
Nacelle		
Type	EN-GJS-400-18U-LT	AMA 500L4 BAYH

Table 9: Table of generic specifications for test turbines - Vestas V72 and Siemens SWT 2.3-82V wind turbine generator

Technical Drawings of Test Wind Turbine Generators

Te Apiti Wind Farm – Vestas V72

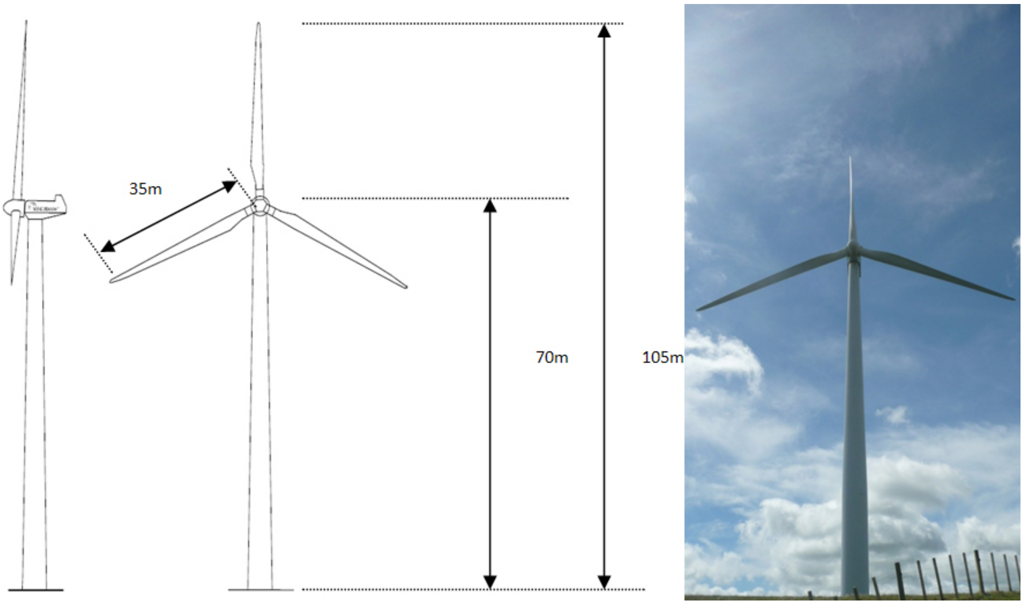


Figure 69: Technical drawing of front and side elevations of Wind Turbine Generator with key dimensions of Vestas V72 [blade length and heights].

Project West Wind [Makara] Wind Farm – SWT 2.3-82V

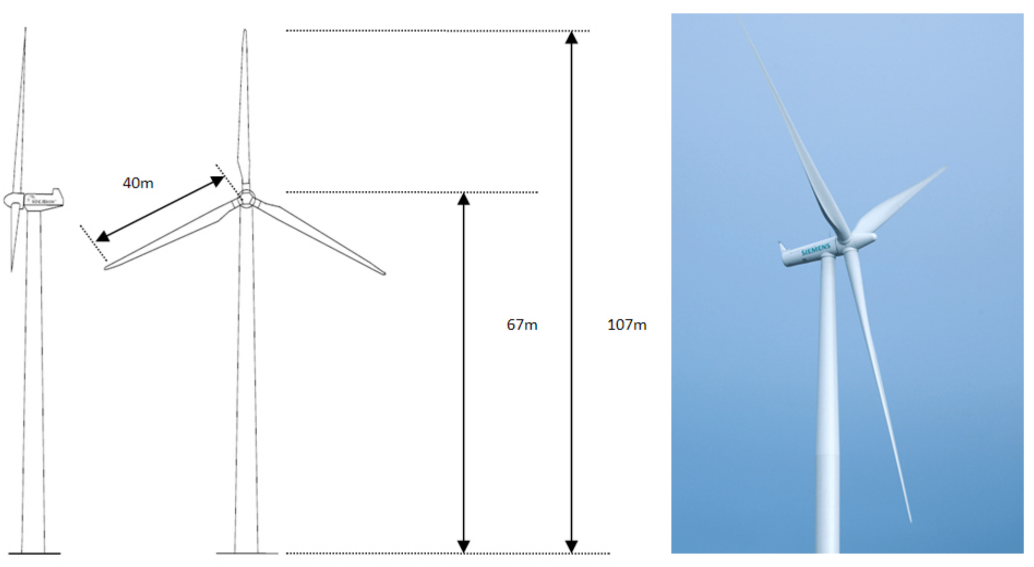


Figure 70: Technical drawing of front and side elevations of Wind Turbine Generator with key dimensions for Siemens SWT 2.3-82V [blade length and heights].

Test Wind Turbine Generator Sound Power Level [L_{wa}]

The sound power levels for which wind farm predictions and assessments [prior to development] are normally designed are based on a worst case design envelope i.e. highest maximum sound power level.

In regards to both test wind farms there are special requirements set by Resource Consent Conditions [governed by legal requirements set in law under powers of the Resource Management Act and/or Environment Court].

The sound power levels below are therefore referred to as 'assumed' only based on available test data for standard settings [mode 0]. The actual sound power level may differ from that below as this depends upon the individual turbine and any sound controls required restricting sound output at receiver locations. It is not uncommon for ratings to be given dependent upon the operating mode i.e. mode 0 [standard], mode 1 [-1 dB], mode 2 [-2dB].

The West Wind, wind turbine generators are pitch controlled variable speed turbines. This allows the blade pitch angle to be set dependant on the electrical power, wind speed and rotional speed. As the wind turbines are variable speed this allows the rotor to change rotional speed between 6 revolutions per minute [rpm] and 18 rpm [depending upon wind speed]. The wind turbine generators at West Wind have individual programing allowing the wind turbines to be 'de-rated' as and when required.

The variable speed programing relates to an underlining process in regards to an alternative power curve realtionship with the function alternateing between wind speed, power and rotor speeds such that turbines can be controlled under real time conditions so that under certain wind speeds and environmental condtions [i.e. wind direction for example] the turbines may have lower rotional speeds and hence less aerodynamic sound.

The wind turbine generators are controlled under the various conditions to always comply with the required permitted legal sound levels at the closest receiver locations. This variable control would only apply to wind turbines in close proximity to dwellings such as D12. This is because the closest wind turbine generator will be the dominant sound source in terms of sound levels received off site.

The following are the *assumed* 'apparent sound power level' [as sourced from actual test certificates]. It is key to note that manufacturers provide sound levels as 'apparent' meaning an A-weighted sound power level based on a downwind testing direction determined at the R_o location for wind speed integer from 6 to 10 m/s.

Assumed Turbine Sound Power Level

The fundamental difference in the two wind turbine generators [and therefore their acoustic output] is that the Te Apiti wind turbine generators control their maximum power output through active stall and are fixed rotational machines. The wind turbines installed at Project West Wind [Makara] control their power by pitch control and are full variable speed machines.

Te Apiti Wind Farm – Vestas V72 Wind Turbine Generator

Apparent Sound Power Level [L_{wa}]	[L_{wa}]
Verified to IEC 61400-11 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques.	103.2 dBA

Table 10: Measured Apparent Sound Power Level for Vestas V72 Wind Turbine Generator.

Project West Wind [Makara] Wind Farm - SWT2.3-82V

Apparent Sound Power Level [L_{wa}]	[L_{wa}]
Verified to IEC 61400-11 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques.	102.3 dBA

Table 11: Measured Apparent Sound Power Level for Siemens SWT 2.3-82V Wind Turbine Generator

The following **Table 12** illustrates the individual sound power levels for West Wind, wind turbine generators for wind speeds between 4 m/s and up to 18 m/s and as a function of frequency. No such wind speed data was able to be sourced for Te Apiti Wind Farm.

Wind Speed m/s	4m/s	5m/s	6m/s	7m/s	8m/s	9 m/s
Standard setting Rated noise emissions [L_{wa}]	89.3	94.0	99.7	101.6	101.9	102.3

Table 12: Measured *Apparent Sound Power Level* for Siemens SWT 2.3-82V wind turbine generator at various wind speeds [standard and setting 4 sound powers operating modes provided].

The above data is represented in graphical format as follows in **Figure 71** - The following graph illustrates the individual sound power levels for West Wind and as a function of wind speed.

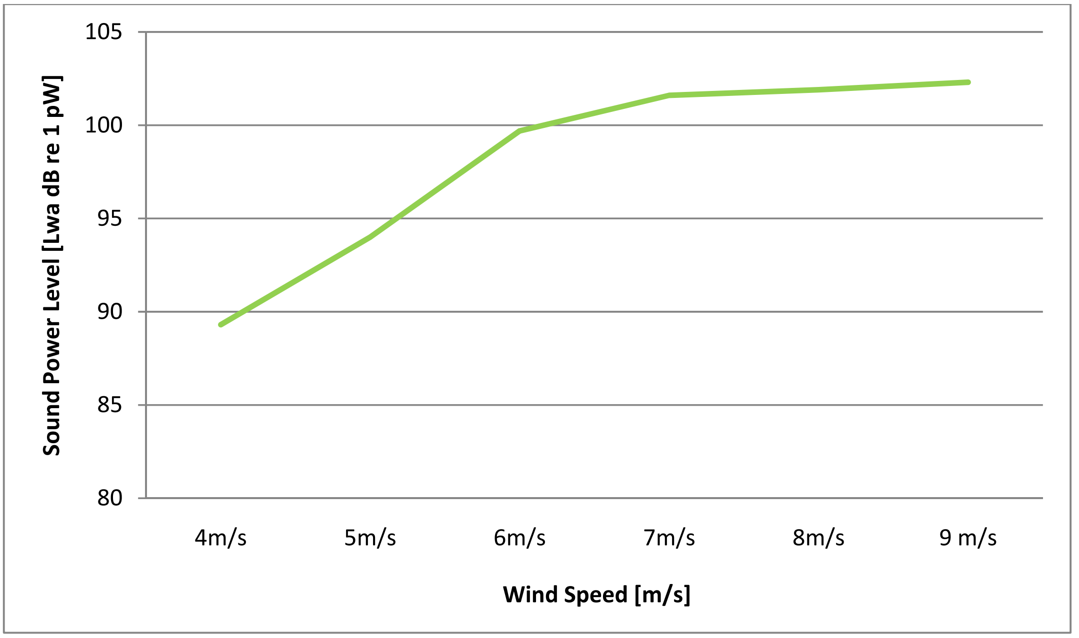


Figure 71: Graph of Sound Power Level [Lw dB re 1 pW] for Siemens SWT 2.3-82V wind turbine generator at various frequencies [standard and setting 4 sound powers operating modes provided].

The following **Table 13** illustrates the individual sound power levels for Te Apiti Wind Farm wind turbine generators as a function of sound level frequency.

Octave Band Hz	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Standard setting rated noise emissions [L_{wa}]	79.4	89.4	98.1	100.2	100.5	97.6	96.0	90.2

Table 13: Measured Apparent Sound Power Level for Vestas V72 Wind Turbine Generator at various frequencies [standard sound power operating mode provided].

Figure 72 illustrates the individual sound power levels for Te Apiti Wind Farm wind turbine generators and as a function of sound level frequency at **8 m/s**.

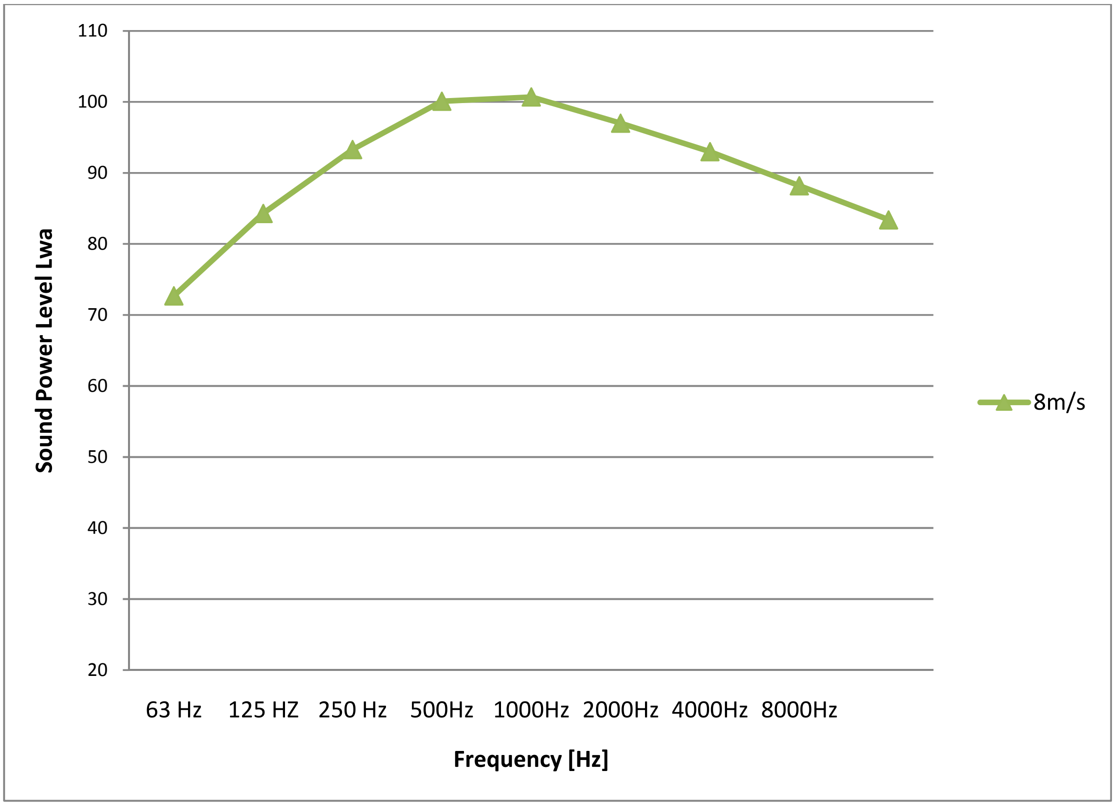


Figure 72: Graph of Measured Sound Power Level for Vestas V72 wind turbine generator at various frequencies for 8 m/s operating speed [standard sound power operating mode provided].

Measurement Equipment

The following sets out the sound level measuring equipment used for the study and related data.

Sound Level Measurement Equipment

Equipment	Manufacture and Type	Serial Number/Details
Bruel and Kjaer 2260 Observer Sound Level Meter	Bruel and Kjaer 2260 Observer Integrating Sound Level Meter	Serial Number: 1931126. Firmware BZ7202 V1.1/BZ7219 V1.0
Bruel and Kjaer Calibrator Type 4230	Bruel and Kjaer Calibrator Type 4230. 94 dB @1000 Hz	622678
Inner and Outer Wind Screens	Bruel and Kjaer 90 mm Foam Wind Screen type UA237 and 200 m foam wind screen	NA
Cables	Bruel and Kjaer Cabling and Connections	NA

Table 14: Description of key sound level measuring apparatus used in study.

The following graphic illustrates the Bruel and Kjaer 2260 Sound Level Meter, wind screens and calibrator used in the study.

Figure 73: 2260 Bruel and Kjaer Integrating Sound Level Meter and calibrator and wind screens [91].

Audio Measurement Equipment

Equipment	Manufacture and Type
Audio Sound Recording Equipment	M-Audio Micro Track II Professional 2-Channel Mobile Digital Recorder

Table 15: Description of audio level measuring apparatus used in study.

The following graphic illustrates the Micro track audio equipment used in the study.

Figure 74: M-Audio Micro Track II and related equipment used in study [92].

Weather System Apparatus

Equipment	Manufacture and Type
Hand Held Digital Thermometer	Holy Oak Air Management Solutions Sh-102
Hand Held Digital Anemometer	Skywatch Xplorer 2 JD Instrument

Table 16: Description of key handheld weather apparatus used in Study.

Global Positioning System Apparatus

Equipment	Manufacture and Type
Garmin GPS Unit	Garmin GPS 60 Navigator
Garmin GPS Software	Garmin
Google Earth GPS coordinator transfer	Garmin / Goggle Earth

Table 17: Description of GPS apparatus used in study.

The following graphic illustrates the Garmin GPS model used in the study.

Figure 75: Garmin GPS Unit [93].

Figure 76: Garmin GPS Unit at base of Tap 44, Te Apiti Wind Farm.

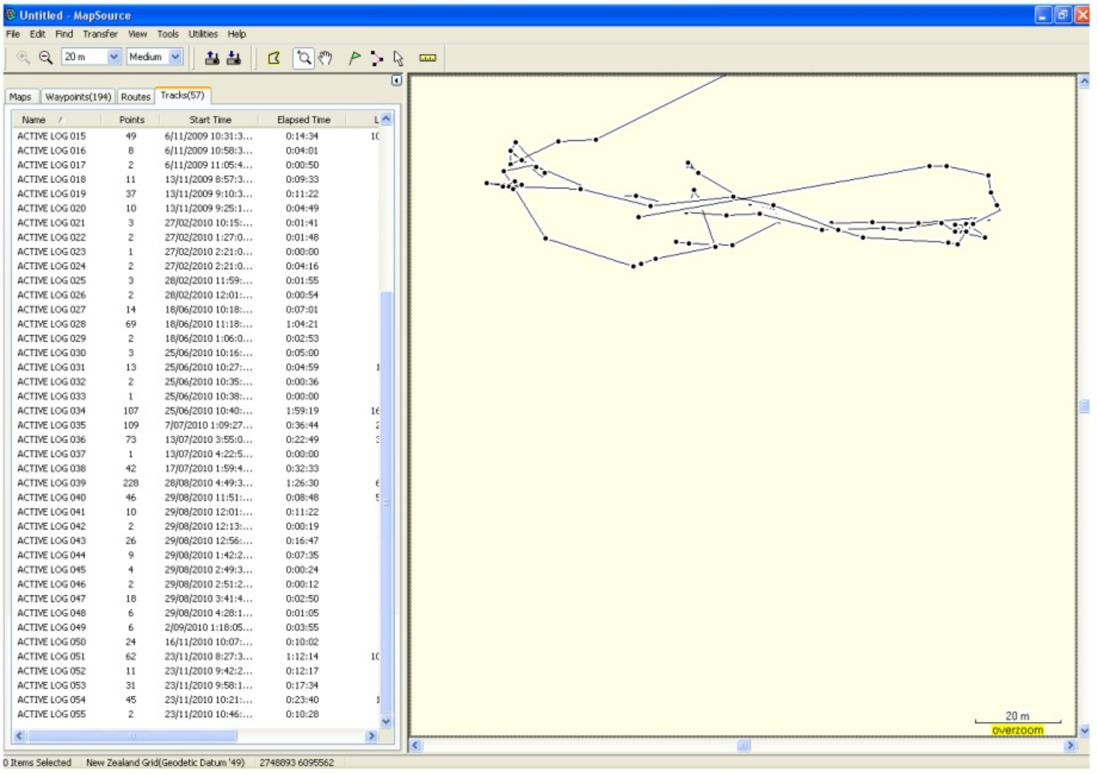


Figure 77: [Top]: Garmin GPS Unit Software and tracking GPS points and point on blank base map. [Bottom] GPS points transferred from Garmin software onto Goggle Earth Map for Tap 44, Te Apiti Wind Farm.

Additional Apparatus

Equipment	Manufacture and Type
Heavy Duty Pelican Cases [weather tight]	Pelican 1510 Cases
Sealed lead rechargeable acid batteries	Exide 12V Batteries [40 amp hours]
Digital Camera [with motion picture functions]	Panasonic Lumix Digital Camera
Headphones	Sennheiser HD201
Computer and software	Dell XPS with Microsoft Excel Software
Heavy Duty Tripod [3 Legs]	-
Cable ties, duct tape, cords	-
Head light and hand torches	-

Table 18: Description of various supplementary apparatus used in study.

The following graphic illustrates the similar model Pelican case used in the study.

Figure 78: Heavy duty pelican case used in study for weather protection of measurement apparatus [[94]].

Calibration and Specifications of Measuring Equipment used in Study

The 2260 Bruel and Kjaer integrating sound level measuring equipment used in the study complies with IEC 60651 Type 1, IEC 804 Type 1, and IEC1260 Class 1 specifications for Sound Level Meters.

In addition to the above equipment on the infrequent occasion other sound level meter types such as the EL316 data logger and Rion NA-27 sound level meters were required to be used. This measuring equipment complies with IEC 60651 Type 1, IEC 804 Type 1, and IEC1260 Class 1 specifications for Sound Level Meters. All sound level meters held current calibration certificates apart from one being the Massey University Bruel and Kjaer 2236 Sound Level Meter which is understood to be out of laboratory calibration.

The reason a Bruel and Kjaer 2236 sound level meter was used without laboratory calibration was due to the fact that all fore mentioned measuring equipment was not available for use at all times It is noted that there were two Bruel and Kjaer 2236 sound level meters used. One had octave capabilities the other did not. The two Bruel and Kjaer 2236 sound level meters were Massey University sound level meters and it is understood these comply with Type 2 [Class 2] specifications for sound level meters. It is important to note that the two 2236 sound level meters did not hold current laboratory calibration certificates during the periods used for measurements as part of this study. All remaining instruments did have full and up to date calibration certificates [as did the handheld calibrator]. It is also important to note that on a handful of occasions field calibration was not checked after all measurement periods as a calibrator was not always available at that time.

Based on the above information use of any data from this study would need to be discussed with the author regarding its accuracy validity before any conclusions should be drawn for purposes other than this study – being to allow for data collection for analysis within the scope of this study only.

Third Party Data

In several cases external data was required to complete the study, this included weather data and data relating to the operation of the wind farm. In the case of all external data, this was provided by several third parties and hence the author cannot guarantee or assure the accuracy of the data for any use other than for within the scope of this study. Data accuracy and calibration of measuring equipment regarding all third party data is unknown and hence any use of the data in this study should be validated with the third parties.

Measurement Personnel

The author undertook all measurements and data collection presented in this study, apart from any third party data such as wind data which was provided to him from third parties such as [but not limited to] wind turbine generator hub height wind data and local weather data [wind, precipitation, extraneous noise data events etc]. The author was also solely responsible for the set up and operation of all data on site. Basic training and assistance was provided in regards to audio recording techniques i.e. correct set up and recording methods.

On several occasions the author was accompanied by different persons for assistance with equipment cartage, namely on the Te Apiti wind farm site due to steep terrain. On several occasions Dr Stuart McLaren [Supervisor] attended visits to both Te Apiti [day time] and Makara [day and night time].

Surrounding Environments of Wind Farm Test Sites

The environment which surrounds the measurement location plays a key role in obtaining suitable measurement data. The ability to hear and measure the wind turbine at the measurement location depends on the background noise level. The background noise levels are a function of various factors including the surrounding noise sources from the natural environment such as wind disturbance in surrounding trees and wind noise.

An optimal background noise level must exist to allow for measurement of the wind turbines. Generally 'optimal' means a background noise level much lower than the wind turbine sound pressure level at the receiver locations.

The sound levels from the turbine may still be audible however it would not be able to be measured due to the high level of unwanted background noise. As discussed further below there are tools to allow for analysis of the wind turbine sound levels to be 'subtracted' from the background noise [if the background noise is higher].

As the sound output from a wind turbine generator increases with wind speed so does the background noise level. In regards to the two measurement sites increasing wind speeds caused increased background noise levels and hence the wind generated significantly higher background noise levels produced by moving trees and grasses. This background noise masks the sound from the wind turbine generator at the receiver location.

As detailed further below several 'filters' of the raw data have been provided in order to remove all extraneous or unwanted data including basic analysis of background noise levels from masking.

The following discusses the *surrounding* environments of the two test sites.

Te Apiti Wind Farm

Te Apiti Wind Farm is located approx 10 km north-east of Palmerston North CBD. The surrounding environment is rural. There are several other wind farms in the surrounding area [and further planned wind farm developments at Resource Consent Stage]. Existing wind farms include Te Rere Hau and Tararura. Proposed wind farms and extensions to existing wind farms include the newly proposed Turitea Wind Farm and the eastern extension to Te Rere Hau.

Figure 79 illustrates a map of the surrounding area and Te Apiti Wind Farm.

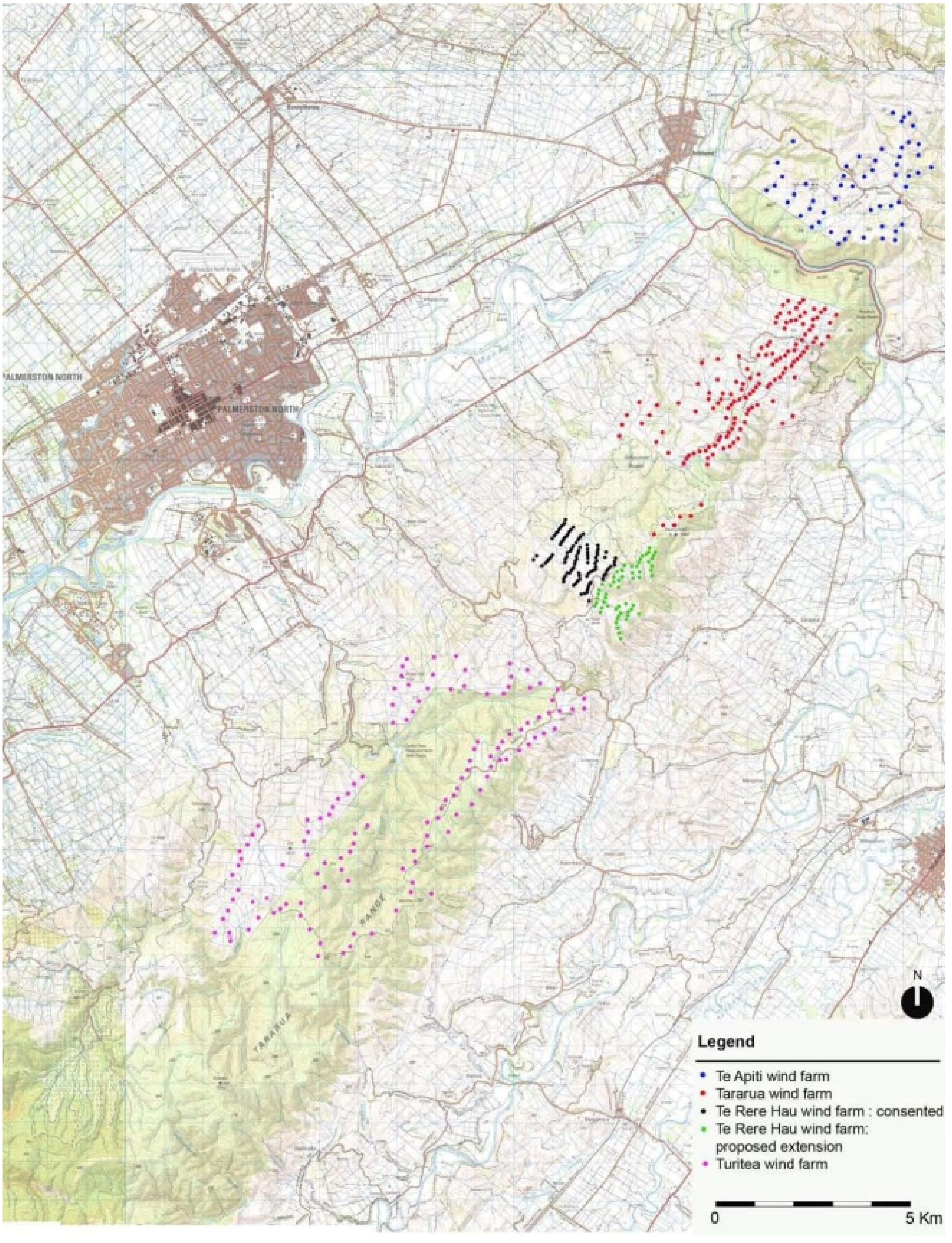


Figure 79: 2D map with Te Apiti Wind Farm and wider surrounding environment [including existing and proposed wind farm developments.

The test wind turbine generator [Tap 44] is located on the southern boundary of Te Apiti Wind Farm. Due to the remote rural location of the wind farm, there were no significant noise sources contributing to the background noise [when the turbines are turning and producing aerodynamic sound]. The measurement location was in proximity to some vegetation. Inspection showed that the vegetation was low lying and not 'leafy' and hence not a source for additional unwanted background noise. Observations showed noise from the interaction between the wind and vegetation was nil to minor during the measurement of wind turbine sound.

Other sound sources noted were very low levels of traffic noise from Manawatu Gorge. This was only just audible above background noise levels and only audible when the turbine was not operating. Man made noise from aircraft overfly was also noted on a few occasions in the wider environment. On one occasion a crop duster aircraft was within close proximity to the wind farm.

Transformer sound [at base] and low level gear sound [nacelle] were also observed from the turbines on site. Both noises were only just audible above background noise levels and were at least 10 dB lower than wind turbine sound contributions.

When measurements were conducted sound from the wind turbines blades was dominant. All other sound sources were at a much lower level when compared to the wind turbine aerodynamic sound produced at the receiver measurement location.

However the contribution of sound [aerodynamic] from other turbines was noted on some occasions. The question is to what level did the other surrounding turbines contribute to the measured levels?

Analysis has shown that because the R_o measurement location is at a similar distance from Tap 44 as to Tap 45 the sound from this wind turbine did contribute to the overall total measured sound levels during the measurements. A calculation has been made and the contribution is believed to be no more than 3 dB [total]. As stated above the final data sets used for the analysis have included various 'filters' of the raw data to remove unwanted or extraneous noise.

Project West Wind [Makara] Wind Farm

West Wind [both wind farm and dwelling] are located on the south-west coast of Wellington City. There are various wind farm developments *planned* for the surrounding area including Long Gully Wind Farm and Mill Creek Wind Farm. However at the time of preparing this study the Meridian V27 Vestas Wind Turbine Generator was the only existing and operating wind energy producer in Wellington. The single Meridian V27 Vestas Wind Turbine Generator is however located several kilometres away from West Wind hence having no effect on the sound level measurements.

As detailed above the sound assessment location was 403 Makara Road, Makara, Wellington. The dwelling is located on a generally flat footprint; however the site itself lies at the bottom of a valley which slopes towards the foothill of this valley. The site is surrounded by undulating terrain which is approx 125 m to the north [before the foot of the hill starts] and approx 130 m to the west [before the foot of the hill starts]. South of the site at a distance of approx 125 m uphill from the dwelling is a large plantation forest which contributes to the background noise levels at the site under both northerly and southerly wind conditions.

East of the site is open terrain which lowers in elevation the further you move from the dwelling towards Makara Road. The following **Figure 80** illustrates a 3D schematic of the subject site and closest turbine. To the left of the 3d schematic is a 2D plan illustrating the 20 m terrain contours. Both the schematics below illustrate how steep the terrain is around the subject site.

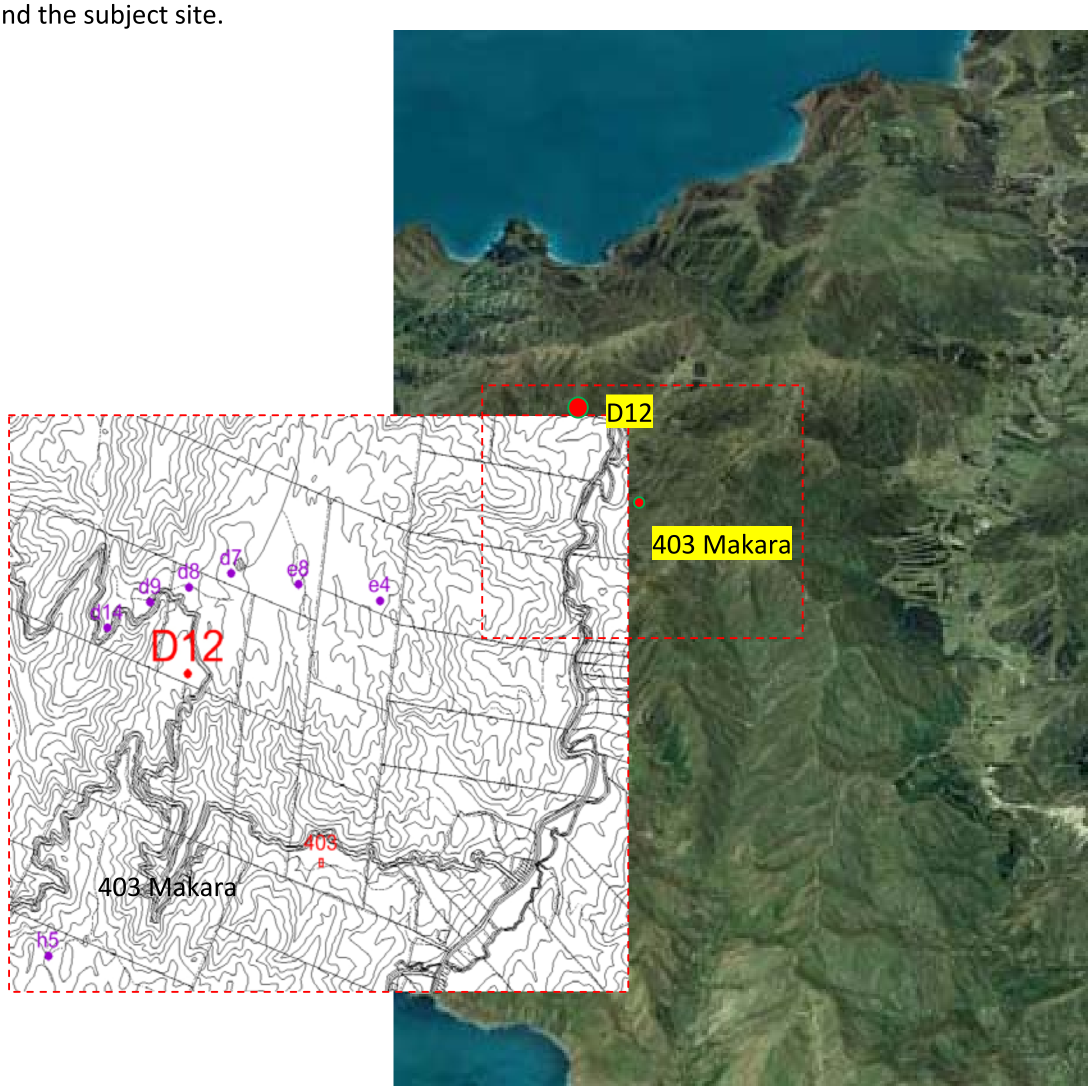


Figure 80: 3D colour schematic of 403 Makara Road location relevant to D12 wind turbine generator. Note steep surrounding terrain and hills. Inset 2D 20m contour map illustrating D12 wind turbine generator and additional surrounding turbines relative to 403 Makara Road.

The Makara site is rural with various surrounding noise sources. Surrounding the site in the adjacent hills and valleys is vegetation in the form of trees. These do under certain conditions i.e. winds blow down ridge [north-easterly] produce vegetation noise which can be fairly dominant at times. Inspection showed that the vegetation surrounding the dwelling was low lying from trees and grass.

Observations showed noise from the interaction between wind and vegetation was an important issue to consider as even under very calm conditions at the site, for example up to 1.5 m/s [Beaufort Land Scale 1] local wind effects could potentially mask wind turbine sounds.

Man made noise from aircraft overfly [fixed and rotary wing] was also noted on several occasions in the wider environment. Flight tracks do fly adjacent the site for Wellington International Airport. Noise from the dwelling at 403 Makara Road [people, cars, plant noise] was also noted [chiefly during day time and evening] as was noise from the dwellings power generator [again mainly during daytime].

During the period where background noise was its lowest in the surrounding environment from most sources, natural wind noise appeared to be the biggest contributor at the measurement site.

Wind and Climatic Conditions for Test Sites

The “roaring 40’s” and “furious 50’s” are names used to describe the latitude between 40 and 50 degrees south of the equator. The bottom of the North Island and South Island of New Zealand is located at latitudes between 40 and 50 degrees south of the equator.

These are latitudes of prevailing winds, namely westerly because there is less land mass to slow the wind energy across the open oceans and hence the winds are especially strong in the southern hemisphere - being strongest at latitudes of 50 degrees south. Both test wind farms have prevailing [north] westerly winds.

Figure 81 illustrates a NIWA annual median wind speed map, note the high wind speeds where Te Apiti and West Wind sites are located.

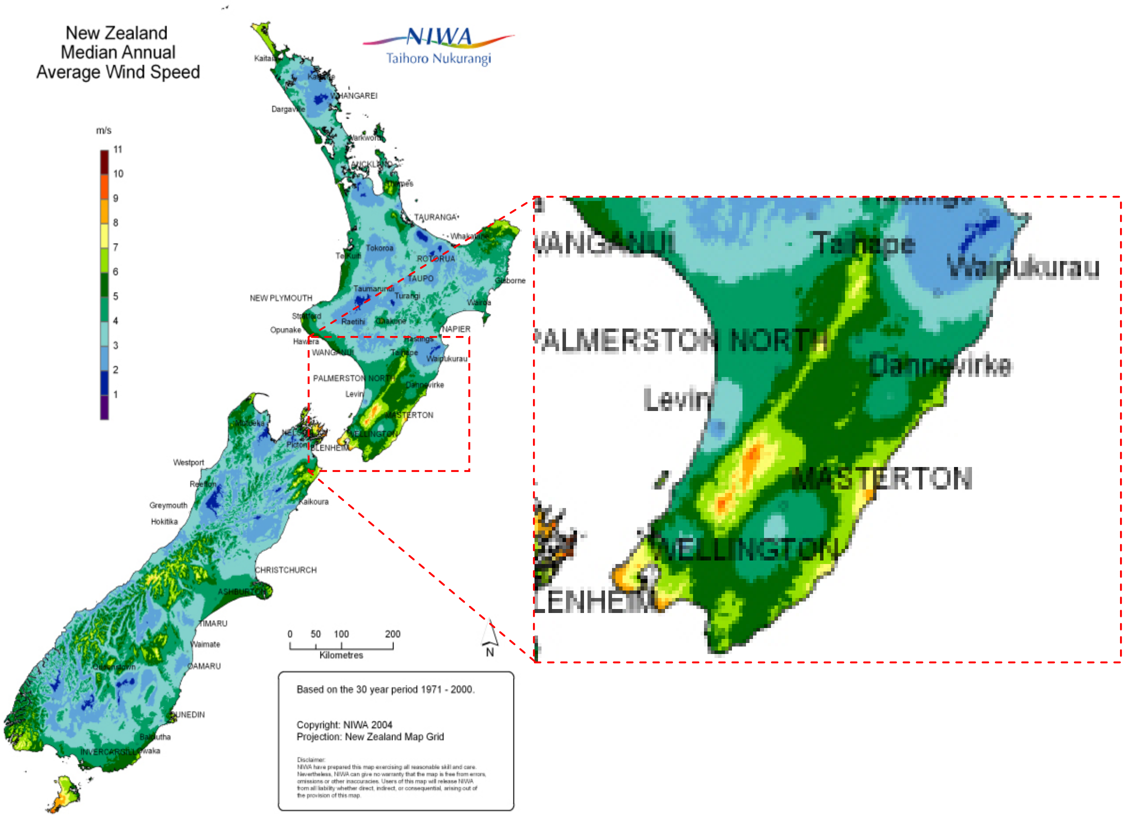


Figure 81: NIWA median annual average wind speed map for New Zealand.

Project West Wind [Makara] Wind Farm

Wellington is located on the south coast of the North Island [New Zealand]. The subject site [both wind farm and dwelling] are located on the south-west coast of Wellington City. The Makara area [and Wellington] in general has a temperate cool climate most of the year. The climate does not have temperature extremes. Strong winds are a feature of Wellington's Climate.

Wellington sits at latitude 41 degrees [South of the equator]. Wellington is cooler because of the moderating effects of the surrounding Pacific Ocean. Makara Wind Farm is adjacent to the coast line overlooking the Tasman Sea and Cook Strait which joins the North and South Islands of New Zealand.

The effects of the local wind scales are created by unequal heating of the earth, in this case the fact that the wind farm is located on a large body of land adjacent an even larger body of water and hence has what is known as a land-sea breeze effect created along coast lines where the land and water create variations in wind pressures due to differences in the temperatures between the two bodies. This is primarily because there are differences in the way land and water bodies heat and cool.

The land-sea breeze conditions see that both the water and land initially receive the same amount of solar radiation, however during the day time the land heats faster than the body of water, which results in a low pressure over the land.

The air moves from over the water towards land in response to a pressure gradient to creating what we refer as a sea breeze. During the evening and night time period the land cools faster than the water, thus promoting a higher pressure over the land and lower pressure over the water. This pressure gradient induces the air to flow from the land toward the water creating what we refer to as a land breeze. A land breeze would best be described as a Southern Wind as a sea breeze dominates northerly, north westerly winds.

The Cook Strait also has a funnelling effect on the wind which means the site has strong and consistent wind speed as there are no major structures or land mass to slow the wind down over the relatively flat waters of the Cook Strait, allowing for a good wind resource.

Project West Wind [Makara] Wind Farm Wind Rose

The following **Figure 82**, wind rose [Makara Area] exhibits a considerable bias in the north-west and south east directions; this wind rose is for a period of approx 40 years.

Figure 82: Sample Wind Rose for Makara area – All wind directions [95].

The following wind rose [**Figure 83**] exhibits a similar bias in the north-west and south-east directions, the following wind rose is for the Makara area [all wind directions]. Below this is the data split for day and night [**Figure 84**]. Data and related wind roses illustrate a similar pattern [north-west and south-east] for each month of the year in the Makara area.

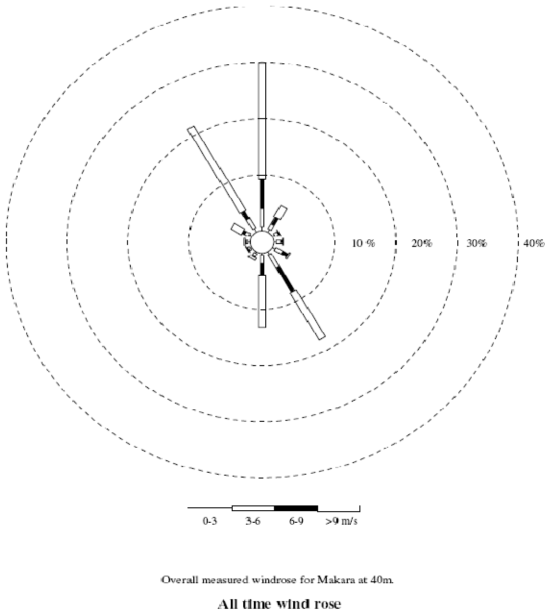


Figure 83: Sample wind rose for Makara area – All wind directions [32].

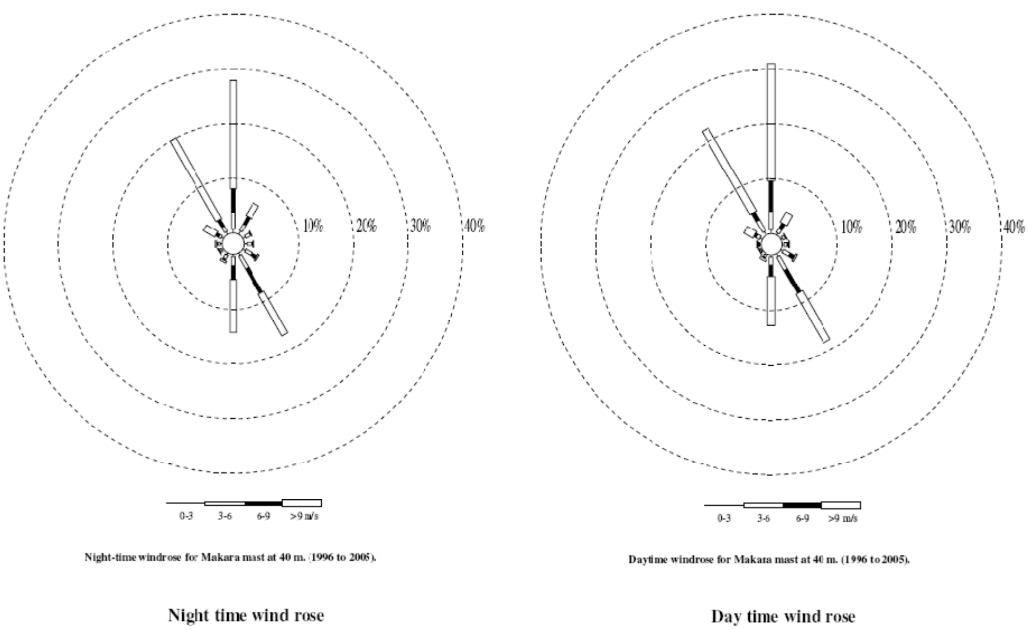


Figure 84: Sample wind rose for Makara area – [Left] Night time [Right] Day time wind directions [32]. .

Generally the above wind roses show a similar pattern for different months, seasons and times of day for the Makara area. Monitoring results show the area has two predominant wind directions described as follows [relative to true north]:

- North North West [NNW]
- South South East [SSE]

Te Apiti Wind Farm

Palmerston North is located approximately 150 km north of Wellington and lies in the eastern part of the Manawatu Plains. The subject site for the study was Te Apiti Wind Farm located approx 10km north-east of Palmerston North CBD. As with Wellington, Palmerston North also has a temperate cool climate. Strong winds are also a feature of Palmerston North's climate. Palmerston North sits on latitude of 40 degrees [South of the equator].

As Te Apiti is inland, there is a well known concept called the mountain-valley winds. These conditions occur when the mountain slopes warm during the day time causing the air over the slopes to be warmer than the air over the valley at the same elevation. The warmer air is forced to rise upwards creating an effect referred to as a valley wind. The reverse occurs during the evening and night when the air cools to a loss of surface energy radiated out to space, the cool dense air moves back down the slope and this is known as a mountain wind effect.

Te Apiti Wind Farm Wind Rose

The following [**Figure 85**] wind rose illustrates all wind directions for the Te Apiti area.

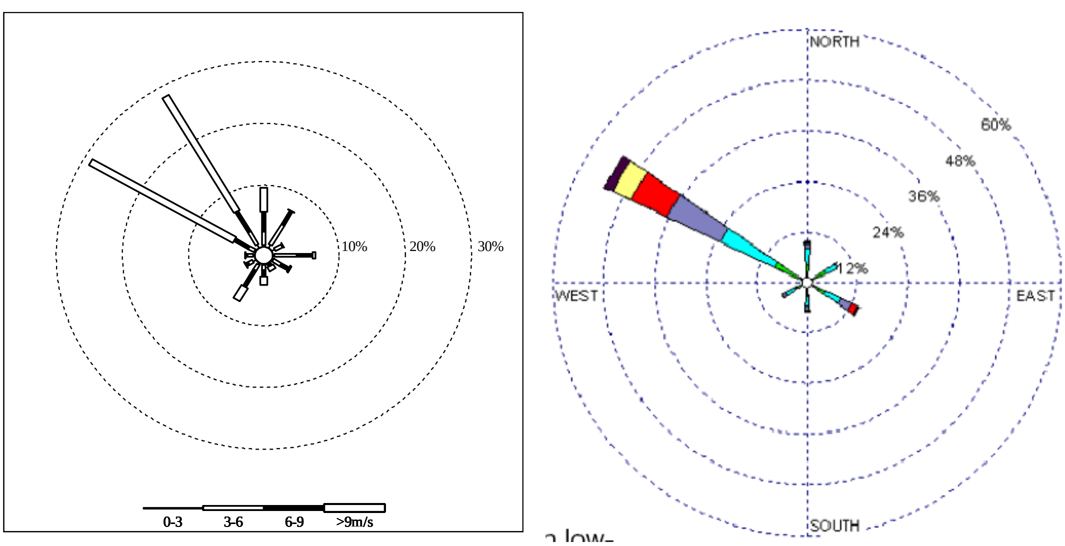


Figure 85: Sample wind rose for Te Apiti – All wind directions [[95]].

Monitoring results show the area has two predominant wind directions described as follows [relative to true north]:

- North West [NW]
- North North West [NNW]

The above concepts regarding wind conditions are very simplistic ways of looking at very complicated issues of wind. In real life because New Zealand's climate has various factors which affect the local wind [and micro wind climates around each turbine] the true wind pattern is extremely complicated. Because New Zealand is a long narrow shape surrounded by large ocean this mountain chain provides a barrier for the prevailing westerly winds, dividing the country into dramatically different climate regions. While the above concepts do exist the vast majority of winds for the two wind farms are driven by weather fronts passing over the country [as is the case for winds over most of New Zealand]

The following section illustrates the method of investigation for equipment set up and data analysis.

Method of Investigation

According to the New Zealand Wind Turbine Standard NZS6808 sound level measurements should be made during a representative range of wind speeds and directions generally expected at the wind farm site. These include the normal operating [wind speed] ranges for the wind turbine generator that is from cut-in to rated power and cut out wind speeds.

The sample set and number of measurements made needs to be sufficient to allow reliable assessment and analysis to be obtained between the sound levels and the wind speeds.

The New Zealand wind turbine standard states that a minimum of continuous monitoring is required to provide suitable results and a suitable range of data. This equates to 1440 10 minute data points of measured sound correlated against the wind data.

The standard states further measurements are required if the measurement results show a distribution of points which is not uniform i.e. one wind speed or area of the graph is densely populated for example a large cluster around the 4 m/s point and no other data spread up to cut out.

The standard also recommends there is no *sparseness* for more than one wind condition i.e. a data set which showed high sound levels at very low wind speeds may indicate an issue with the data. Further the standard also recommends that there is significant variation in the data across the range of wind speeds and seasonal factors i.e. there may be cicada noise in summer not present in winter or changes in stream levels during high and low water table periods.

In regards to the primary study at 403 Makara Road, a collection of over 10,000 raw [10 minute] sound level pressure samples were obtained.

The data has also been collected over a period of approx 12 months and hence all four seasons have been accounted for in one way or another. It is noted however no attempt has been made to collect equal amounts of data for each season. Also due to the data being collected over an annual period any changes in wind speeds and directions have also been accounted for, as have changes in day and night. Overall the collected raw data shows strong correlations and spread of measured sound pressure levels across the wind speed spectrum and key directions of wind.

The following discusses the methods used to capture the raw data sets for analysis at the two test sites.

Project West Wind [Makara] Wind Farm

Field Measurement and Test Method 1

The method of investigation revolves around the concept of trying to capture sound pressure levels from the wind turbine generator *only* as opposed to wind turbine generator sounds and additional extraneous background noise which might also be present at the time of measurement. Although a number of filters have been applied to the raw data it is best practice to attempt to avoid measuring unwanted extraneous noise to start with. This is however simply not possible under real world conditions and hence was unavoidable as this study is based around actual field sampling.

The sound level meter and related software *cannot* differentiate between what it is measuring and hence even with observed measurements the operator needs to be trained in order to understand what it is they are measuring and what the sound level meter may be recording.

Due to these factors the initial method of investigation was to try and capture wind turbine sound pressure levels only by manning the sound level meter and undertaking the measurements at times which would provide the best chance of capturing wind turbine generator sounds only i.e. night time, down wind and with low background noise levels at the measurement location.

The concept behind this method is unwanted background noise can be paused out or noted and removed later. This method was attempted on several occasions during both day and night time however it was a slow laborious process which took a considerable amount of time to capture very small amounts of data.

Key issues with this method were ensuring that the correct weather and sound propagation conditions were present. For a majority of the time, measurements ended up almost always including extraneous noise from background noise sources i.e. vegetation noise from long grass swaying in the wind. It soon became apparent that night time represented best case measurement conditions due to high background noise levels from extraneous noise being present during the day time.

The problem with this method was that although it was possible to capture some very small samples being only a few minutes in duration, these could not be correlated against wind data. This is because wind data is sampled every 10 minutes and not part of.

This data collection method also meant that although the sound level meter was manned and wind turbine sound could at most times be distinguished between that and unwanted background noise, in order to collect a very small number of 10 minute samples from wind turbine sound only it would of literally taken hours and hours. In fact from site observations and work carried out a single 10 minute sample could have taken over an hour, when all extraneous noise was marked and excluded.

This attempted method did however provide very valuable background information. Although visits to the site meant measurements were of no use for the study, site observations of the sound levels when the wind turbines were operating and handheld wind speed measurements allowed for an estimated range for times when wind turbine sounds were audible compared to local wind speeds.

The result of this was only during certain periods i.e. downwind, at night time when there were low wind speed levels at the dwelling [e.g. <1.5m/s] was wind turbine sound able to be heard [and measured] without the additional contribution of extraneous noise from wind or vegetation.

The first attempted test method to capture wind turbine sound only lead to the conclusion that this method [given the limited period for the study to be completed in] would not allow for a minimum set of data to be captured and analysed. As noted above the New Zealand wind turbine standard for acoustics recommends a data set of 10 to 14 days which equates to between 1000 and 1444, 10 minute samples. This data set is the recommended amount for sampling before development of a new wind farm.

The conclusion was to therefore try and capture a larger set of data [unmanned] which would allow for extraneous sounds to be filtered out as far as possible. This lead to a second test method being an amended method which was based on 10 minute samples being collected continuously during both day and night in conjunction with real time audio track recordings being carried out simultaneously.

Field Measurement and Test Method 2

The second test method of investigation looked to be promising in theory i.e. the fact that real time audio recordings [using a M-Track Audio Recorder] could capture and analyse side by side the various sound pressure levels and any extraneous data removed to allow for a clean set of samples. The following diagram [**Figure 86**] illustrates the field equipment set up used for test method 2:

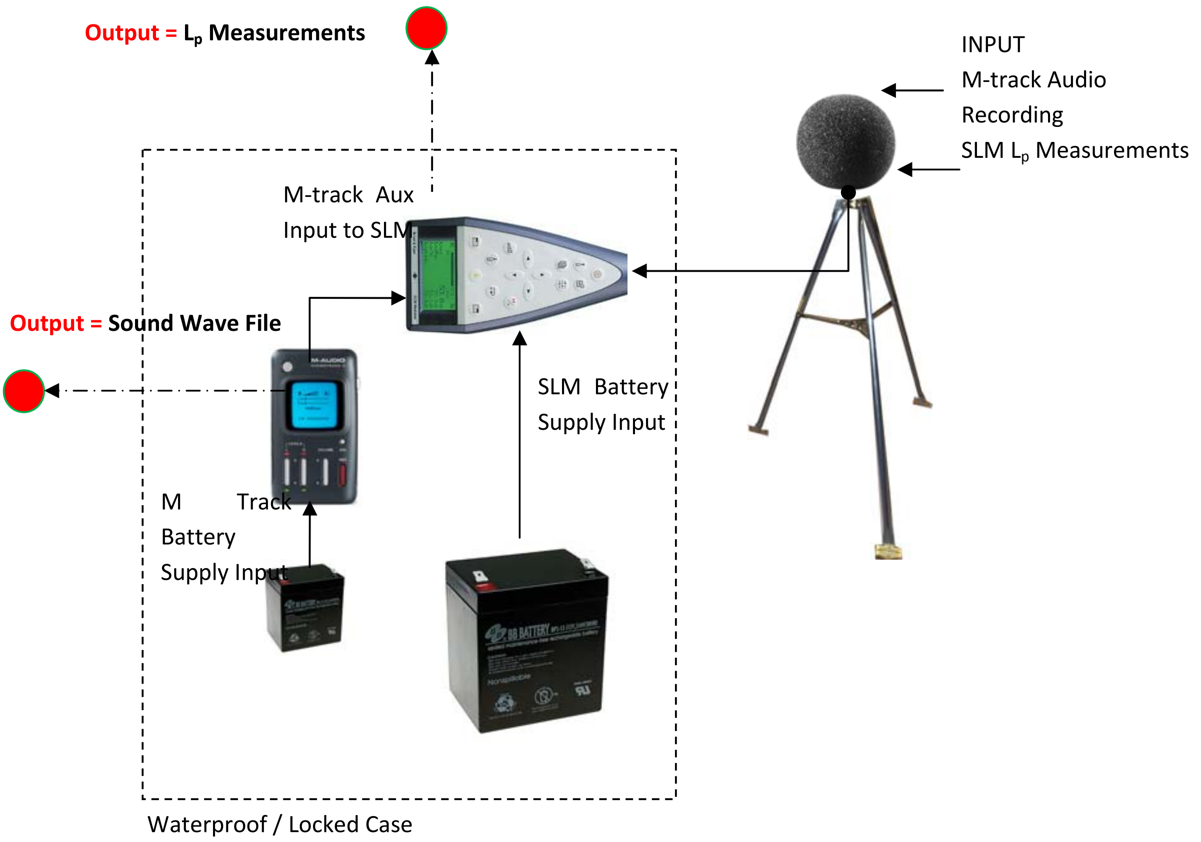


Figure 86: Schematic flow diagram of set up for field measurement testing of sound pressure levels and audio recording.

Although this method appears good in theory in practice there were several key drawbacks. The first major issue was in order to capture the minimum target of around 1000, 10 minutes samples would mean that 10 full days [or 240 hrs] of listening was required. In real time this would well equate to 40 days of real time listening which in itself is a substantial task given the limited time frames.

In turn even if this method was an option, when listening to the captured samples in conjunction with the measured sound levels it could be seen that all 10 minute samples did include some form of background extraneous noise and not just wind turbine sounds.

This method also illustrated that for a majority of samples wind turbine sound is also not present for long *continuous* periods hence when measuring the L_{A90} sound from other sources would contribute to the overall 10 minute level. This is because the true L_{A90} sound level for a 10 minute sample equates to sound levels present for 540 seconds [or 9 minutes] of the total 600 seconds [10 minute] period being measured. Even under the best cases this was not the case for the limited audio samples collected.

It is also noted that very careful care must be taken to ensure the clock and timing on the sound level meter is exactly the same [or as close as can possibly be calibrated] as that of the recorder. If the clock on the audio recorder and sound level meter are out the data will be compromised.

In this case the sound level meter had its clock calibrated to the atomic clock service. The atomic clock is a service provided by a Telecom New Zealand 0900 number. When one rings up the time is given at the end of a series of peeps. This clock is known as the most accurate time standard available. Once the sound level meter clock was calibrated to the atomic clock this was repeated on an electronic watch. The M-track audio recorder used does not have a clock which marks the start and stop times; it only produces a single wave file reference number.

In order to align the times with the sound pressure levels with the audio recorder the sound level meter was started at a known time. After 10 minutes of sound level recording the audio recorder was started and the two time signatures were aligned. In order to 'mark' the time on the audio recording a clap board was used. Other methods exist to mark the time period on the audio recording such as using an external source plugged into the recorder i.e. beeps on National Radio Program. The method chosen was done so due to its simplicity.

This method also illustrated that the amount of data collected in terms of not only listening times but download times and storage was a major issue. An example for this is for one hour of 10 minute measurements using the M-Track Audio Recorder approximately 300 Mb of data storage is required on the SADA Card.

The card only has a maximum capacity of 2 Giga Bytes and hence even with the largest cards available only limited periods would be able to be captured before a site visit was required and card changed over. In addition to this download time from the audio device to PC of approximately 300 MB equated to around 1 hour per 100 MB for a modern high spec computer.

There was a further issue with this second test method and this related to the fact that both the audio recorder and sound level meter required separate high amp hour heavy duty cycle batteries. The issue here was weight and ensuring they were able to be safely stored within large Pelican cases for water proofing and security.

Battery life and drain on the battery for the audio recorder was also a limiting factor. The overall issue with this being only short samples could be obtained before a site visit was required.

The final limitation for this second attempted test method, and the most important, was being able to differentiate between wind turbine sounds and background noise when analysing the recorded data in tandem with the measured sound pressure levels.

In order to capture good clean recordings the M-track audio recorder was plugged into the sound level meter through the auxiliary channel. This enabled the superior sound level meter microphone to be utilised as opposed to the less sensitive and responsive M-track microphone.

Although the author has spent time listening to wind turbine sounds under various conditions [in the field] play back of audio sound is a challenge to ensure that what one believes is wind turbine sound actually is. This is open to error and mis-interpretation.

Even with the use of high quality head phones [Sennheiser] this appeared to be a challenge. Although the headphones were not the same level used by audio professionals, they were sufficient for the study.

Final Field Measurement and Test Method 3

Based on the two above methods attempted this lead to the final selected test method which was capturing the sound pressure levels with just the use of the sound level meter on its own and applying best practice filtering to the final data sets.

This test method involved the sound level meter being set up so as to align with 10 minute periods which were on the hour i.e. 13.10, 13.20, 13.30. 13.40 and so on. This was to ensure that when the sound level data were analysed it could be directly compared to the 10 minute interval wind speed data collected at hub height of the test wind turbine generator. This method is the same method which is currently used by many consultants for sound level monitoring. The method allows for 10 minute data to be sampled and then directly compared and correlated to the wind speed and direction data at hub height.

The following diagram [**Figure 87**] illustrates the method set up used:

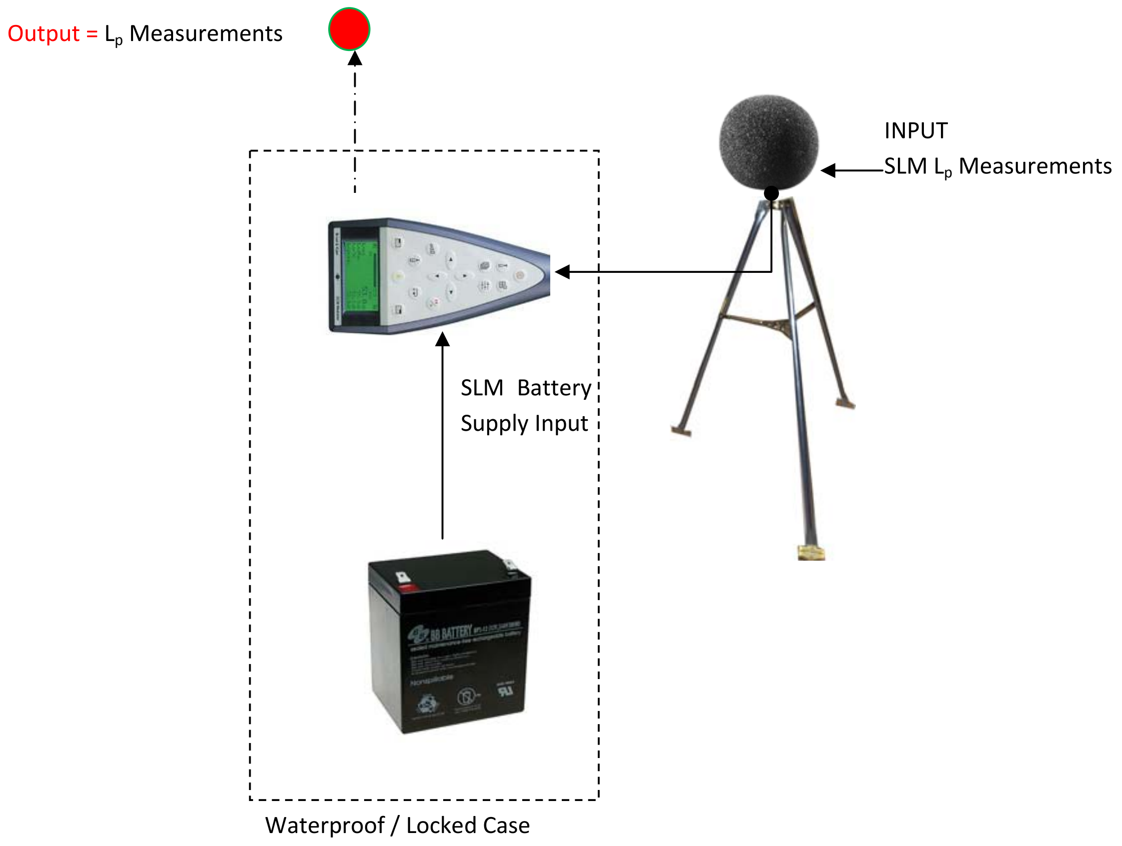


Figure 87: Schematic flow diagram of set up for field measurement testing of sound pressure levels.

It is obvious that in order to collect thousands of samples that the sound level meter cannot be manned all the time. Although this would be an ideal way to allow for notes to be taken i.e. when wind turbine sound and non background noise was present, a considerable amount of time would be required on site.

Key to this method is the data filtering. This filtering involves taking the raw data collected and based on information known such as when wind turbine sounds are likely to be present at the receiving location, filter the data set so that any unwanted data is removed.

In our case having collected around 10,000 samples 9000 samples were filtered out with less than 40 being viewed as suitable to draw the final conclusions of this assessment. This illustrates the fact that a great deal of raw data is needed in order to provide analysis of wind turbine sound only.

Te Apiti Wind Farm

Field Measurement and Test Method

The method of investigation at Te Apiti was the same final test method as used at West Wind [test method three] however the period of measurement was greatly scaled back as this was only a secondary site. A number of visits were made to this site [approximately 15 to 20] however these had to be at a time which suited the operator of the wind farm. Weather also restricted many visits. It was not uncommon to travel to the site and the weather change due to fog, lightning, rain or the wind direction change from northerly to southerly and hence measurements could not be conducted.

As Te Apiti is a working wind farm, site visits involved being inducted by a member of staff. It also meant follow up inductions when procedures changed were required.

The induction focused on site safety and protocols in case of an emergency or other events i.e. sudden changes in weather, for example fog fall or lightning strikes. Once the detailed induction was complete site visits were able to be carried out. It also meant that the author was responsible for anyone they took on site. Each time a site visit was carried out, Vestas requested they were given at least one week’s prior notice. Once a date was agreed a site visit was conducted.

Each visit involved being issued with a set of keys which allowed access through many gates. For very good reasons security and protocols for safety are taken extremely seriously by the wind farm owners and operators. Although this did take up a great deal of time, it is totally necessary for ones safety and the safety of others while on site.

Once on site measurement equipment at the R_o position was established. The R_o position was calculated using a GPS for distance and direction. Long term monitoring over a period of two weeks was carried out. Shorter measurements were also attempted [at the base of the turbine].

As with West Wind the method involved data collection capturing the sound pressure levels with just the use of the sound level meter on its own. The sound level meter was set up so as to align with 10 minute periods for wind speed and wind direction as collected at hub height of Tap 44. The major issues here related to the turbine locations, having to be at Tap 44 there was contribution from other turbines, and although the absolute level is not critical for this study the concept of attempting to measure only turbine sound without the contribution of other sources is key. Other factors which limited the study on the wind farm were weather and access. These factors were beyond the author’s control. Generally access to the site had to be taken when granted and meaurments had to be conducted when the option arose, as opposed to being able to pick and choose ‘best parameters’ for field work.

Data Filtering and Additional Limitations for Field Work

In regards to the site survey there were several key limitations for both test sites. Other than the limitations discussed above [weather, access and the like] there were several other factors which should be noted if the study were to be repeated. These are discussed as follows:

The biggest factor that delayed the study was battery 'failure'. Although a high amp/hr heavy duty cycle battery was used [which in itself had issues due to size, weight and transport etc] this provided the option to allow for long term unmanned measurement to occur. As Makara is around a 45 minute journey from Wellington CBD, driving to the site was not a major problem; hence the goal was to allow the sound level meter to run until all data slots were filled. However this did not occur in all cases as the battery failed first.

403 Makara Road does not have mains power and hence relies on solar collection. It was therefore not possible to run any external leads from the house and use 'mains power' to run the sound level meter. Using an external solar panel [to top up the battery charge] was an option but did not appear to be of any benefit as observations showed battery life was mainly dependent on external temperatures. The battery was always fully charged and cycled each time before being used on site. The battery was also always in a solid Pelican Case with foam surrounds to attempt to provide extra thermal insulation.

Regardless a period of no more than 10 days continuous collection was ever obtained. In some cases the sound level meter was set up and left to run for an expected period of 10 days but on return has stopped operating due to battery failure after just one cold night. New batteries were also sourced for the project but new or fully cycled batteries made no difference.

There were two possible explanations as to why the sound level meter stopped logging due to weather conditions.

The function between absolute internal/external battery temperature and a problem occurring such as prematurely terminating was obvious as the battery can only operate within a certain temperature range. Generally any external temperature around or below zero would cause the battery to stop. When this occurred the sound level meter would stop and store the data and then power down.

In other cases it may have been that the sound level meter stopped operating independent of the battery. The operating temperature of the sound level meters used is given to approx -10^{o}C to 50^{o}C, however on more than one occasion during the colder winter months there was ice on the case, cable, tripod and wind foam. During these periods we can only presume that the sound level meter itself could not operate in such harsh temperatures.

There were other occasions when the readings were compromised due to the equipment being tampered with. Although the sound level meter extension cord was attached via a secured lemo plug, on two occasions something had interfered with the sound level meter equipment affecting the readings.

As the sound level meter itself [and all equipment other than the microphone and tripod] was locked within the Pelican case[s] the connections between the extension cord and sound level meter could not be touched. However the connection between the extension cord and external microphone were exposed. On two occasions at 403 Makara Road data that would have been used was lost as the logger was still operating but microphone had been unplugged and hence no data was being recorded.

It was also clear from the samples due to previous recordings some activities were being conducted in very close range. As the sound level meter was in a secured area it would have likely been cattle [with their head between the wooden fence] dogs on the property sniffing or wildlife such as possums showing an interest at the equipment. It would have been very unlikely the occupants touched the equipment.

The following graph [**Figure 88]** illustrates an example of collected data when the equipment has had the microphone pulled out. The levels suddenly drop until they reach the noise floor of the sound level meter and then 'drift' up and down as time passes.

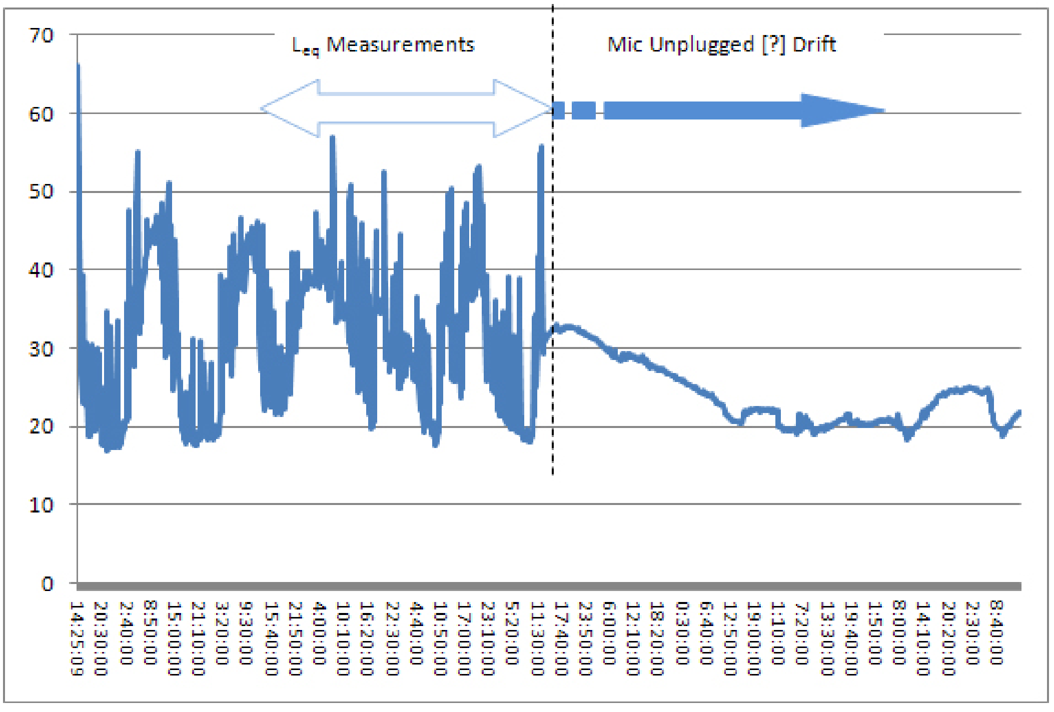


Figure 88: Graph of measured sound pressure levels with equipment failure of microphone versus time.

As 403 Makara Road does not have mains power it operates a diesel powered generator. This data had to be removed from the data set. This was generally not a big issue as the generator chiefly operated during the day or evening periods when background noise levels were high and hence measurements already contained extraneous noise data which ended up being removed regardless.

Other issues relating to extraneous data was the occupants carrying out farm activity on site such as land maintenance or the children playing in the evenings during summer. This was no issue as these events were also removed in the final data sets.

Mother Nature also caused issues. Wind noise and noise from vegetation movement [even in very low winds at local ground level] created extraneous noise which masks the wind turbine sounds making it extremely hard to measure just wind turbine sound.

Wind noise across the microphone was reduced by using a two-fold wind screen system which was an inner and outer wind screen/foam system.

Work by Hessler [[96]] shows various tests to determine wind-induced noise and windscreen attenuation effects on microphone response. In regards to Hessler's testing he concludes that in low wind conditions using a 60 mm inner wind screen and 175 mm outer wind screen test results would be expected to be reasonably good [especially at lower frequencies where the larger windscreen offers enhanced attenuation from wind].

Based on this a 90 mm inner and 200 mm outer wind screen was used. It is noted once the data is filtered [as discussed below] the night time downwind samples selected are at low wind conditions [at the microphone]. The wind screen had a bird spike on top to stop animals or birds touching the wind foams.

The other environmental effect was rain [precipitation]. Along with the third party wind data, corresponding information regarding rain fall was also obtained. Monitoring was never started in wet conditions or when rain was forecast. As discussed further below any monitoring with known rain was also removed. Several methods were used for weather forecasting.

In regards to forecast of rain the met service rain radar was used to see if rain was due to fall before setting up equipment on site [**Figure 89**]. If equipment had been set up and rain fell during the monitoring, these periods of rain were identified and removed. Data regarding rain was sourced from third parties including the met service and 'weatherunderground.com' [**Figure 90**].

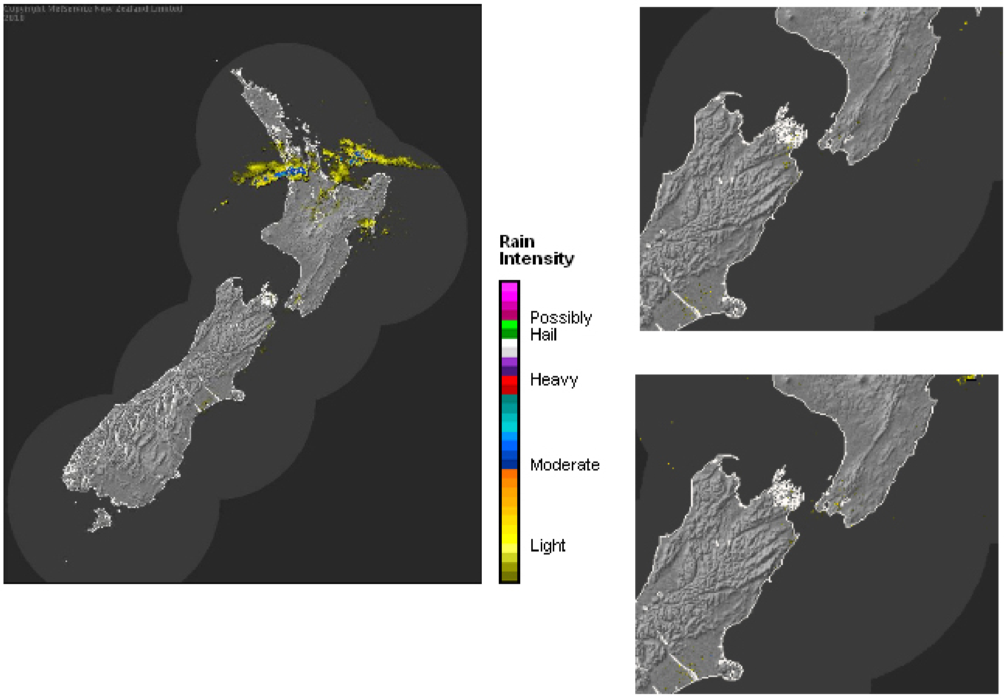


Figure 89: Graphic of rain radar from New Zealand Met Service [97].

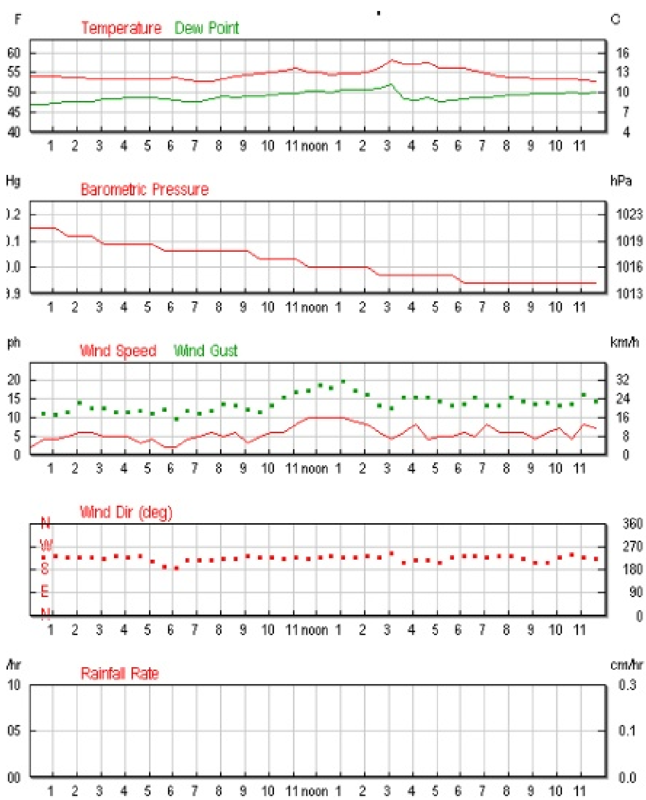


Figure 90: Graphic of weather data for 24 hour period from weatherunderground.com [98].

There were also periods when monitoring may have been set up but the wind turbine generators were not turning due to insufficient winds at hub height.

For a significant period of time [months] certain turbines were not fully operational including D12 which was parked due to commissioning and testing procedures being conducted during the study period.

Third party data, namely out-liers in the data set, were also a matter for consideration. What is meant by out-liers within the raw data was that when supplied there was a small number of data sets that contained the number '999' as opposed to the actual data such as wind speed. This is due to an operational error or default i.e. no data could be collected so the system simply placed 999 in the cell. All out-lying data was removed from the sample sets used.

In summary a total of around 10,000 raw samples were collected at 403 Makara Road. The exact number of additional data which could have been collected is hard to estimate and superfluous to the study outcomes as a sufficient sample has been collected for the purposes of this study.

The sound level meter saves the data in various formats as text files. Following the collection of each set of data this was filed in both hard copy and electronic copy. A separate folder was provided for each site and each set of individual data sets. After completion of the field work all raw data and related data was saved from text files into Microsoft Excel and then saved as Excel files.

The data is presented as time varying sound levels of measured sound levels versus date and time. Once all raw data was in Excel third party data was collected which included wind speeds and directions both on the wind farm sites [at hub height] and at the local receiving sites. The third party data also included information such as precipitation levels and in some case when the turbines were producing power [turning above cut-in wind speeds].

Once all raw data was collected it underwent filtering. This meant the raw data went through various stages of being sorted until a final set of data was derived which included only wind turbine sound.

As discussed above filtering of the data was required due to the chosen method of field analysis i.e. because a large sample of data needed to be collected to have any statistical relevance the data collected was unmanned and hence all non relevant wind turbine sound [as far as possible] needed to be removed from the samples. However rather than simply jumping from the raw data to the final data set required, a number of intermediate steps have been carried out so that during the analysis stages if any general relationships and patterns exist these can be analysed.

In addition to filtering the data all raw data has been adjusted for day light savings time stamps.

The following sets out a discussion of the filters and qualifications for their application:

Data Filtering Project West Wind [Makara] Wind Farm [Data Logger]

A total of 11,150 ten minutes raw sound level pressure samples [as L_{A90} and L_{Aeq}] were collected at the receiver location of 403 Makara Road from data logging between June 2009 and July 2010, being over 12 months of data collection.

Additional time was spent before and after this period on site visits and site observations and analysis. In addition to this [as discussed below] data were also collected at Te Apiti Wind Farm.

The following **Table 19** illustrates a summary of the overall filters, number per set and percentage for each set expressed as a portion of the total filtered raw Data Set B.

Data Set Reference and Description	Number of Samples in Data Set	% Total Raw Data Set B
Data Set A – All Raw Data	11,150	
Data Set B – All Raw Data with Superfluous data removed	8,682	100%
Data Set C – Daytime Only	5,411	62.3%
Data Set D – Night time Only	3,271	37.6%
Data Set E – Downwind	6,078	70.0%
Data Set F – Upwind	2,604	29.9%
Data Set G – Daytime/Downwind	3,814	43.9%
Data Set H – Daytime/Upwind	1,597	18.3%
Data Set I – Night time/Downwind	2,264	26.0%
Data Set J – Night time/Upwind	1,007	11.6%
Data Set K – All/Directly downwind	3,321	38.2%
Data Set L – Daytime/Directly downwind	2,174	25.0%
Data Set M – Night time/Directly downwind	1,174	13.5%
Data Set N – FINAL DATA SET WIND TURBINE SOUND ONLY Night time/Directly downwind [wind turbine sound only]	39	1.1%

Table 19: Description of filters applied to measured sound pressure levels and number of raw samples [presented as n and percentage of total raw data collected] for 403 Makara Road.

Figure 91 illustrates the filtered data as a radar chart expressing the total number of samples for each data set [excluding A].

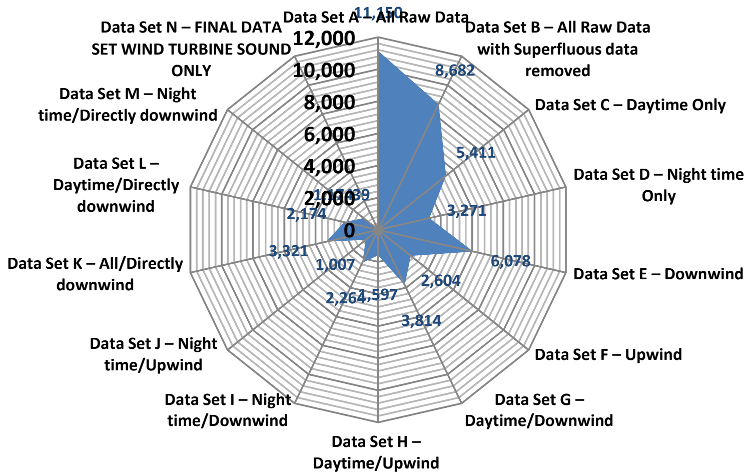


Figure 91: Graph of filters applied to measured sound pressure levels and number of raw samples [presented as total number of data in each set] for 403 Makara Road.

Data at Project West Wind was filtered down based on known site observations and analysis - the data filtering discussed above is based on the following filters and related qualifications:

Data Set A – All Raw Data [n=11,150]

This data set *includes* all data collected, including the data which cannot be used such as incomplete data sets, data collected during rain periods or data which has had recorded extraneous noise removed.

Data Set B – All Raw Data with Superfluous data removed [n=8682]

This data set has taken Data Set A and filtered out all data which cannot be used such as incomplete data sets, data collected during rain periods or data which has had recorded extraneous noise removed.

Data Set C – Daytime Only [n=5411]

This data set has taken Data Set B and filtered out all data which is not present during daytime hours being 7.00am to 10.00pm.

Data Set D – Night time Only [n=3271]

This data set has taken Data Set B and filtered out all data which is not present during night time hours being 10.00pm to 7.00am

Data Set E – Downwind [n=6078]

This data set has taken Data Set B and filtered out all data which is not downwind [of the measurement location]. In this case the downwind direction was taken as between 0 to 90 degrees and 270 to 360 degrees.

Data Set F – Upwind [n=2604]

This data set has taken Data Set B and filtered out all data which is not upwind [of the measurement location]. In this case the upwind direction was taken as 90 to 180 degrees and 180 to 270 degrees.

Data Set G – Daytime/Downwind [n=3814]

This data set has taken Data Set B and filtered out all data which is not daytime AND which is not downwind [of the measurement location].

Data Set H – Daytime/Upwind [n=1597]

This data set has taken Data Set B and filtered out all data which is not daytime AND which is not upwind [of the measurement location].

Data Set I – Night time/Downwind [n=2264]

This data set has taken Data Set B and filtered out all data which is not night time AND which is not downwind [of the measurement location].

Data Set J – Night time/Upwind [n=1007]

This data set has taken Data Set B and filtered out all data which is not night time AND which is not upwind [of the measurement location].

Data Set K – All/Directly downwind [n=3321]

This data set has taken Data Set B and filtered out all data which is not *directly* downwind [of the measurement location]. In this case directly downwind has been treated as being 30 to 300 degrees.

Data Set L – Daytime/Directly downwind [n=2174]

This data set has taken Data Set B and filtered out all data which is not daytime AND which is not directly downwind [of the measurement location]. In this case directly downwind has been treated as being 30 to 300 degrees.

Data Set M – Night time/Directly downwind [n=1174]

This data set has taken Data Set B and filtered out all data which is not night time AND which is not directly downwind [of the measurement location]. In this case directly downwind has been treated as being 30 to 300 degrees.

Based on the above filtering a final data set has been used for the analysis and discussion of this Thesis, this Data Set N is described as follows for Project West Wind in relation to 403 Makara Road measurement location:

Final Data Set Analysis – Data Set N [n=39]

The above data sets A to N are viewed only as 'generic' in that they provide relationships of the measurement data for day and night time versus wind direction. The following data sets and related filters move beyond this to attempt to filter out all extraneous data to a point where the closest possible data set of wind turbine sound only exists [or where there is the least masking of background/extraneous noise samples]. This data set is referred to as **final Data Set N.** Some small variations within the data set have been explored as detailed below.

The final filter used is the filter which is believed to provide the closest possible data set which would provide a magnitude or relationship between the L_{A90} and L_{Aeq} relationship, based on the least hindrance or masking from extraneous background noise sources.

Data Set N is based on the following filter and related qualifications:

Night-time [11.00pm to 5.00am]

Originally Data Sets A to M were based on night time periods of 10.00pm to 7.00am. This is because from the data collected and observations showed that during night time this is a period where there is the least extrusion from extraneous noise sources such as [but not limited to] human activity.

The night time filter is used as it is clear from observations and the historic background noise surveys that the night time periods have the quietest background levels and therefore the least extraneous noise.

It is important to understand that wind farm sound is the same throughout the day as night however background noise is not, hence by using the 'night time only' filter this allows for an analysis where the wind farm sound level is at its greatest level with respect to the unwanted noise sources [background extraneous noise] i.e. there is an enhanced probability of a greater wind turbine sound signal to background noise ratio.

From reviewing the Data Sets A to M it appears [and this is supported by site visits and historic data] the lowest background noise levels appear to be between 11.00pm to 5.00am. The reduction is two hours between Data Set M and N i.e. data filtered at night between 11.00pm to 5.00am for Data Set N rather than 7.00am for Data Set M.

This small change is important and relates to wildlife, chiefly because after 5.00am is a time period [depending upon weather and time of year] when birds and wildlife start to produce noise for example bird song and morning calls.

In summary night time filtering has been used in terms of the raw data as this provides the best signal to noise ratio i.e. the best chance of measuring only the required wind turbine sounds pressure levels with the least corruption of unwanted background noise.

<u>Wind Direction [Northerly – Downwind]</u>

Wind speed and directions are key to the study results. It is a well known fact that the transmission path of sound plays a key role in the received sound pressure levels i.e. sound pressure levels reduce with distance. The sound propagation path and effects are discussed in detail further below, however in regards to downwind measurements this filter has been selected due to various factors including the distance between source and receiver.

For distances [say less than 100 m for example] wind has minor to nil influences on measured sound pressure levels however when the distance is greater than say 250 m various factors can enhance or decrease sound pressure levels at source.

Generally under downwind conditions wind gradients refract sound downward toward the surface and eliminate acoustic shadows, hence providing the best chance for an increased signal to noise ratio. Generally measuring upwind or side winds decreases the sound pressure level; in the case of the study this means a decreased sound pressure level from wind turbine sounds.

In the case the final filter uses a downwind direction of 315 degrees. In summary downwind is preferred as it provides the highest probability of wind turbine sound levels being able to be measured above any unwanted masking background noise i.e. an enhanced signal [wind turbine sound] to noise [unwanted sound].

<u>Operational Wind Turbine Wind Speed [Wind Speeds at Hub Height]</u>

In the case of measuring wind turbine sound this is only obviously possible when the turbines are turning on site and hence producing aerodynamic sound.

The following graph [**Figure 92**] is a sample of the wind speed at hub height on the wind farm versus the wind speed at 10 m at 403 Makara Road for all data during night time periods [downwind]. The graph clearly shows a correlation of increasing wind speed at hub heights with an increase of wind speed at the 10 m mast. The graph shows a regression line with an r-squared [R^2] of 0.7 showing a very [expected] strong correlation.

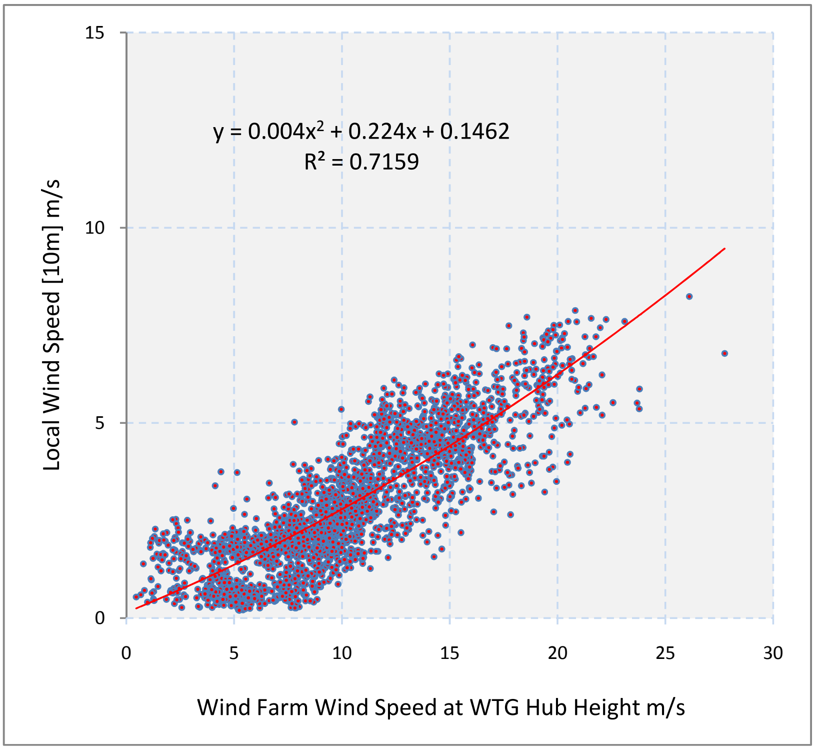


Figure 92: Scatter graph with second order polynomial curve of measured 10 minute sound pressure levels versus measured wind speed at V_{10m} and $V_{Hub\ Height}$. Note R^2 value of 0.7

It should be noted that the use of a 10 m reference height for wind speed measurements during acoustic measurements of wind turbines is historic and may have been appropriate for the lower tower heights and related hub heights at the time. Today's wind turbines [including those in the study] are generally much taller and the reference height of 10 m is no longer viewed as appropriate.

In general the faster the blades turn the greater the sound power output of the aerodynamic sound, however when the wind speeds increase at the hub height so does the wind speed at local ground level and hence also increases unwanted background noise.

In this case cut-in wind speed for the wind farms turbines is 4 m/s and cut-out is around 25 m/s. Cut in may occur at lower speeds say around 3 m/s depending upon where the wind data is provided from i.e. the met mast may provide a wind speed of 3 m/s however the wind at hub height of the turbine may in fact be 4 m/s.
For the purpose of this study a filter has been used to only include data above 4 m/s [at hub height]. In regards to setting a maximum hub height wind speed wind farm sound pressure levels can only be assessed where the operational sound levels are greater than the background noise levels.

A study into the difference between the operational wind farm noise and the background sound levels carried out by Paul Botha [2] of Meridian Energy for the 403 Makara Road site revealed that the greatest level difference between historic measured background sound levels [pre-construction of the wind farm] and actual measured wind farm sound levels [with all background sound removed] occurs between 4 m/s and 15 m/s with background sound levels being higher than wind turbine sounds at levels below 3 m/s or above 15 m/s i.e. there is a negative difference which indicates that the wind farm sound pressure levels are lower than the background noise levels.

The following graph [**Figure 93**] illustrates a summary of the Botha Study. The graph [green line] shows the expected sound pressure levels from the wind farm only [downwind/northerly/night time] versus wind speeds [this is based on actual measured levels]. The remaining two lines represent the background sound level [blue line] before the development of the wind farm and wind farm sound pressure levels plus background [red line]. These are based on logarithmic trendlines of the actual measured data. The expected sound pressure levels from the wind farm only are based on background [before development] minus background and wind farm sound pressure levels [*logarithmically* subtracting one from the other].

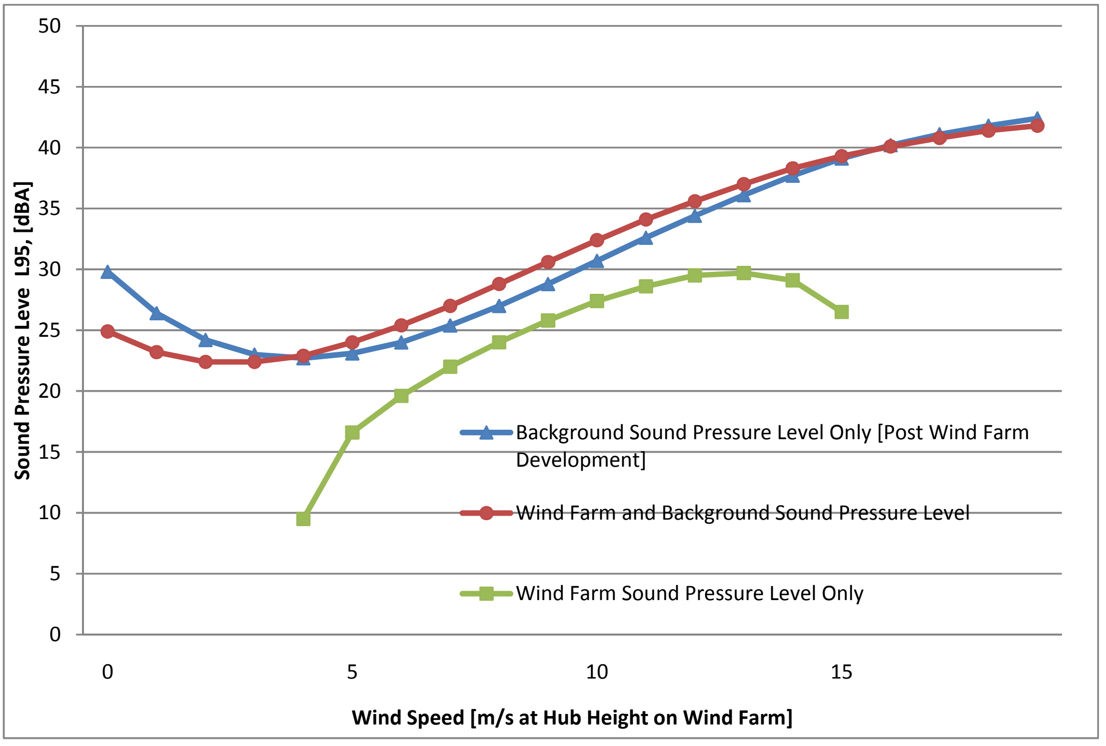


Figure 93: Graph of expected wind farm sound pressure levels only versus actual measured wind farm and wind farm plus background sound pressure levels [shown as best fit logarithmic curves]. All levels presented as L_{A95}.

[2] *"The Use of 10 m Wind Speed Measurements in the Assessment of Wind Farm Developments"* Paul Botha, presented at the First International Meeting On Wind Turbine Noise: Perspectives for Control Berlin 17th and 18th October 2005

In summary a filter of sound pressure levels at hub height between 4 m/s and 15 m/s has been applied [15 m/s is approx rated output for the turbine].

Local Wind Speed [Wind Speeds at Measurement Location]

As discussed above wind speed [and direction] are key to the project outcomes as these parameters have direct relationship with background noise and wind turbine sound pressure levels. In regards to local wind speeds these play a key role in that even low levels of wind at the measurement location can allow for trees or long grass to produce background noise which masks the wind turbine sound pressure levels. This decreases the signal to noise ratio from the wind turbine sounds.

For the study site observations have indicated even at very low local wind speeds say for example less than 3 m/s masking sounds occur at the measurement location. Based on handheld wind speed measurements the Land Beaufort Scale has been used as a key tool for the final filter by comparing measurements at the microphone with available 10 minute data samples at 10 m above local ground level.

The Beaufort Scale was originally developed for use at sea, however there is a land version. The Beaufort Scale is useful for the purpose of this study as it is based on actual field observations and hence provides a good base for calibrating the observations at ground level with field observations.

The scale is also of use in this study as it is based on an empirical formula $v = 0.836\ B^{3/2}$ where v is the equivalent wind speed at 10 m above the ground level and B is Beaufort Scale Number. **Figure 94** illustrates the relationship between Beaufort Scale number [which technically only goes up to 17] and wind speed at 10 m above ground level.

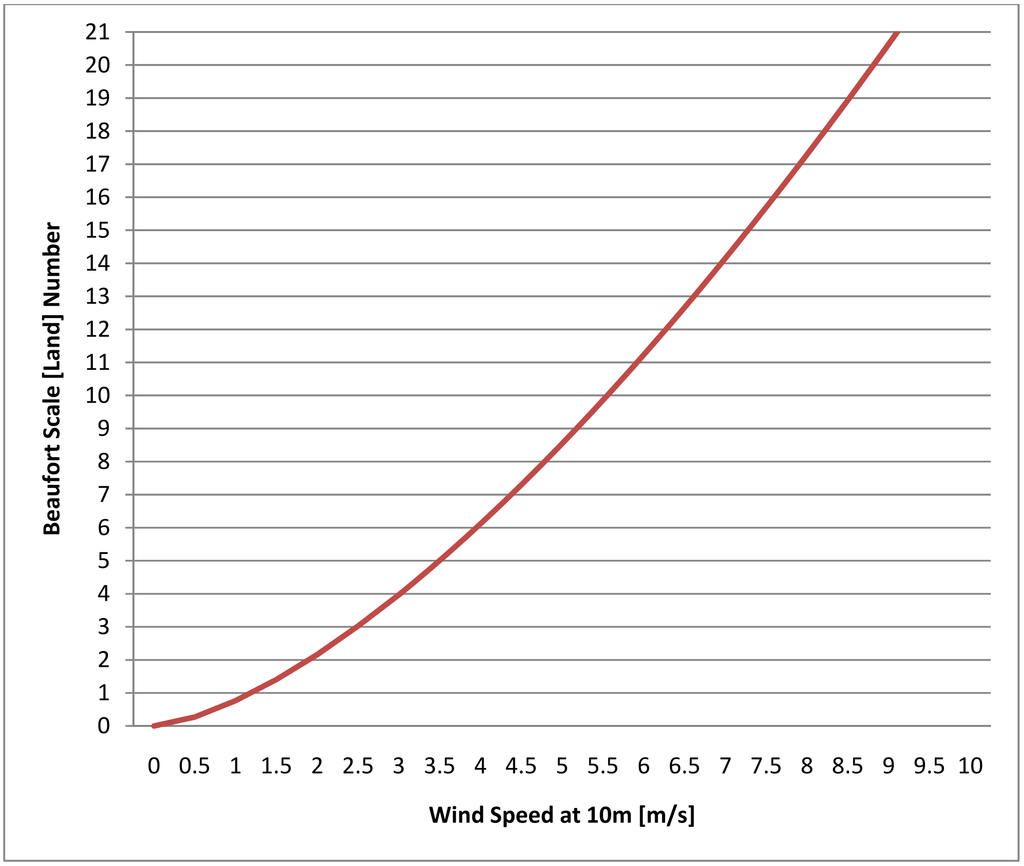


Figure 94: Graph of fundamental relationship between wind speed levels at V=10 m and Beaufort Scale Number [Land scale]

Botha [[3]] has shown that wind speed profiles vary significantly between different sites and with time of day.

In terms of the scale a Beaufort Number of 1 [up to 1.5 m/s at 10 m mast] relates to 'smoke drift and still wind vanes'. Above this say at Beaufort Number 2 [1.6 to 3.4 m/s at 10 m mast], the scale states that 'Leaves rustle, vanes begin to move'.

Generally as the equation is exponential at the low level of 1.5 m/s at ground the level at 10 m is approx to 1.5 m/s. According to the Beaufort Equation a wind speed of 1.5 m/s max at ground level equates to a maximum wind speed of around 1.5 m/s at 10 m/s. Therefore a filter of 1.5 m/s max [and below where required] has been adapted to the 10 m wind data to ensure there is minimal masking for non wind turbine noise [at the microphone].

[3] *"The Use of 10 m Wind Speed Measurements in the Assessment of Wind Farm Developments"* Paul Botha, presented at the First International Meeting On Wind Turbine Noise: Perspectives for Control Berlin 17th and 18th October 2005

Wind Turbine Power Output [kW]

The power output for the wind turbine was obtainable with the data set. Only data which shows wind turbine power output has been used i.e. if there is no power output this means the turbines were not turning and hence not producing aerodynamic sound.

In summary the following filter for final Data Set N has been adopted:

- Night-time [11.00pm to 5.00am];
- Wind Direction [Northerly - Downwind at 315 degrees];
- Operational Wind Turbine Wind Speed [4 m/s to 15 m/s];
- Local Wind Speed at the sound level meter microphone [0 to 1.5 m/s as derived from, 10 m mast];
- Wind turbine output kW [when turbine producing power only].

Data Filtering Te Apiti Wind Farm R_o Measurement Location [Data Logger]

A total of 1400 continuous 10 minutes raw samples were collected at the R_o position from data logging between Saturday 17th and Tuesday 27th July 2010 [10 days].

This data was filtered down based on known site observations and analysis of the data collected to attempt to remove any extraneous [non wind turbine noise]. Site visits were carried out before, during and after the logging period.

The final data set is based on the following filter and related qualifications:

Time

There is normally the least extrusion from extraneous noise sources such as [but not limited to] human activity occurring at night time. In terms of wind turbine sound output this is the same albeit day or night.

In regards to the remote location of the subject site and the fact that the measurement location was actually on the subject site in close proximity day time and night time sound levels from the wind turbine is the same i.e. the output does not change in terms of sound, only the background noise for which measurements are conducted. Regardless unwanted noise, even from natural environment does not appear to favour any single time periods.

This is likely because there are no trees or bush which birds would occupy as the site is fairly baron with only limited low level shrubbery. In summary no filtering for day or night has needed to occur for this data set.

Wind Direction [NW to NNW – Downwind]

Downwind is preferred as it provides the highest probability of wind turbine sound levels being able to be measured above any unwanted masking background noise. Hence in this case the study has only taken down wind conditions, based on all data falling between

North West [NW = 315 degrees] and North North West [NNW=337.5 degrees] quadrants as this is the highest percentage of time for both day and night.

In addition by its very definition, measurements according to ISO 61400 at the R_o location must be downwind.

Operational Wind Turbine Wind Speed [Wind Speeds at Hub Height]

In the case of the Te Apiti wind turbines cut-in for the wind farm is 4 m/s and cut-out is around 25 m/s. Cut-in may occur at lower speeds say around 3 to 4 m/s depending upon where the wind data is provided from i.e. the met mast may provide a wind speed of 3 m/s however the wind at hub height of the turbine may in fact be 4 m/s. Rated wind speed is around 14 to 15 m/s.

In summary a filter of sound pressure levels at hub height between 4 m/s and 25 m/s has been used. It is noted that rated [nominal] wind speed is around 15 m/s and turbine sound output is minimal above this when compared to levels between 4 and 15 m/s. ISO 61400 requires wind speed analysis of between 4 and 10 m/s for the purpose of rating sound power levels of turbines. In order to try and attempt to collect the largest data set data above 10 m/s has been used.

Local Wind Speed [Wind Speeds at Measurement Location]

For the study site observations have indicated local wind speeds don’t provide high background noise relative to the measured wind turbine aerodynamic sound and hence masking sounds from vegetation is treated as nil as wind turbine sound is 10 dB above background [even at lower wind speeds]. However the higher the wind speed the greater the introduction of ‘wind induced noise’ across the microphone [or at the microphone].

Overall no filter of data has been adopted for local wind speeds due to an enhanced signal to noise ratio on site i.e. the simple fact that the measured sound levels are dominated by wind turbine [aerodynamic] sound due to the close proximity between wind turbine itself and sound level meter.

Wind Turbine Power Output [kW]

The power output for the wind turbine was obtainable with the data set. Only data which shows wind turbine power output has been used as if there is no output this means the turbines were not turning and hence not producing sound.

Miscellaneous

In addition to the above data sets any incomplete data sets, data collected during recorded rain periods or data which had known extraneous noise was removed.

Graphical Analysis

The final filter was an analysis of graphed data and its patterns. The above data filters were used to produce a graph of sound pressure levels versus time.

It was clear from the graphical analysis that when at the R_o position the graph of sound pressure levels was the dominant sound source and hence a fairly linear pattern emerges [say 0 to 3 dB range for L_{Aeq} sound levels], as opposed to a graph which has various peaks and troughs which indicates interference from non turbine noise.

The following graph [**Figure 95**] illustrates a sample of the above description. The left portion of the graph starts with dominant levels from wind turbine sound. As you move to the right side of the graph this illustrates interference from non wind turbine sound [shown as with the time varying line changing from a flat line to one with peaks and troughs]. In this case the extraneous noise and interference from other non wind turbine noise sources is a distant crop plane doing crop dusting overflies.

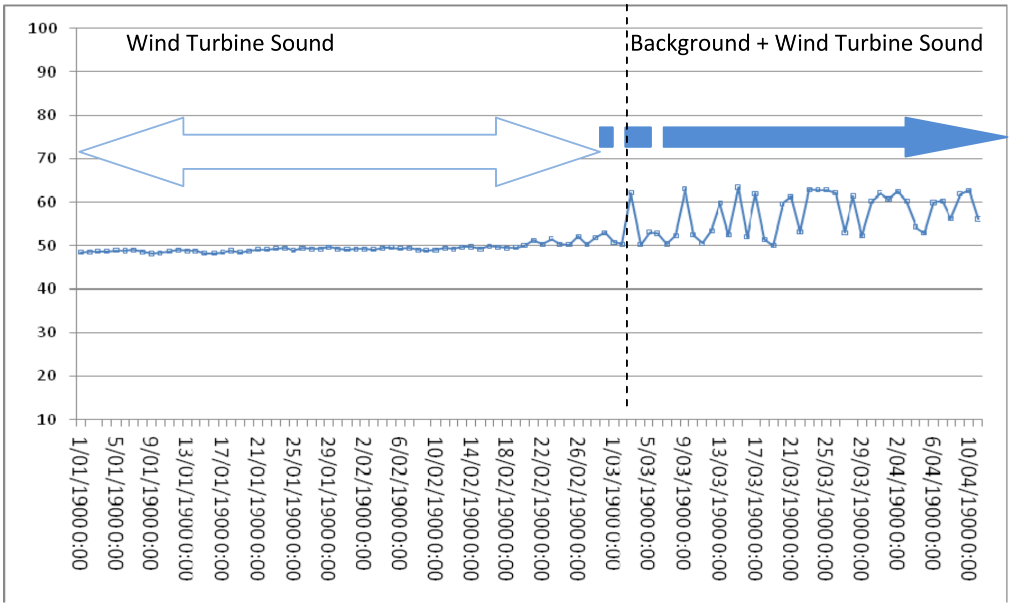


Figure 95: Graph of measured wind turbine sound and background noise versus time - L_{Aeq}.

Therefore by physically graphing the data analysis has allowed non turbine noise to be removed.

In summary the following has been adopted:

- Time [No filtering of data];
- Wind Direction [NNW to NW- Downwind];
- Operational Wind Turbine Wind Speed [4 m/s to 25 m/s];
- Local Wind Speed [no data filtering];
- Wind turbine output kW. [when turbine producing positive output only];

- Miscellaneous data [all known extraneous data or weather affected data i.e. rain removed].

Additional Te Apiti Wind Farm [Handheld Measurements at R_o & Base of Turbine]

In addition to the above unmanned data set numerous hand held measurements were also conducted at the base of Tap 44 and at the R_o position of Tap 44 [being the same location as the logger]. These measurements were carried out at the base of the turbine where aerodynamic sound was dominant and well above any other noise sources.

As the R_o position at Tap 44 is at a similar distance from Tap 45, this meant the hand held measurements were conducted during a period when Tap 45 was not operational [due to maintenance work] and hence the sound from Tap 45 did not contribute to total measured levels during the noise measurements.

As stated above the likely contribution from any additional noise from any other turbines other than Tap 45 at the R_o position would be less than 3 dB [max]. This is based on a decrease in sound of 3 dB per doubling of distance for two point sources.

It is also noted that the data collected during the hand held measurements from Tap 44 at the base and R_o logger the wind speed at hub height is not provided as it is commercially sensitive. This is very important as the data presented here is only presented based around min and maximum filters i.e. the exact data wind speeds for example are known but not provided.

Estimates and observations show that the measured levels were the dominant sound source and well above any background noise levels [in the case of the base measurements in excess of 10 dB above background]. Regardless the turbine measurements are estimated as being taken between 4 m/s [cut-in] and rated wind speed [around 14 to 15 m/s].

This observation is only an estimate based on wind speeds measured with the wind speed anemometer at ground level [being based on the formula:

$$\mathbf{V}_{[\text{wind speed at hub height}]} = [\mathbf{H}_{[\text{hub height}]} / \mathbf{H}_{[\text{measurement height}]}]^{\alpha \text{smooth grass}} \mathbf{v}_{[\text{measured wind speed at ground}]}$$

In addition to the base turbine measurements a number of short samples were also conducted at the R_o measurement location downwind of Tap 44. These measurements were conducted when wind turbine sounds were at least 10 dB above background and the dominant sound source.

A summary of the hand held measurements and relative qualifications are provided as follows for measurements conducted at the base of Tap 44 wind turbine generator.

Data Set 1 Base of Turbine – 1 Second Sampling [n= 600 / Total Time = 10 minutes]

This data set is a sample of sound levels from wind turbine sound sampled at a height of 1.2 m above local ground level at a distance of 10 m from the base of the turbine. The slant distance to the hub is approx 68.8 m. The slant distance to the leading tip of the blade was approx 33.8 m. A total of 600, one second samples were conducted over a period of 10 minutes.

Data Set 2 Base of Turbine – 10 Second Sampling [n= 60 / Total Time = 10 minutes]

This data set is a sample of sound levels from wind turbine sound sampled at a height of 1.2 m above local ground level at a distance of 10 m from the base of the turbine. The slant distance to the hub is approx 68.8 m. The slant distance to the leading tip of the blade was approx 33.8 m. A total of 60, ten second samples were conducted over a period of 10 minutes.

A summary of the hand held measurements and relative qualifications is provided as follows for measurements conducted at the downwind R_o location of Tap 44 turbine for various sample periods with the turbine being the dominant sound source.

Data Set 3 Downwind R_o Position of Turbine – 10 Second Sampling [n= 60 / Total Time = 10 minutes]

This data set is a sample of sound levels from wind turbine sound sampled at a height of 1.2 m above local ground level at the downwind R_o position of the wind turbine. A total of 60, ten second samples were conducted over a period of 10 minutes.

In addition to the time varying sound levels collected a basic third octave analysis from the data set was also conducted.

Data Set 4 Downwind R_o Position of Turbine – 1 Minute Sampling [n= 10 / Total Time = 10 minutes]

This data set is a sample of sound levels from wind turbine sound sampled at a height of 1.2 m above local ground level at the downwind R_o position of the wind turbine. A total of 10, one minute samples were conducted over a period of 10 minute.

Data Set 5 Downwind R_o Position of Turbine – Various Time Periods [n= 9]

This data set is a sample of sound levels from wind turbine sound sampled at a height of 1.2 m above local ground level at the downwind R_o position of the turbine. A total of nine samples were conducted over various times with a maximum period of 10 minutes.

Observations during all the above measurement locations illustrates a “whoosh” “whoosh” “whoosh” or “swish” “swish” “swish” sound which periodically lasted 1 to 2 seconds [depending upon the rotational speed of the blades] being the sound generated by the blades coming down. Based on a rotational speed of 17.3 rpm this equates to 0.87 cycles per second.

This is subjectively much greater at the base of the turbine compared to R_o locations. At times the transformer inside the base could be heard but this was not present during the measurements conducted here.

Method of Data Analysis

This section discusses the method used to present and physically analyse the data once sorted into its selected filtered sets i.e. description of the filtered data sets, graphs and tables presented in the following results section.

Following the raw data being filtered into the various data sets [as described above in detail] the various data sets have been graphed and data tabled. Graphical analysis has been used to view overall patterns and variations while tables have been used to present the actual data set.

The relationship between measured sound levels [L_{A90}/L_{Aeq}] and wind speed [on the wind farm and at the test sites] has been investigated by using both time varying and scatter graphs. Time varying graphs of data have been presented as measured sound pressure levels versus time. Graphs of sound pressure levels versus wind speeds are also presented. These graphs provide an overall representation of the data in a visual format to illustrate relationships between the variables and spread of data such as season, day versus night, measured sound pressure levels versus wind speed, measured sound pressure levels across the wind speed and direction spectrum.

For presentation purposes a number of the data sets are presented but on various graphs, for example a graph may contain both L_{A90}/L_{Aeq} sound descriptors versus wind speed on one graph and then a second graph may represent just one of the two noise descriptors. This is because there are thousands of data points which are closely aligned on the graphs] [within a few db in scale] and hence difficult to read.

Following the presentation of time varying sound levels data has also been graphed as scatter graphs. As with the time varying graphs a number of graphs are presented. This includes a number of unconventional data sets, the purpose being to visually study patterns between the data collected and see if any interesting findings are provided i.e. graphs illustrating 10 m versus hub height wind speeds for example.

The 'dots' on all the time varying and scatter graphs represent individual monitored 10 minute L_{Aeq} or L_{A95} values, with a corresponding 10 minute data sample i.e. wind speeds measured over the exact same time period at the 10 m anemometer mast on site or hub height of the subject wind turbine located on the wind farm site, representative of the wind energy affecting the operation of the wind turbine.

Each 'dot' on all the time varying and scatter graphs represent individual monitored sample i.e. 10 minute L_{Aeq} or L_{A90} values.

All monitored sound levels are in units L_{A90} or L_{Aeq} and wind speeds in units of metres/second [at either hub height on the wind farm or at a height of 10 m at the measurement location]. No raw data has been adjusted or changed, other than where this is clearly noted in this study as being filtered or removed.

In regards to the scatter graphs a 'best fit' polynomial curve [second order] has been fitted to the measured data using a 'least squares fit' method. The polynomial having the greatest correlation coefficient [R^2 term] has been selected and plotted. In some cases [where noted] including data analysis a 'best fit' logarithmic curve has been applied.

The following 'Result Section' presents the final selected data set for Project West Wind [Data **Set N**]. As this data set has less than 100 final samples the data from Data Set M has also been presented below. Data Set M has over 1500 samples and hence is viewed as providing data which may be greater statistically appropriate [when compared to Data Set N]. However there are unidentified non turbine background noise samples included within Data Set M.

Appendix C contains a flow chart of assessment methods followed under NZS6808:1998 and 2010.

Appendix D illustrates graphs of the measured sound pressure levels and data analysis for Te Apiti Wind Farm. ***Appendix E*** illustrate graphs of the measured sound pressure levels and data analysis for Data Sets A to M while ***Appendix F*** illustrates the measured sound pressure levels and data analysis for final Data Set N

In acoustics the 'signal to noise ratio' or 'sound to noise ratio' is a measure used to quantify how much a signal has been contaminated by noise. In the case of this study the concept is used informally with the term 'signal' referring to the measured wind turbine sound pressure levels and term 'noise' relating to unwanted obtrusive background noise. **Figure 96** illustrates a low signal to noise ratio where the background noise levels [obtrusive noise] masks the measured wind turbine sound [desired signal].

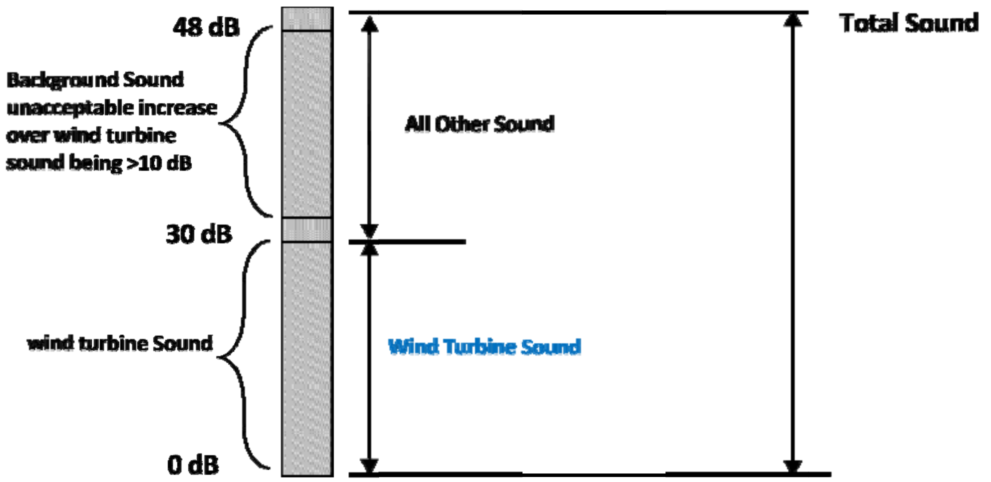


Figure 96: Schematic of a low signal to noise ratio illustrating an obtrusively high background noise level [L_{A90} dB] masking a desired sound signal from the wind turbine sounds [L_{A90} dB].

Figure 97 illustrates a high [and the preferred] signal to noise ratio where the background noise levels [obtrusive noise] is well below the measured wind turbine sound [desired signal] and hence does not mask the desired wind turbine sound being 10 dB lower.

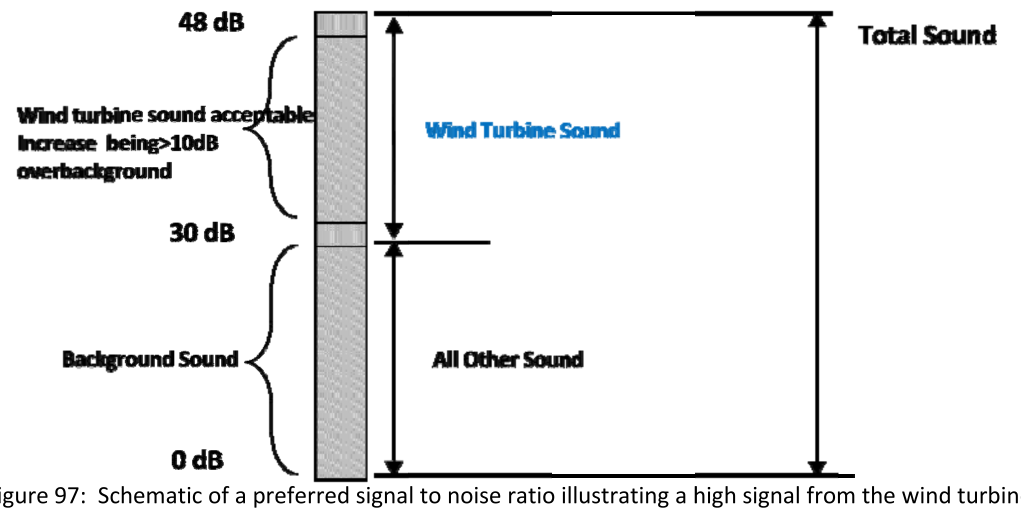


Figure 97: Schematic of a preferred signal to noise ratio illustrating a high signal from the wind turbine [L_{A90} dB] above masking signals from background noise levels [L_{A90} dB].

The higher the technical ratio the less obtrusive the unwanted background noise is. It is generally accepted that 8 to 10 dB above background noise is acceptable to ensure no interference or masking of the measured sound.

As Data Set N only has a limited sample set [less than 100 samples] it may be viewed as not containing a suitable number of data sets to be statistically significant. Regardless Data Set M is similar to Data Set N, however Data Set M has the minimum required number of 14,000 samples, yet contains possible non wind turbine sounds.

Because of this fact a further data analysis of Data Set M has been attempted. This assessment is described as follows: *Wind farm operational noise level only = Wind Farm and Background Sound Pressure Level - Background Sound Pressure Level Only [Pre Wind Farm Development].*

Figure 106 illustrates a sample of historic measured background sound levels at 403 Makara Road carried out in 1997 [pre development].

Figures 99 to 105 and Tables 20 to 27 illustrates graphs of the above operational wind farm only data analysis [Data Set N]**.** As shown in the data the operational measurements [wind farm sound and background noise levels] are very similar to original background [pre-wind farm] levels. The use of the best-fit regression curves take out the unusual shape [and any dips or peaks at the extremes of the wind speed range. Although the data presented shows both the actual data and best fit, such data would usually be presented as a best fit curve only.

Microsoft Excel has been used to graph all results and tables. The statistical functions in Excel have been used to carry out the data analysis for the descriptive statistics.

Figure 98 illustrates an overall summary flow chart of the method of analysis.

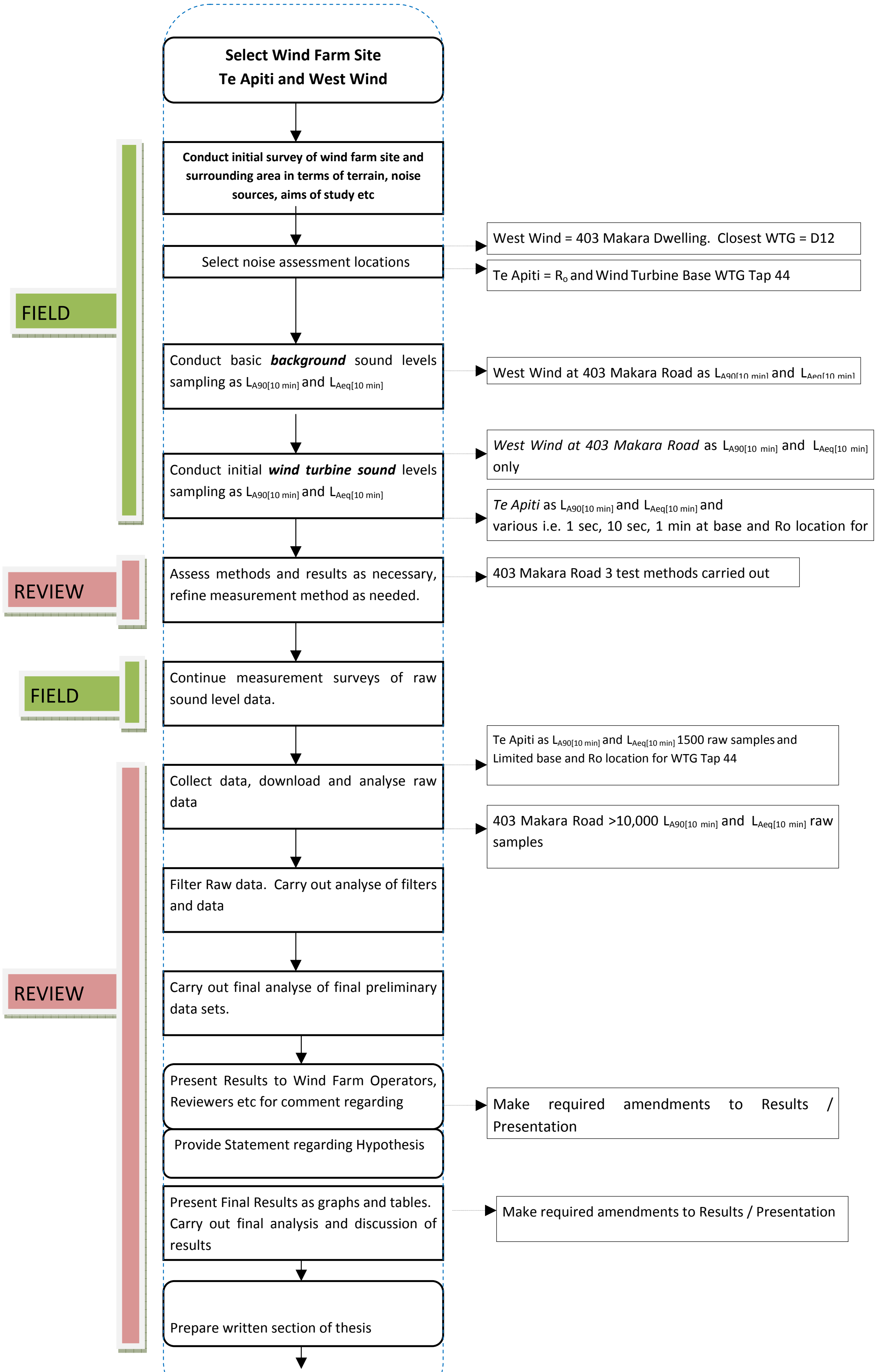


Figure 98: Flow chart of method.

Results

Data Set M – Night time/Directly downwind [n=1174]	Mean	Standard Error	Median	Mode	Standard Deviation	Range	Min	Max	Confidence Level [95.0%]
Level Difference	3.1	0.06	2.7	2.0	2.0	20.1	0.5	20.6	0.1
L_{aeq} dB	38.0	0.2	39.2	39.8	6.8	38.9	18.6	57.5	0.4
L_{A90} dB	34.9	0.1	36.4	38.4	6.3	35.6	16.3	51.9	0.3

Table 20: Statistical table of measured time varying sound pressure level of L_{Aeq} and L_{A90}. 403 Makara Road. 10 minutes Sampling Time. Data Set M.

Data Set N – Night time/Directly downwind [n=]	Mean	Standard Error	Median	Mode	Standard Deviation	Range	Min	Max	Confidence Level [95.0%]
Level Difference	2.4	0.2	2.5	2.6	1.4	5.1	0.5	5.6	0.4
L_{aeq} dB	25.4	0.3	25.1	24.4	2.3	11.3	19.8	31.1	0.7
L_{A90} dB	23.0	0.3	22.9	22.5	2.0	9.0	18.5	27.5	0.6

Table 21: Statistical table of measured time varying sound pressure level of L_{Aeq} and L_{A90}. 403 Makara Road. 10 minutes Sampling Time. Data Set N

Data Set N – Night time/Directly downwind [n=] m/s	Mean	Standard Error	Median	Mode	Standard Deviation	Range	Minimum	Maximum	Confidence Level [95.0%]
Level Difference 4	3.5	0.5	2.9	1.3	2.7	10.0	0.6	10.6	1.0
Level Difference 5	3.3	0.5	1.7	1.0	3.6	14.6	0.5	15.1	1.1
Level Difference 6	3.9	0.5	3.0	2.1	3.9	19.9	0.7	20.6	1.1
Level Difference 7	2.4	0.2	1.9	2.2	1.7	8.8	0.8	9.6	0.4
Level Difference 8	2.8	0.2	2.1	1.6	2.0	11.0	0.5	11.5	0.4
Level Difference 9	2.9	0.2	2.3	2.0	2.4	19.0	1.1	20.1	0.5
Level Difference 10	3.5	0.	2.6	2.1	2.5	13.4	1.0	14.4	0.5
	Mean	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
L_{aeq} dB 4m/s	26.5	0.8	25.3	27.2	4.8	18.8	19.8	38.6	1.8
L_{aeq} dB 5m/s	26.9	0.9	24.4	23.5	5.8	28.4	20.4	48.8	1.8
L_{aeq} dB 6m/s	31.6	0.9	29.3	22.7	6.8	24.2	22.7	46.9	1.9
L_{aeq} dB 7m/s	30.9	0.6	30.9	26.4	4.7	22.9	22.8	45.7	1.2
L_{aeq} dB 8m/s	33.6	0.4	33.6	32.6	3.9	16.4	25.9	42.3	0.9
L_{aeq} dB 9m/s	35.4	0.3	34.7	34.3	3.4	22.1	29.6	51.7	0.7
L_{aeq} dB 10m/s	36.9	0.4	36.2	34.3	3.7	19.7	29.6	49.3	0.8
	Mean	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
L_{A90} dB 4m/s	22.9	0.7	22.5	22.5	4.2	16.3	18.5	34.8	1.5
L_{A90} dB 5m/s	23.5	0.5	22.5	22.5	3.6	14.7	19.0	33.7	1.1
L_{A90} dB 6m/s	27.7	0.8	25.6	21.5	6.0	22.1	16.3	38.4	1.7
L_{A90} dB 7m/s	28.4	0.5	28.3	30.6	4.5	20.1	20.6	40.7	1.1
L_{A90} dB 8m/s	30.8	0.3	30.8	30.8	3.0	15.8	23.8	39.6	0.7
L_{A90} dB 9m/s	32.4	0.2	32.5	32.6	2.3	10.8	27.7	38.5	0.4
L_{A90} dB 10m/s	33.4	0.2	33.3	34.4	2.3	10.3	28.6	38.9	0.5

Table 22: Statistical table of measured time varying sound pressure level of L_{Aeq} and L_{A90} at wind speeds 4 to 10 m/s. 403 Makara Road. 10 minutes Sampling Time. Data Set N

Data Set B – All Raw Data with Superfluous data removed [n=8682]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	4.7	0.05	3.3	2.0	4.5	47.9	0.2	48.1	0.1
L_{aeq} dB	39.2	0.09	40.6	41.7	8.2	68.4	18.0	86.4	0.1
L_{A90} dB	34.5	0.08	36.3	38.4	7.5	35.7	16.3	52.0	0.1

Data Set C – Daytime Only [n=5411]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	5.6	0.07	3.80	3.0	5.1	47.5	0.6	48.1	0.1
L_{aeq} dB	39.2	0.09	40.6	41.7	8.2	68.4	18.0	86.4	0.1
L_{A90} dB	36.2	0.09	37.8	40.4	6.9	32.9	18.5	51.4	0.1

Data Set D – Nighttime Only [n=3271]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	3.3	0.05	2.5	2.0	2.8	31.0	0.2	31.2	0.1
L_{aeq} dB	34.9	0.14	36.2	39.2	8.2	41.7	18.0	59.7	0.2
L_{A90} dB	31.7	0.13	32.9	18.4	7.6	35.7	16.3	52.0	0.2

Data Set E – Downwind [n=6078]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Mini-mum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	4.5	0.06	3.1	2.0	4.3	47.9	0.2	48.1	0.1
L_{aeq} dB	39.7	0.10	40.8	40.5	8.0	67.8	18.6	86.4	0.2
L_{A90} dB	35.2	0.09	36.8	40.4	7.2	35.6	16.3	51.9	0.1

Data Set F – Upwind [n=2604]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	5.24	0.1	3.6	2.5	4.9	40.7	0.3	41.0	0.1
L_{aeq} dB	38.1	0.1	39.9	41.7	8.6	51.7	18.0	69.7	0.3
L_{A90} dB	32.9	0.1	34.3	18.4	7.9	34.6	17.4	52.0	0.3

Data Set G – Daytime/Downwind [n=3814]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	5.3	0.0	3.7	1.9	4.9	47.5	0.6	48.1	0.1
L_{aeq} dB	42.1	0.1	42.8	42.4	7.1	66.7	19.7	86.4	0.2
L_{A90} dB	36.8	0.1	38.4	40.4	6.8	32.4	18.5	50.9	0.2

Data Set H – Daytime/Upwind [n=1597]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	6.2	0.1	4.3	3.0	5.5	40.4	0.6	41.0	0.2
L_{aeq} dB	41.2	0.1	42.0	41.7	6.6	49.9	19.8	69.7	0.3
L_{A90} dB	34.9	0.1	36.7	39.5	6.9	32.9	18.5	51.4	0.3

Data Set I – Nighttime/Downwind [n=2264]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	3.1	0.06	2.4	2.0	2.6	31.0	0.2	31.2	0.1
L_{aeq} dB	35.6	0.1	37.0	39.2	7.6	38.9	18.6	57.5	0.3
L_{A90} dB	32.5	0.1	33.9	38.4	7.1	35.6	16.3	51.9	0.3

Data Set J – Nighttime/Upwind [n=1007]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	4.5	0.1	37.0	39.2	7.6	38.9	18.6	57.5	0.3
L_{aeq} dB	33.4	0.2	32.9	27.6	9.2	41.7	18.0	59.7	0.5
L_{A90} dB	29.8	0.2	28.5	18.4	8.3	34.6	17.4	52.0	0.5

Data Set K – All/Directly downwind [n=3321]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	4.1	0.1	3.9	5.0	8.1	74.4	26.0	48.4	0.3
L_{aeq} dB	41.4	0.1	42.0	42.0	6.8	67.8	18.6	86.4	0.2
L_{A90} dB	37.2	0.1	38.2	38.4	6.0	35.6	16.3	51.9	0.2

Data Set L – Daytime/Directly downwind [n=2174]	**Mean**	**Standard Error**	**Median**	**Mode**	**Standard Deviation**	**Range**	**Minimum**	**Maximum**	**Confidence Level [95.0%]**
Level Difference	4.7	0.09	3.6	3.0	4.2	47.4	0.7	48.1	0.1
L_{aeq} dB	43.5	0.1	43.7	45.7	5.9	63.7	22.7	86.4	0.2
L_{A90} dB	38.8	0.1	39.6	40.4	5.2	31.4	19.5	50.9	0.2

Table 23: Summary statistical table of measured time varying sound pressure level of L_{Aeq} and L_{A90}. 403 Makara Road. 10 minutes Sampling Time. Data Sets B to L

	R^2 Value **Measured Sound Pressure Levels** **L_{Aeq} vs L_{A90} dB**	**R^2 Value** **Measured Sound Pressure Levels** **L_{Aeq} vs Wind Farm Wind Speed $V_{Hub\ Height}$**	**R^2 Value** **Measured Sound Pressure Levels** **L_{A90}Wind Farm Wind Speed at $V_{Hub\ Height}$**
Data Set B All Raw	$R^2 = 0.7$	$R^2 = 0.4$	$R^2 = 0.3$
Data Set C Daytime Only	$R^2 = 0.5$	$R^2 = 0.2$	$R^2 = 0.3$
Data Set D Night time Only	$R^2 = 0.8$	$R^2 = 0.6$	$R^2 = 0.7$
Data Set E Downwind	$R^2 = 0.7$	$R^2 = 0.3$	$R^2 = 0.5$
Data Set F Upwind	$R^2 = 0.6$	$R^2 = 0.2$	$R^2 = 0.4$
Data Set G Daytime/Downwind	$R^2 = 0.6$	$R^2 = 0.2$	$R^2 = 0.4$
Data Set H Daytime/Upwind	$R^2 = 0.4$	$R^2 = 0.1$	$R^2 = 0.3$
Data Set I Night time/Downwind	$R^2 = 0.8$	$R^2 = 0.6$	$R^2 = 0.7$
Data Set J Night time/Upwind	$R^2 = 0.8$	$R^2 = 0.6$	$R^2 = 0.7$
Data Set K All/Directly downwind	$R^2 = 0.7$	$R^2 = 0.3$	$R^2 = 0.4$
Data Set L Daytime/Directly downwind	$R^2 = 0.6$	$R^2 = 0.2$	$R^2 = 0.3$
Data Set M Night time/Directly downwind	$R^2 = 0.9$	$R^2 = 0.6$	$R^2 = 0.7$
Data Set N Final Data Set Analysis	$R^2 = 0.6$	$R^2 = 0.0$	$R^2 = 0.06$

Table 24: Summary statistical table of R^2 values L_{Aeq} versus L_{A90} versus wind speed [$V=_{Hub\ height}$]. 403 Makara Road. 10 minutes Sampling Time. Data Sets B to N

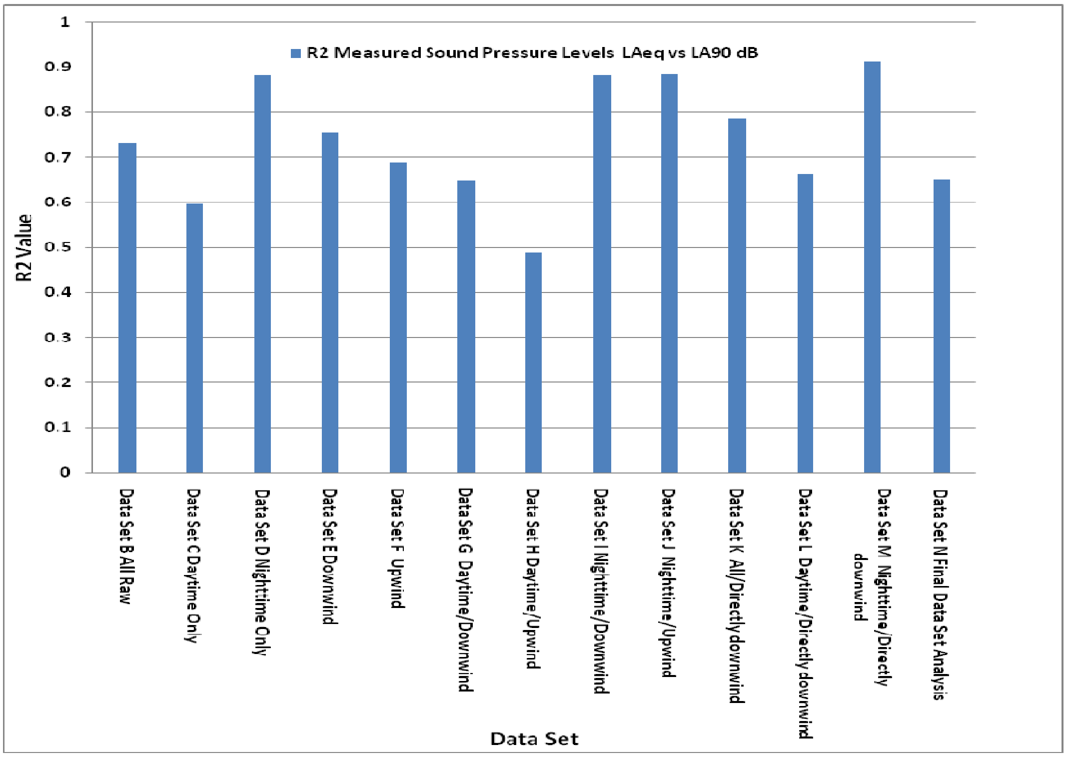


Figure 99: Graph of R^2 values L_{Aeq} versus L_{A90}. 403 Makara Road, 10 minutes Sampling Time, Data Sets B to N

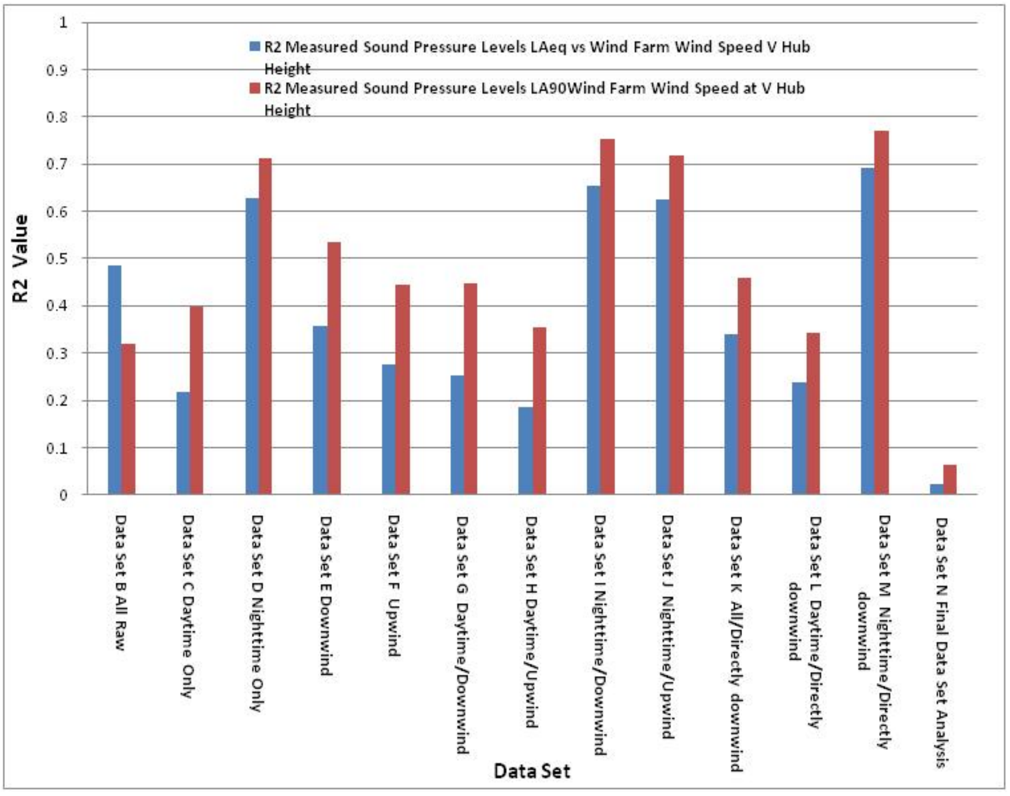


Figure 100: Graph of R^2 values L_{Aeq} / L_{A90} versus wind speed [$V=_{\text{Hub height}}$]. 403 Makara Road. 10 minutes Sampling Time. Data Sets B to N

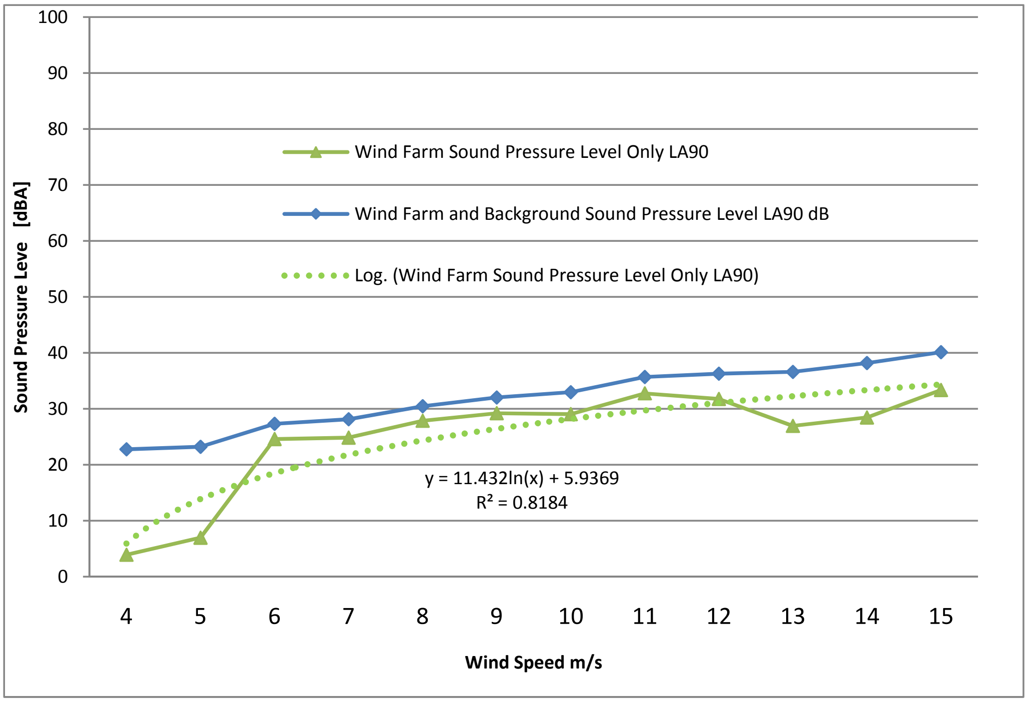


Figure 101: Graph of actual measured time varying sound pressure level of L_{A90} vs wind speed and expected wind farm sound level only [expressed as best fit line [log function]. 403 Makara Road.

Wind Speed at Wind Farm @ Hub Height [m/s]	**Background Sound Pressure Level Only [Post Wind Farm Development] L_{A90} dB**	**Wind Farm and Background Sound Pressure Level L_{A90} dB**
4	22.7	22.8
5	23.1	23.2
6	24	27.3
7	25.4	28.1
8	27	30.5
9	28.8	32.0
10	30.7	33.0
11	32.6	35.7
12	34.4	36.3
13	36.1	36.6
14	37.7	38.2
15	39.1	40.1

Table 25: Summary table of actual measured time varying sound pressure level of L_{A90} vs wind speed and expected wind farm sound level only [expressed as best fit line [log function]. 403 Makara Road.

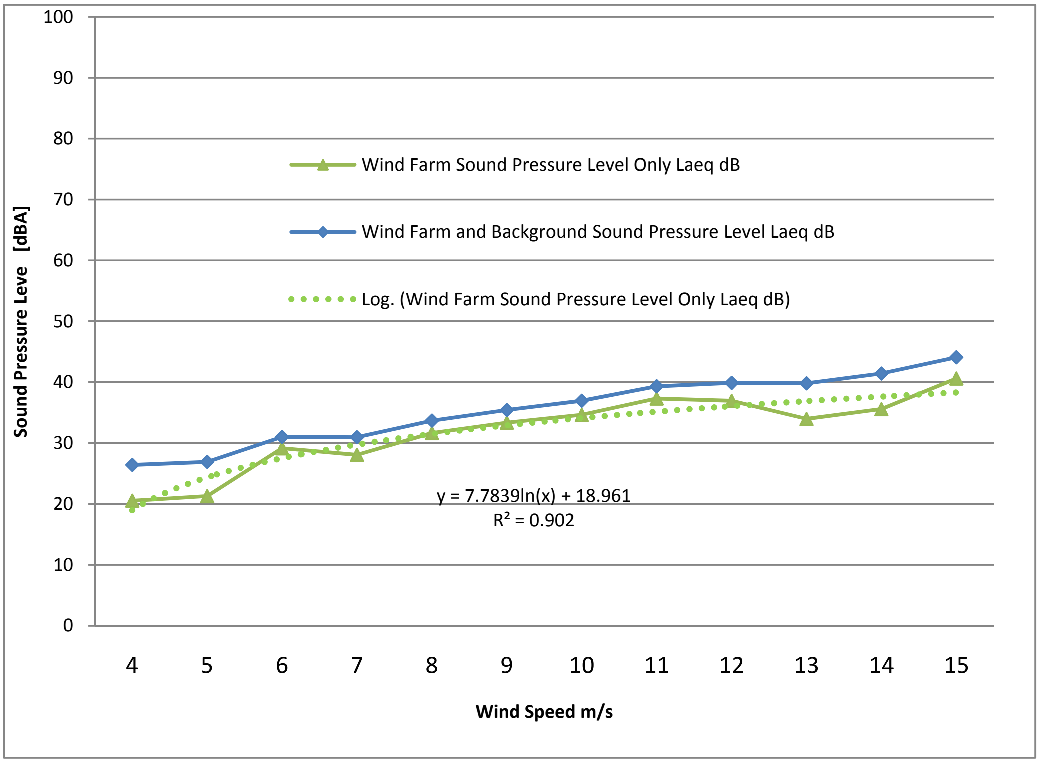
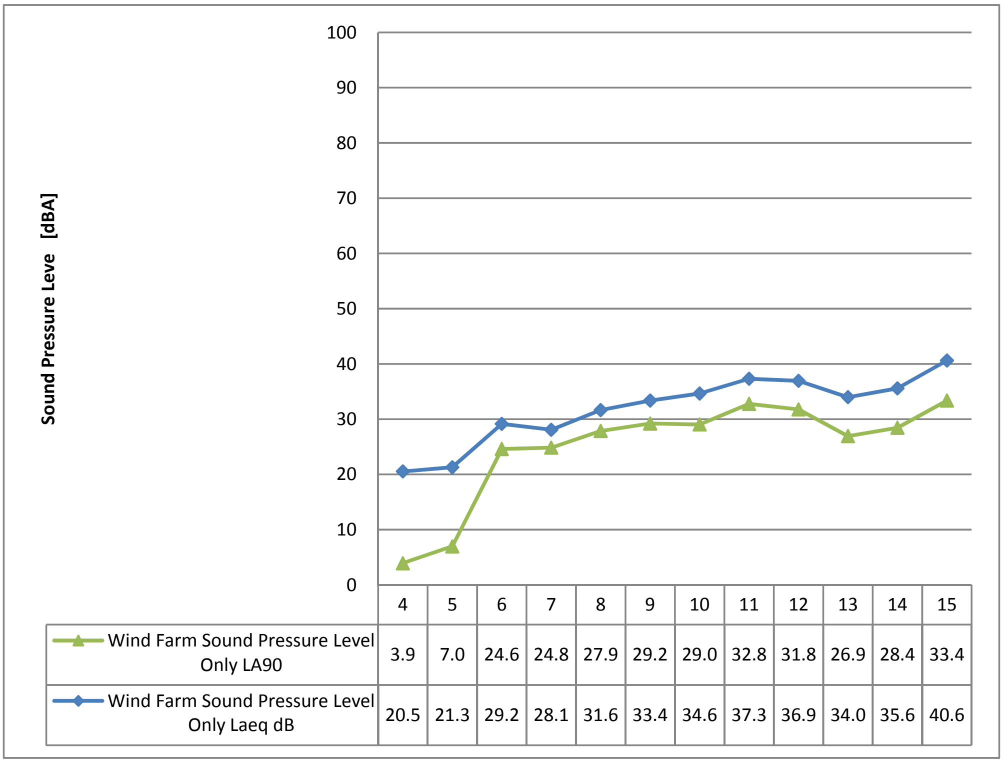


Figure 102: Graph of actual measured time varying sound pressure level of L_{Aeq} vs wind speed and expected wind farm sound level only [expressed as best fit line [log function]. 403 Makara Road.

Wind Speed at Wind Farm @ Hub Height [m/s]	**Background Sound Pressure Level Only [Post Wind Farm Development] L_{Aeq} dB**	**Wind Farm and Background Sound Pressure Level L_{Aeq} dB**
4	25.1	26.4
5	25.5	26.9
6	26.4	31.0
7	27.8	30.9
8	29.4	33.7
9	31.2	35.4
10	33.1	36.9
11	35.0	39.3
12	36.8	39.9
13	38.5	39.8
14	40.1	41.4
15	41.5	44.1

Table 26: Summary table of actual measured time varying sound pressure level of L_{Aeq} vs wind speed and expected wind farm sound level only [expressed as best fit line [log function]. 403 Makara Road.



	4	5	6	7	8	9	10	11	12	13	14	15
Wind Farm Sound Pressure Level Only LA90	3.9	7.0	24.6	24.8	27.9	29.2	29.0	32.8	31.8	26.9	28.4	33.4
Wind Farm Sound Pressure Level Only Laeq dB	20.5	21.3	29.2	28.1	31.6	33.4	34.6	37.3	36.9	34.0	35.6	40.6

Figure 103: Graph of calculated expected wind farm sound pressure level only expressed as L_{Aeq} and L_{A90} vs wind speed 403 Makara Road.

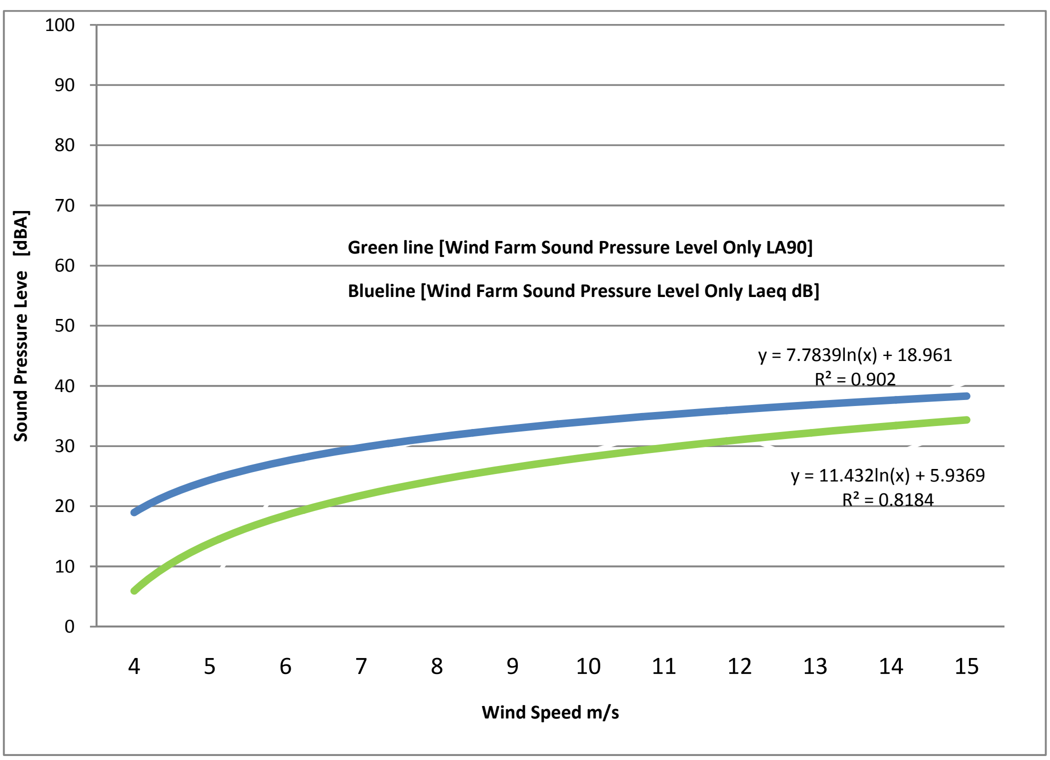


Figure 104: Graph of calculated expected wind farm sound pressure level only expressed as L_{Aeq} and L_{A90} vs wind speed 403 Makara Road ([expressed as best fit line [log function])

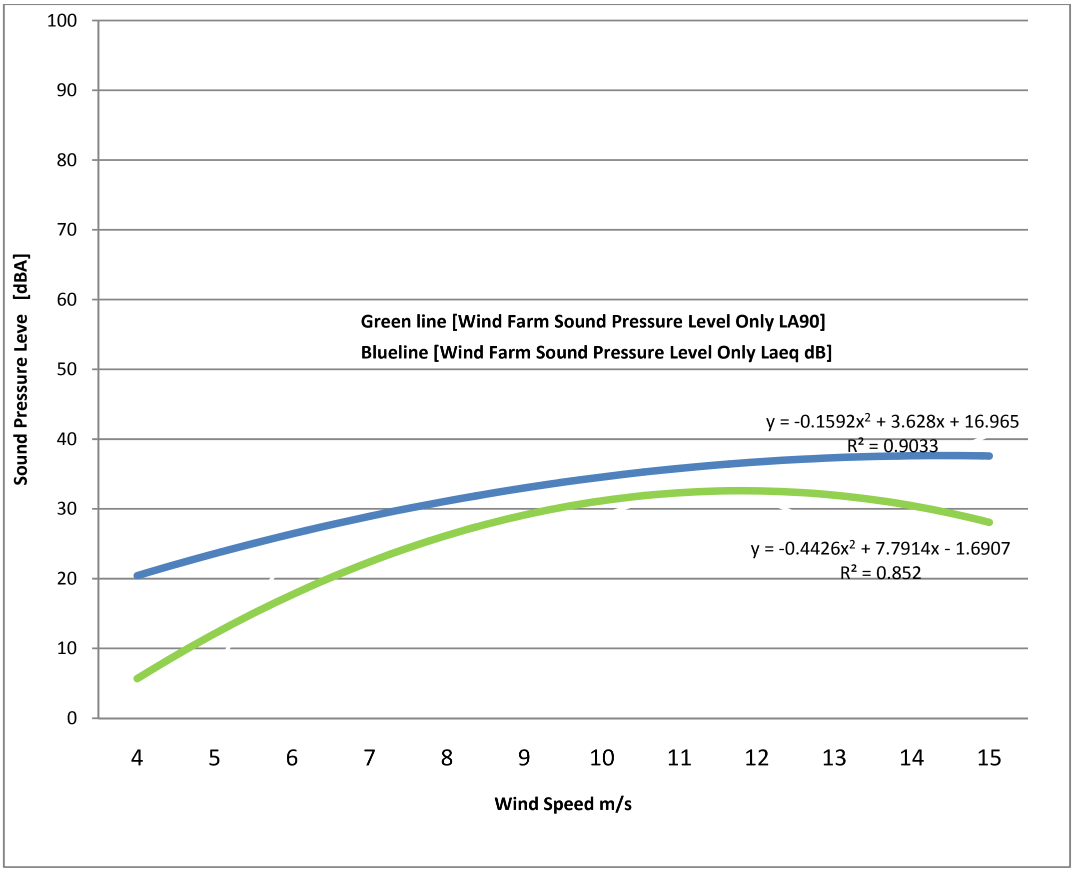


Figure 105: Graph of calculated expected wind farm sound pressure level only expressed as L_{Aeq} and L_{A90} vs wind speed 403 Makara Road (expressed as 2nd order polynomial line [polynomial function])

Wind Speed at Wind Farm @hub height [m/s]	**Estimated Wind Farm Sound Pressure Level Only L_{A90} dB**	**Estimated Wind Farm Sound Pressure Level Only L_{aeq} dB**
4	3.9	20.5
5	7.0	21.3
6	24.6	29.2
7	24.8	28.1
8	27.9	31.6
9	29.2	33.4
10	29.0	34.6
11	32.8	37.3
12	31.8	36.9
13	26.9	34.0
14	28.4	35.6
15	33.4	40.6

Table 27: Summary table of calculated expected wind farm sound pressure level only expressed as L_{Aeq} and L_{A90} vs wind speed 403 Makara Road

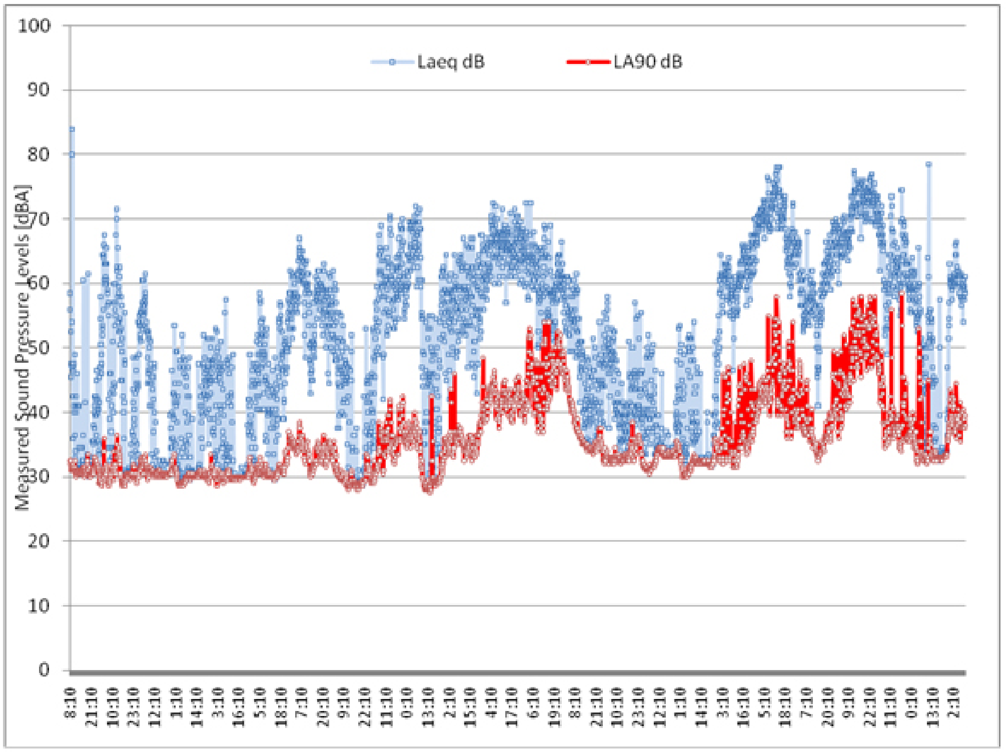


Figure 106: Graph of historic measured time varying sound pressure level of L_{Aeq} and L_{A90}. Date of sample 23 June 1997 to 14 August 1997 [22 days].

Descriptive Statistical Summary of Results and Observations

The following qualifications are made regarding the data set. It is noted below that some data are shown to two decimals places; this is only because the sound level difference is such that sound levels are within a couple of dB. It is noted however that fractional dB i.e. measurements presented less than 1 dB should be treated with caution as measurement uncertainties and error does not generally allow measurements accuracy greater than a whole decibel.

General Observations

<u>What are the things we know or understand about the data sets collected?</u>

- In statistical terms the data collected would best be described as "primary type" data as the analyst has been involved in collecting the data relevant to the investigation.

- The data collected would best be described as 'time series' data as the data has been collected over several time periods.

- The purpose of the study was to obtain information [level difference] about the L_{A90} and L_{Aeq} sound descriptors. As it is not feasible to test all scenarios and situations the study is described as limited yet reasonable in terms of time and other constraints.

- In any 'good' field or laboratory study all variables of interest are [attempted to be] identified, then one or more factors in the study are controlled so that data can be collected in terms of how the factors influence the variables. This study could best be described as an 'observational field study' so far as no attempt has been made to control or influence the variables of interest [other than by filtering the raw data collected]. As such the control of variables such as wind turbine operation, propagation of sound or background noise sources was outside the control of the study anyway. Regardless best practice in terms of the collection of field data has been carried out.

- As expected there is good correlation between wind speeds increasing at the wind turbine generator hub height and wind speeds also increasing at the 10 m mast and microphone on the receiving site.

- As expected there is good correlation between wind speeds increasing at hub height and sound pressure levels increasing at the receiver location [as rotor speed and noise output is a function wind speed].

- There is very little difference between the day and night wind speed wind profiles. From review of the data there does not appear to be any significant pattern relating to wind speed or direction relative to time i.e. day time with solar heating or night time with no solar heating [and earth cooling patterns].

403 Makara Road – Project West Wind [Makara Wind Farm]

<u>What are the major field observations and patterns in the overall data collected?</u>

- In regards to sound level data in the far field at 403 Makara Road a major observation is that sound levels generally increase as wind speeds increase. However only when wind speeds at the microphone are very low could any endeavour be made to use measured wind turbine sounds only, and hence although measured sound level data appeared to increase with wind speed this was generally non wind turbine noise.

- Even at low wind speeds at the microphone, say <3 m/s masking still occurred and not until wind speeds decreased at the microphone to around less than 1.5 m/s did masking from non wind turbine noise decrease to acceptable levels allowing for wind turbine sound only to be measured.

- Wind turbine sound power levels increase with wind speed [specifically for variable speed turbines] and hence the background noise level tended to increase at a greater rate than wind turbine sound level and hence the wind turbine sound was most noticeable [audible] in the absence of background noise [at very low wind speeds]. It is the difference in the rate of change that causes the wind turbine sound to be more noticeable or audible at a specific wind speed.

- To what level wind effects on the microphone or masking occurred will not be entirely identified, other than to observe and note the majority of the noise had a contribution from non turbine noise.

- As expected general patterns in the data arise, that is daytime sound level samples are greater than night time sound level samples, however this is a factor of extraneous background noise and not turbine operation as wind turbine sound output would be the same day or night;

- Based on the fact that sound levels contain both background noise and wind turbine sound, absolute levels are not representative of wind turbine sound only in Data Set M, but are as close as could be sampled in Data Set N. It would however be unconsidered to say even Data Set N contains absolutely no unwanted extraneous noise. To what degree or effect will never be 100% known for a study and control of this type.

How are the West Wind Conditions relevant to the study data collected?

- We know from Project West Wind that noise conditions set by the Environment Court [Environment Court Decision W 59/2007 dated 20th July 2007] are very intensive in that they are the largest number of noise conditions, measured by number of conditions, words or pages, in New Zealand.

- For the majority of the time the conventional NZS6808:1998 limit applies at Project West Wind/403 Makara Road i.e. 40 dBA or the background + 5 dB, whichever is the greater. However West Wind also has a 'sub condition' which states in conditions where the background level is very low i.e. <25 dBA and the local wind speed is <1.5 m/s [at 10 m], a limit of 35 dBA applies at the dwelling.

- We know from work carried out for the wind farm by the operator that monitoring conditions will be met at all times by the wind farm operator [noting noise condition 40[c] that requires the turbines to be de-rated by loading an alternative power curve to reduce rotational speeds of the blades and hence noise output].

- In regards to 403 Makara Road the analysis shows that the lower limit of 35 dBA would only apply very rarely [if at all] and in the rare cases it would only apply when the wind farm is at or below its cut in wind speed. In these conditions the turbines will either be not producing any sound [and hence cannot be measured] or any sound which is produced would be far lower than the permitted maximum levels [40 dBA or the background + 5 dB, whichever is the greater]. In other words when local background noise levels [and wind speeds] are low enough to be able to measure a 'clean' sample of wind turbine sound only [without masking or interference] the output of sound produced from the wind turbines as received off site at 403 Makara Road is very low [this is supported by both subjective assessment on site and the data collected].

- At the receiving environment of 403 Makara Road it is almost impossible to measure just wind turbine sound as per the requirements of the conditions, without some type of contribution from background noise [even if slight]. This assessment is based on sampling of 10 minute intervals i.e. the fact that during a 10 minute sample period there is likely always going to be unwanted extraneous noise present.

- It is however possible to measure discrete short samples of a few seconds of wind turbine sound only, however from the field work and observations this is only possible with short sample times and when there is very low background noise levels at the microphone. Such conditions on the wind farm result in reduced wind speeds and hence overall reduced sound pressure levels at the receiving environment.

<u>What are the relationships, trends and generalisations among the results?</u>

- Data Set M is similar to Data Set N, however the key difference between the two sets is Data Set N has only 39 samples is wind turbine sound only [or as close to as could be collected].

- Data Set M contains approx 1,500 samples [the minimum sample set recommended by NZS6808] it is however acknowledged that this minimum recommended amount contains a high percentage of samples of both background noise plus wind turbine sound.

<u>What are the relationships and trends for Data Set M?</u>

- The mean sound pressure level for Data Set M regarding the L_{Aeq} was 38.0 dB, the mean L_{A90} was 34.9, this equates to a mean, or average level difference [$L_{Aeq} - L_{A90}$] in sound pressure levels of approx 3.1 dB.

- The *standard error* indicates how close the *sample* mean is from the extrapolated *population* mean which in these cases is treated as the average of all the items in a population. In regards to Data Set M the standard error for the L_{Aeq} was 0.2 dB, for the L_{A90} it was 0.1 dB.

- The *margin of error* in this study is treated as similar to a *confidence interval* [presented here with a margin of error at the 95 percent confidence interval]. In this case the confidence internal has been calculated as an *interval estimate of the mean*. The confidence interval generates a lower and upper limit for the mean. The interval estimate provides an indication of how much uncertainty there is in the estimate of the true population mean - The narrower the interval, the more precise is our estimate.

- In regards to Data Set M the margin of error for the L_{Aeq} was 0.4 dB, for the L_{A90} it was 0.3 dB, this equates to a mean level margin of error difference in sound pressure levels of approx 0.1 dB.

- The standard deviation [spread of data about the average/mean] for sound pressure levels for Data Set M regarding the L_{Aeq} was 6.8 dB and 6.3 dB for the L_{A90}.

- The standard deviation is one of several statistical indices of variability used to characterise the 'dispersion' among measures i.e. the standard deviation could be viewed as the average amount by which measured levels differ from the mean [the spread of data around the mean]. The standard deviation data in this survey is based on the measured L_{Aeq} and L_{A90} sound descriptors.

- Generally a high value represents a sound climate that *fluctuates* significantly [as expected for L_{Aeq} which includes both background noise and wind turbine sound]. A low value corresponds to a more stable level of sound [as would be expected for the L_{A90} from wind turbine sound only]. The standard deviation for Data Set M for both sound descriptors is high illustrating high fluctuating levels, likely from wind turbine and background sources [as opposed to just wind turbine sound]. The level difference [$L_{Aeq} - L_{A90}$] standard deviation of approx 2 dB.

- The *mode* [most occurring value] sound pressure level for Data Set M regarding the L_{Aeq} was 39.8 dB, the mode for the L_{A90} was 38.4 dB.

- The *minimum* sound pressure level for Data Set M regarding the L_{Aeq} was 18.6 dB, the *maximum* L_{Aeq} was 57.5 dB, from the analysis of wind turbine sound only L_{Aeq} values over 40 dB can be concluded to include both wind farm sound and background noise. This equates to a range [max value – min values] of 39.0 dB.

- The *minimum* sound pressure level for Data Set M regarding the L_{A90} was 16.3 dB, the *maximum* L_{A90} was 51.9 dB, from the analysis of wind turbine sound only L_{A90} values over 30 dB can be concluded to include both wind farm sound and background noise.

- There are a number of strong correlations for Data Set M which includes a strong correlation between an increase of hub height wind speeds and increase of local wind speeds. This tells us that when wind speeds increase at hub height so do wind speed at the 10 m mast and microphone. This allows the conclusion to be drawn with reasonable confidence that although the terrain between the receiving site and turbine is complex there is a relationship between the two for 403 Makara Road. This is important as there could for some sites and situations be a low correlation between wind speed at hub height and at the 10 m mast i.e. in certain complex terrains wind speeds could be lower in a sheltered valley or higher in an exposed part of the site for example.

- Data Set M appears to provide a good relationship between wind turbine and background noise as opposed to just wind turbine sound on its own. This is based on the fact that sound level samples collected are at levels well above those that have been collected in Data Set N which is wind turbine sound only. In the case that samples were from wind turbine sound only one would expect to see the L_{Aeq} and L_{A90} time varying lines run in parallel which indicates a stronger correlation of a constant type sound i.e. wind turbine sound only.

- There is a strong correlation between both an increase in wind speed and an increase in the measured L_{A90} / L_{Aeq} sound descriptors. This correlation is strongest between 20 dB to 40 dB with the spread of data points being a lot more spread out below 20 dB or above 40 dB. However given what is known regarding the output of sound from the wind turbine generator and expected sound levels from wind turbine sound only across the wind speed spectrum, it is safe to assume anything above 35 dB is not wind turbine sound alone in Data Set M.

- Although it is acknowledged that there is the presence of extraneous background noise included within Data Set M, when viewing the data it is clear that for local wind speeds of less than 2 m/s [which would be equal to hub height wind speeds of around 8 m/s] this data shows sound levels of between 20 dB to 30 dB appears to be clusters of ‘tight data’ illustrating a strong relationship with very little spread. In other words this cluster between 20 to 30 dB with local wind speeds of 0 to 2m/s relates to the data extracted further as Data Set N.

What are the relationships and trends for Data Set N?

- Data Set N is viewed as the closest possible data set of wind turbine sound only, however as Data Set N has the highest degree of filtering there are only 39 samples [from an original raw data set of 11,150]. Therefore caution must be taken when drawing any conclusions including statistical statements or analysis from the results.

- All data collected is at low wind speeds, that is a wind speeds of 4 – 7 m/s for 34 samples and 5 samples are at wind speeds >7m/s.

- While the sample size of Data Set N is small [n=39] this does not mean it does not represent the 'behaviour' of wind turbine sound descriptors in the receiving environment for the measurement site.

- Based on the filtering process and sample observations, Data Set N is believed to be representative and accurate of wind turbine sound only [or as far as best practice will allow it to be measured in the presence at a receiver site in a real operating environment]. Such assumptions are based on the fact that the filtering of the data is very well structured so as to gain the best possible means of wind turbine sound only while removing unwanted background noise [as far as possible]. This represents best practice.

- Because Data Set N is only relative to the parameters around the study i.e. type of test turbine, terrain, propagation of sound between turbine and microphone, caution should be taken when applying any results from the study to all wind farms or sites without understanding the background first.

- The mean sound pressure level for Data Set N regarding the L_{Aeq} was 25.4 dB, the mean L_{A90} was 23.0 dB.

- In regards to Data Set N the standard error for the L_{Aeq} was 0.39 dB, for the L_{A90} it was 0.3 dB.

- The standard deviation [spread of data about the average/mean] for sound pressure levels for Data Set N regarding the L_{Aeq} was 2.3 dB and 2.0 for the L_{A90}.

- The *mode* [most occurring value] sound pressure level for Data Set N regarding the L_{Aeq} was 24.4 dB, the mode for the L_{A90} was 22.5 dB.

- The *minimum* sound pressure level for Data Set N regarding the L_{Aeq} was 19.8 dB. The *maximum* L_{Aeq} was 31.1 dB.

- The *minimum* sound pressure level for Data Set N regarding the L_{A90} was 18.5 dB, the *maximum* L_{A90} was 27.5 dB.

- Based on the wind turbine generators sound level as a function of wind speed at hub height [for Data Set N] the minimum value of sound level difference [$L_{Aeq} – L_{A90}$] across all wind speeds occurs at 7 m/s with a *range* of 8.8 dB. This level difference [$L_{Aeq} – L_{A90}$] is around rated power of the turbine being 8 m/s for the V72/NM72. At this wind speed [7 m/s] the sound level difference [$L_{Aeq} – L_{A90}$] *mode* value between L_{A90} and L_{Aeq} is 2.2 dB, while the *mean* is 2.4 dB and median 1.9 dB.

- The sound level difference [$L_{Aeq} – L_{A90}$] at 7 m/s *standard error* value is 0.2 dB, while the standard deviation is 1.7 dB. The confidence interval is 0.4 dB.

Comparison of Data Set B [Initial Raw Data B] and Final Filtered Data Set [Data Set N]

- Data Set B has been treated as a possible 'control' for the study in that no filtering or changes have been made to the data set. Data Set B has therefore been compared to Data Set N which is the final completed data set of wind turbine sound only [or as close as could be measured].

- The range for Data Set B regarding the L_{Aeq} was 68 dB, the range for Data Set N regarding the L_{Aeq} was 11 dB.

- The difference between the range for Data Set B and Data Set N regarding the L_{Aeq} was 57 dB.

- The range for Data Set B regarding the L_{A90} was 35 dB, the range for Data Set N regarding the L_{A90} was 9 dB.

- The difference between the range for Data Set B and Data Set N regarding the L_{A90} was 26 dB.

- The range for Data Set B sound level difference [$L_{Aeq} – L_{A90}$] was 48 dB, the range for Data Set N sound Level difference [$L_{Aeq} – L_{A90}$] was 5 dB.

- The mean for Data Set B regarding the L_{Aeq} was 39 dB, the mean for Data Set N regarding the L_{Aeq} was 25 dB.

- The difference between the mean for Data Set B and Data Set N regarding the L_{Aeq} was 14 dB.

- The mean for Data Set B regarding the L_{A90} was 34 dB, the mean for Data Set N regarding the L_{A90} was 23 dB.

- The difference between the mean for Data Set B and Data Set N regarding the L_{A90} was 11 dB.

- The mean for Data Set B sound level difference [$L_{Aeq} - L_{A90}$] was 4.7 dB, the mean for Data Set N sound Level difference [$L_{Aeq} - L_{A90}$] was 2.4 dB.

- The median for Data Set B regarding the L_{Aeq} was 41 dB, the median for Data Set N regarding the 25 L_{Aeq} was dB.

- The difference between the median for Data Set B and Data Set N regarding the L_{Aeq} was 16 dB.

- The median for Data Set B regarding the L_{A90} was 36 dB, the median for Data Set N regarding the L_{A90} was 23 dB.

- The difference between the median for Data Set B and Data Set N regarding the L_{A90} was 13 dB.

- The median for Data Set B sound level difference [$L_{Aeq} - L_{A90}$] was 3.3 dB, the median for Data Set N sound Level difference [$L_{Aeq} - L_{A90}$] was 2.5 dB.

- The standard deviation for Data Set B regarding the L_{Aeq} was 8.2 dB; the standard deviation for Data Set N regarding the L_{Aeq} was 2.3 dB.

- The difference between the standard deviation for Data Set B and Data Set N regarding the L_{Aeq} was 5.9 dB.

- The standard deviation for Data Set B regarding the L_{A90} was 7.5 dB; the standard deviation for Data Set N regarding the L_{A90} was 2 dB.

- The difference between the standard deviation for Data Set B and Data Set N regarding the L_{A90} was 5.5 dB.

- The standard deviation for Data Set B sound level difference [$L_{Aeq} - L_{A90}$] was 4.5 dB, the standard deviation for Data Set N sound Level difference [$L_{Aeq} - L_{A90}$] was 1.4 dB.

Te Apiti Wind Farm

- Te Apiti Wind Farm was granted Resource Consent on 3rd September 2003. The wind farm had a total of 20 conditions. A total of 11 conditions addressed sound with the measurement of sound having to be conducted using NZS6808:1998. The sound conditions were for the receiving environments [not on site as tested for the study here] and hence any available historic data provides little assistance with on site testing.

- For commercial reasons the wind speeds at which sound levels were sampled are not able to be provided or discussed and hence graphs of wind speed at hub height or the microphone at R_o versus sound level descriptors is not provided as part of the study results. This therefore limits the ability to graph wind speed versus sound levels but more importantly limits applying best fit curves. Regardless the data at Te Apiti has provided a useful background to sound from wind turbines and provided answers and assistance regarding sound in the far field.

- The mean sound pressure level for the 10 minute logging data [R_o] regarding the L_{Aeq} was 49.3 dB, the mean L_{A90} was 48.1 dB, this equates to a mean, or average level difference [$L_{Aeq} - L_{A90}$] in sound pressure levels of approx 1.2 dB.

- The standard error for 10 minute logging data [R_o] regarding the L_{Aeq} was 0.12 dB, for the L_{A90} it was 0.09 dB.

- The margin of error for the 10 minute logging data [R_o] for the L_{Aeq} was 0.2 dB, for the L_{A90} it was 0.1 dB.

- The *mode* sound pressure level for the 10 minute logging data [R_o] regarding the L_{Aeq} was 49.2 dB, the mode for the L_{A90} was 48 dB.

- The *minimum* sound pressure level for the 10 minute logging data [R_o] regarding the L_{Aeq} was 48.1 dB. The *maximum* L_{Aeq} was 53.1 dB.

- The *minimum* sound pressure level for the 10 minute logging data [R_o] regarding the L_{A90} was 47.2 dB, the *maximum* L_{A90} was 51.1 dB.

- The *median* sound pressure level for the 10 minute logging data [R_o] regarding the L_{Aeq} was 49.2 dB, the median for the L_{A90} was 48 dB.

- There is good correlation of the statistical results from the data logging when compared to short term hand held measurements [i.e. when comparing results at similar hub height wind speeds, measurement sample durations and at the R_o location]. The mean for the R_o 10 minute logging was 1.2 dB, while the mean for the R_o hand held measurements were 1.4 dB.

Chapter 8: Discussion

Introduction

This chapter provides a number of statements relating to the difference between the wind turbine generator sound level descriptors L_{Aeq} and L_{A90} based on the measured data and observed environment. Comment is provided on further work, the study's limitations and key assumptions.

Synopsis of Final Results [Data Set N – 403 Makara Road]

Table 28 illustrates the final measurement results for 403 Makara Road.

Data Set N – Night time / Directly downwind [n=39]	Mean	Standard Error	Median	Mode	Standard Deviation	Range	Minimum	Maximum	Confidence Level [95.0%]
Level Difference	2.4	0.2	2.5	2.6	1.4	5.1	0.5	5.6	0.4
L_{aeq} dB	25.4	0.3	25.1	24.4	2.3	11.3	19.8	31.1	0.7
L_{A90} dB	23.0	0.3	22.9	22.5	2.0	9.0	18.5	27.5	0.6

Table 28: Statistical table of measured time varying sound pressure level of L_{Aeq} and L_{A90}. 403 Makara Road. 10 minutes sampling time. Data Set N

Synopsis of Final Results [R_o Measurement Position]

Table 29 illustrates the final measurement results for Te Apiti Wind Farm Tap 44 [R_o].

Ro	Mean	Standard Error	Median	Mode	Range	Minimum	Maximum	Confidence Level [95.0%]
WTG Base 1 Second	1.1	0.01	1.1	1.3	4.1	0.2	4.3	0.04
WTG Base 10 Second	1.1	0.05	1.2	1.3	1.8	0.3	2.1	0.1
R_o 10 Second	1.0	0.03	1.0	1.0	2.1	0.6	2.7	0.07
R_o 1 minute	1.1	0.04	1.1	1.1	0.4	1	1.4	0.1
R_o 10 minute	1.4	0.1	1.6	1.0	1.6	0.6	2.2	0.4

Table 29: Statistical table of measured time varying sound pressure level of L_{Aeq} and L_{A90}. Te Apiti Wind Farm Tap 44 – R_o measurement location and base of wind turbine generator. Sampling time as shown.

Summary Statement of Final Results

As illustrated by the study at 403 Makara Road, sound produced by the wind turbine generators [as received off site] ranged from low levels of audible sound to levels of sound that were at most times immeasurable in the context of unwanted background noise via the use of a sound level meter as the measurement tool.

In terms of on-site measurements at Te Apiti Wind Farm, the study revealed levels of sound at a normal audible hearing range which dominated above background noise and could easily be measured under controlled conditions.

One key commentary the study has revealed is the measurement of wind turbine sound only, both on and off site, is an extreme challenge however it can be done accurately when carried out in line with best practice and years of experience.

Based on the field data collected, observations and subsequent analysis of the results, the following summary statements are made:

- *The overall mean level difference for wind turbine sound for the L_{Aeq} dB and L_{A90} dB sound pressure levels based on the actual measured field data at the R_o location for the Vestas V72 three bladed horizontal wind turbine generator at Te Apiti Wind Farm was 1.4 dB [based on R_o measurement location].*

- *The overall mean level difference for wind turbine sound for the L_{Aeq} dB and L_{A90} dB sound pressure based on the actual measured field data at 403 Makara Road location for the Siemens three bladed horizontal wind turbine generator located on the Project West Wind [Makara Wind Farm] was 2.4 dB.*

Figure 107 illustrates the above statements in graphical format for 403 Makara [Left] and Te Apiti R_o location [right]:

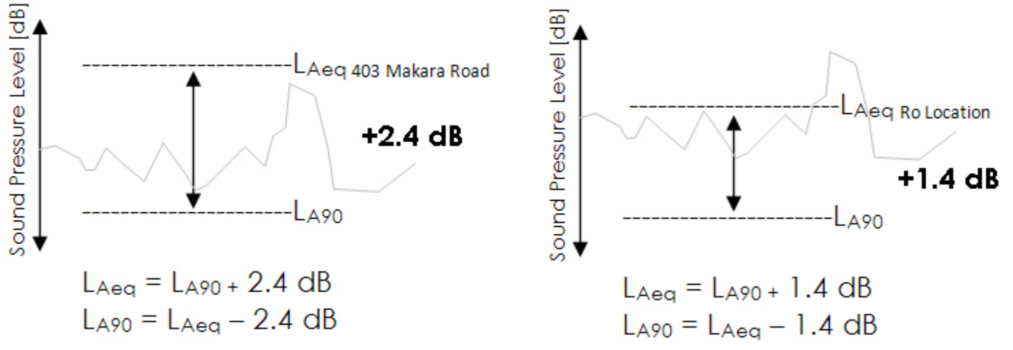


Figure 107: Graphic of mean level sound level differences for 403 Makara Road and Te Apiti Wind Farm.

The above analysis and data collected has lead to a final conclusion and overall purpose of this thesis - being able to provide a concluding statement in terms of the relationship between the L_{A90} and L_{Aeq} sound descriptors as used in the New Zealand Standards for wind farm sound. This key statement is:

From the research carried out for this study the declaration made in Section 4.2.1 of the historic New Zealand wind turbine noise standard NZS6808:1998 that 'L_{95} is typically 1.5 dB – 2.5 dB lower than its L_{eq} level' is warranted for modern three bladed horizontal wind turbine generators operating in a complex environment [both in the far field and at the R_o reference position recommended by IEC61400 – Part 11].

The key implication under the historic standard was that wind turbine sounds could potentially exceed the allowable 40 dBA design limit [or average background sound level + 5 dB] by up to a further 2.5 dB and still remain in compliance with the limits recommended under the NZS6808:1998.

As a result of the study's findings it is concluded that although the field data indicated a quantifiable level difference between the two sound level descriptors the current wind turbine noise standard [NZS6808:2010] appropriately removes any uncertainties by stating that $L_{Aeq} = L_{A90}$ when carrying out the assessment process. This removal of any uncertainty is chiefly due to the fact that although a quantifiable level difference between the two sound level descriptors was measured for this study the sound level difference is prone to change and hence any precise or exact level difference is therefore a factor of the wind turbine generator models tested, site conditions and related intervening variables.

The above statements should be viewed in terms of the design of the overall study and its range of limitations.

Background to Study

The concluding statement relates back to the first ever wind turbine standard created for use in New Zealand being NZS6808:1998 Acoustics – *The Assessment and Measurement of Sound from Wind Turbine Generators*. This 1998 standard was partially based on work carried out in the United Kingdom by the Working Group on Noise from Wind Turbines, documented in ETSU-R-97 *The Assessment and Rating of Noise from Wind Farms* report [[99]] published in 1996. The ETSU working group was made up of independent experts being established by the Department of Trade and Industry of the United Kingdom Government [now the Department of Business Industry and Skills, UK Government].

The 1998 wind turbine noise standard was updated in 2010 with the release of NZS6808:2010 Acoustics – *Wind Farm Noise.* The updated 2010 standard related to technical refinements and incremental enhancements which followed in part previous scoping work and field investigations carried out by Malcolm Hunt Associates, Marshall

Day Acoustics and others for the Wind Energy Association of New Zealand [28]. ***Appendix C*** illustrates the prediction, measurement and assessment process for noise level descriptors under NZS6808, 1998 and 2010 relevant to the study topic.

NZS6808:2010 Acoustics – *Wind Farm Noise,* requires background noise pressure levels to be measured at selected relevant receiving locations off site *before* the wind farm is developed. Allowable wind turbine design sound limits are then derived from a comparison of the *predicted* wind turbine[s] sound pressure levels and the *actual* measured average background noise level for each selected receiving location. NZS6808:2010 recommends the cumulative wind turbine sound level for each assessment location should not exceed 40 dB or the average background noise level + 5 dB, whichever is the greater of the two.

In line with the international standard *IEC 61400-11: Wind Turbine Generator Systems Part 11: Acoustic Noise Measurement Techniques,* NZS6808:2010 uses the L_{Aeq} sound descriptor as the basis of known rated wind turbine sound power output for sound *predictions*, however allowable wind turbine sound limits and measurements of background sound levels are set in terms of the L_{A90} sound descriptor [previously L_{A95} in the 1998 standard]. A potential inconsistency therefore arises with the use of two different sound descriptors being used namely a 'historical' statistical descriptor [L_{A90}] versus an energy average descriptor [L_{Aeq}].

As there is an apparent variability between L_{Aeq} and L_{A90} sound descriptors from environmental sound [including wind farms] it is understood that the NZS6808:2010 Standards Committee decided in this particular case it was best to assume that a prediction based on the L_{Aeq} source data be taken to be equal to the L_{A90}, hence theoretically providing a small degree of conservatism in predictions. To what degree this variability between the two sound level descriptors was, was not absolutely known at the time, especially at far field receiving environments. Nevertheless it is understood the Committee accepted that there was likely a measure of variability based on the best technical information available to them from current literature and past work.

At the time of preparing the original 1998 wind turbine standard, NZS6808:1998 did not specifically account for the difference in the then used L_{A95} and L_{Aeq} sound descriptors, rather the standard relied on best practise and information available at the time which included information provided by the Working Group on Noise from Wind Turbines in the UK and subsequent reporting.

Specifically ***Section 4.2.1*** of NZS6808:1998 stated that a L_{95} sound descriptor is typically 1.5 dB – 2.5 dB lower than its L_{eq} level [for wind turbine sound]. It is understood the standard refers to work done in the United Kingdom by the Working Group on Noise from Wind Turbines, documented in ETSU-R-97.

The UK-ETSU-R-97 document sets an outdoor night time sound level limit defined as 5 dB above the L_{A90}, or 43 dBA whichever is higher. The exclusionary limit of 43 dBA for night time is used since the concern is to minimise sleep disturbance inside a residence. This level was established to satisfy the World Health Organization [WHO] guidelines to minimise sleep disturbance by ensuring that sound levels indoors did not exceed a L_{Aeq} 35 dB sound level. Thus the 43 dB [L_{A90}] outdoor night time sound level limit is based on the premise that $L_{A90} = L_{Aeq} – 2$ dB and assumes Noise $_{outdoor}$ = Noise $_{indoor}$ + 10 dB [allowing for openable windows].

There are believed to be various issues and limitations as documented in ETSU-R-97 which relate to modern wind turbine generators. Such limitations include the fact that the document was prepared now over 14 years ago hence any historic measurements were based on the operation and measurement of wind turbine generators being 'first generation'. These wind turbines typically had much smaller ratings in terms of electrical and acoustical power outputs than that compared to modern day wind turbine generators, noting of course as wind turbine technology develops the turbines become taller and rotor diameters increase and newer technology advances allow for wind turbine generators to operate in lower wind speed environments. First generation turbines were generally no more than 40 m high and had rotor diameters of 30 m to 40 m [300 kW to 500 kW power range], compared to modern turbines being 90 m plus in height with rotor diameters in excess of around 3 to 5 times larger than first generation machines.

It is also not entirely apparent if the difference in L_{A90} and L_{Aeq} sound descriptors referred to in the ETSU work or NZS6808:1998 is on the wind turbine site itself or off site at key receiving locations[[4]]. This fact is important as the study here has attempted to look at both situations, but is ultimately interested in results presented off site from wind turbine sound where people reside. There is little benefit assessing sound where people would not be potentially affected, other than to provide background data.

To extrapolate data measured on site from wind turbine sound to distant locations could to some degree and circumstances be possible in countries where there is flat terrain or limited undulating terrain, however in terms of New Zealand or any environment where complex hilly terrain exists, this makes such extrapolation and prediction no simple task as it is a sturdy challenge to apply such extrapolation of data accurately. This is simply due to the fact that in complex terrain the intervening variables between source and receiver include vast complexities relating to sound propagation and sound transmission variables.

[4] It is noted that the ETSU document [see Pages 56 and 57] that the sound level difference between the L_{Aeq} and L_{A90} sound levels close to the wind turbine and in the absence of other noise sources, is typically less than 2 dB[A] [as shown in Figure 6 of the ETSU document]. Figure 6 show sound levels in the order of 60 dB[A] which would be at the R_o location, however the ETSU document then states Figure 7 is taken at residential sites hundred of meters away from the nearest turbines. Figure 7 is labelled "nearby residence" and refers to wind farm noise rather that wind turbine noise, hence the reading is the ETSU document is taken by some parties to mean that measurements have considered both on site at the R_o and distant off site residential locations.

The fact remains that even with modern computing and modelling tools there is never going to be any substitute for actual objective field testing and measurements.

There has therefore been an actual need for some scientific verification and assessment to look at the difference between the L_{A90} and L_{Aeq} sound descriptors from current modern commercial utility wind turbine generators in the New Zealand environment and at key receiving locations.

The study here has therefore been based on two test locations being outside a dwelling in the 'far field' adjacent a wind farm in Wellington known as 'Project West Wind' and at the R_o measurement location [see IEC 61400 Part 11] on the wind farm itself at a wind farm called 'Te Apiti Wind Farm' located in Palmerston North.

Field measurements and assessments were chosen to take place at these two sites as they represent existing modern day operating [commercial] utility wind farms and a real life typical rural residential dwelling environment adjacent an operating wind farm.

Field measurements have been chosen as the preferred method of assessment, compared to that of acoustic modelling, as this allowed for experience to be gained in terms of objective wind turbine measurements and subjective assessment on and off site.

Although the review outcomes provides a statement of sound pressure levels between L_{A90} and L_{Aeq} sound descriptors for wind turbine sound this difference or 'safety margin' between actual measured background noise and predicted sound pressure limits needs to be based around actual field studies of modern commercial wind turbines so any small degree of conservatism in the predictions has some real life scientific verification, as opposed to being based on theories or models. This thesis and related measurements therefore provide a foundation for further work and understanding into this topic.

The overall purpose of the field study has thus been to examine the relationship between L_{A90} and L_{Aeq} sound descriptors from existing commercial wind turbine generators in the New Zealand environment. The study, based around actual field measurements at two wind farms in the lower north Island of New Zealand has allowed for an original endeavour to be made around the statement on the validity of the current approach of NZS6808:2010 [treating the relationship between L_{A90} and L_{Aeq} sound descriptors as similar].

The Studies Individuality, Innovation and Contribution to Wind Turbine Acoustics in New Zealand

At the time of commencing the study the [then] current New Zealand wind turbine standard [NZS6808:1998] was being reviewed by Standards New Zealand. After communications with several committee members this provided the motivation to review the variability between the L_{Aeq} and L_{A90} sound descriptors. This was viewed as being particularly valuable, unique and practical so far as any actual measured field results were relative to wind turbine generators in New Zealand which operate in a complex terrain.

Reference is made in the title of the work here to a 'New Zealand environment'. This reference infers a 'complex terrain' which is taken to be best defined as a varying altitude between source and receiver and varying surface conditions. This means mountainous or hilly terrain with altering surface gradient [as opposed to flat or low level undulating terrain] covered with changing ground cover [forest, bush, long/short grass, scrubs, water etc].

Complex terrain is also sometimes technically referred to as 'heterogeneous terrain' being a term used to describe an object or system consisting of multiple items having a large number of variations. It is the opposite of 'homogeneous terrain' meaning the same i.e. generally flat in contour and with the same surface conditions.

This study is innovative as it has attempted measurement for modern wind turbine generators based on current day hub heights and rotor sizes as opposed to past and possibly redundant studies which are based on much smaller hub heights and rotor diameters. The study also differentiates itself from other work so far as it has carried out acoustic measurements off site where people reside. These off site locations are key as such locations [i.e. the dwelling at 403 Makara Road] are where people are potentially at greatest influence from wind turbine sound.

The choice of wind turbines generator models, wind turbine sites and other intervening variables is vast. The overall purpose of the field data collected was to make an effort to put together an effective use of well composed and sampled data relating to modern wind turbine generators operating in a complex environment found in New Zealand.

Although limited measurements were conducted in a sense that the measurements are based on two test turbines, a larger sample of L_{Aeq} and L_{A90} data at only two test sites was viewed as the best option for analysis compared to less samples at more test sites or for a greater range of wind turbine generator models.

In this sense the field testing has intentionally been designed so that the measured results are practical to time restraints and limitations for the thesis degree. This is because it is clearly not possible [even with great amounts of resources] to have the available time needed to measure or 'test' every situation or intervening variable.

It is interesting to note that when the field testing began the two test turbines represented modern wind turbine generators in terms of hub heights and rotor diameters [for those based on land]. Since that period it is noted that hub heights continue to increase such as the Vestas V112 which has a hub height over 90 m and rotor diameter of 112 m.

It is also significant to note that as technology advances and rotor diameters and hub heights increase to allow for greater yields in electrical power output, sound power levels do not necessary increase. This is mainly due to incremental advances in aerodynamics over the past ten years and other various noise reduction techniques being brought on line such as various operating modes to meet the operational sound level restrictions specific to any one site.

A Semi-Empirical Study

The question is asked - how well does the field data or measurements assist in describing the characteristics of the wider 'population' for wind turbine generators in use in New Zealand? The answer is that due to the intervening variables [discussed further below] applying the sample data and field results to a larger 'population' would need to be treated with vigilance. Nonetheless the final data set on which the 'Summary Statements' in this chapter are based are relevant and based on well formulated field study and observations.

Chapter 7 [Field Work] formed the first part of the data analysis providing assessment of *descriptive* statistics. These statistics provide a summary of the measured data collected for the two wind farms. The filtered data sets have been presented in **Chapter 7** to describe the different statistical characteristics of the collected data, which all apart from final Data Set N include some form of non wind turbine sound.

Generally the data in **Chapter 7** provides a good basis for summarising the raw and filtered data sets in a quantitative manner. The analysis does not however necessary make the information entirely 'meaningful' in the context of the study aims. This is because understand all intervening circumstances is important to be able to draw valid and accurate conclusions from the final data.

The final conclusions and assessment are therefore not just dependent on the objective measured field data, but are also empirically based as they rely on both the objective measured filtered data and hours of field observations both on and off the wind turbine farm sites, including when wind turbines generators were operating or parked.

Relationship between L_{A90} and L_{Aeq} Sound Level Descriptors

Relationships between the two sound level descriptors can occur in various statistical forms including what is known as a 'direct positive' relationship i.e. when one variable [L_{Aeq} or L_{A90}] happens to be 'high' or increasing the other variable also happens to be high or increasing. This concept is shown in **Figure 108**.

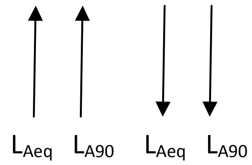


Figure 108: Example of a direct positive relationship between L_{Aeq} or L_{A90} sound descriptors where the arrows represent an increase or decrease in sound levels.

The same may apply with a ‘direct negative’ relationship i.e. when one variable [L_{Aeq} or L_{A90}] happens to be ‘low’ or decreasing the other happens to be ‘high’ or increasing. In other words in terms of a L_{Aeq} or L_{A90} samples both variables have a direct negative relationship and move in the opposite direction. This concept is shown in **Figure 109**.

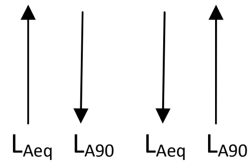


Figure 109: Example of a direct negative relationship between L_{Aeq} or L_{A90} sound descriptors where the arrows represent an increase or decrease in sound levels.

In terms of the final collected Data Set N there is commonly [or more frequently than not] a positive correlation as far as when one sound descriptor increases or decreases so does the other. This is also acknowledged as a monotonic [function] or relationship.

In regards to the final Data Set N it is clear that when reviewing the data a direct positive relationship exists between the two variables. The data set is on whole described as having a direct positive relationship. **Figure 110** illustrates an example of wind turbine sound only from Data Set N.

The time varying graph illustrates a direct relationship between L_{Aeq} or L_{A90} sound descriptors where both descriptors increase or decrease dependent of each other. The analysis shows that 87% or 34 of the 39 samples are directly related i.e. when one increases or decrease so generally does the other.

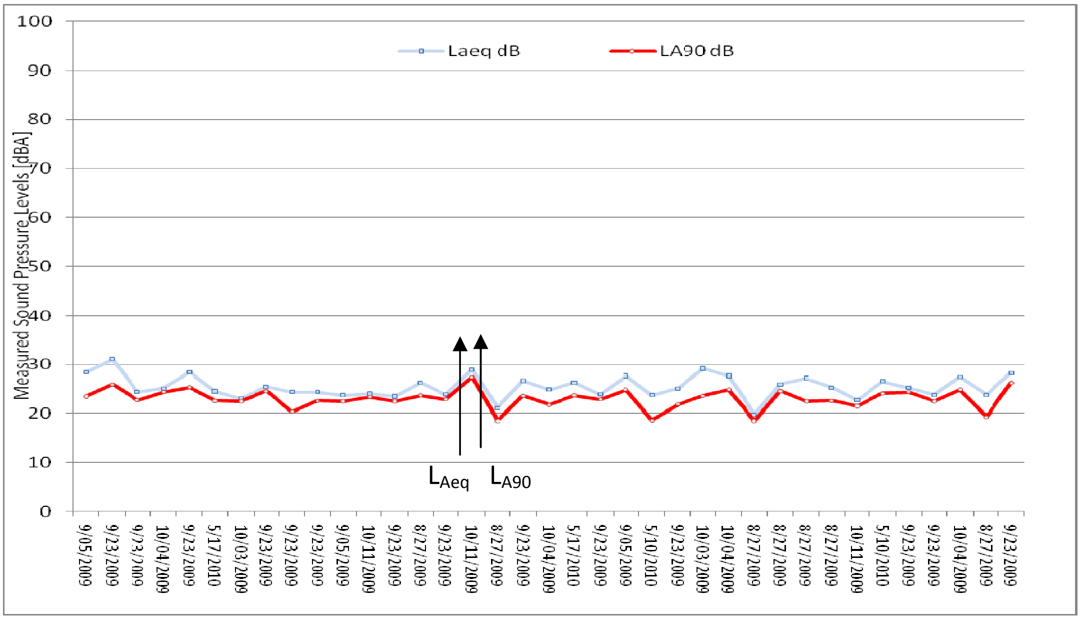


Figure 110: Example of time varying line graph of a direct positive relationship between L_{Aeq} or L_{A90} sound descriptors where the arrows represent an increase or decrease in sound levels.

Variability of Results

There are a number of basic descriptive statistics that have been used for the study. As expected the measured mean L_{Aeq} and L_{A90} sound levels are within what is expected and predicted for wind turbine sound only at the Makara site i.e. a mean level of L_{Aeq} 25.4 dB and L_{A90} 23.0 dB for final Data Set N. We know for a fact these sound pressure levels are within the expected range for the site from sound level modelling conducted and also the earlier summary of expected sound pressure levels carried out in **Chapter 7** [as shown in **Figures 101 to 105**].

Here we can see that the exercise of getting the data filter correct is crucial i.e. final Data Set N is similar to Data Set M except Data Set N has some additional filtering and no non wind turbine sounds. It is however this additional filtering which allows for accuracy in the collected data. A mean level of L_{Aeq} 25.4 dB and L_{A90} 23.0 dB [2.4 dB] was collected for final Data Set N, compared to Data Set M which has a mean level of L_{Aeq} 38.0 dB and L_{A90} 34.9 dB [3.1 dB]. The mean level difference of the L_{A90} and L_{Aeq} between the two data sets, approx 1 dB [to 1 SF] is therefore worth mentioning in terms of acoustics measurement by any standards, especially in terms of the varying level differences in this study.

The standard deviation is one of several statistical indices of variability used to characterise the 'dispersion' among measures i.e. the standard deviation could be viewed as the average amount by which measured levels differ from the mean [the spread of data around the mean]. The standard deviation data in this survey is based on the measured L_{Aeq} and L_{A90} sound level descriptors.

The sound level difference [L_{Aeq} - L_{A90}] standard deviation for Data Set N is 1.44 dB, compared to Data Set M which was 2.0 dB. However when compared to the sound level difference [L_{Aeq} - L_{A90}] standard deviation for the earlier data sets such as Data Set C [all data during day time] this is over 5 dB [which is very high in acoustic terms]. This illustrates the fact that as expected due to the high level of filtering there is a much higher value for the standard deviation for all data sets [other than the final Data Set N]. This higher standard deviation level represents a sound climate that *fluctuates* significantly [as expected when samples contain both background noise and wind turbine sound samples]. This is opposed to the much lower standard deviation for Data Set N which represents a more stable level of sound [as expected when turbine sound dominates].

In summary as expected a higher level of filtering applied to the data has lead to a lower standard deviation. Less variability in the sampled sound levels due to the absence of background noise equates to a lower sound level difference between the two sound level descriptors. This is expected when the dominant 'steady' sound being sampled is only wind turbine sounds when compared to general environmental sound such as all sound during the day which includes various noise sources which are not generally steady over the sample intervals.

Accuracy of Measurement Results

In statistics and other applied sciences [including acoustics] the term 'accuracy' has a specific meaning.

In terms of the measurement field results the concept of the term 'accuracy' has been used to mean the association between the two measured sound levels descriptor. The study here has used as a starting point a polynomial regression [2^{nd} order] as per the recommendation of the wind turbine standard NZS6808 [NZS6808:1998 Page 16, A1.2.4]. A 2^{nd} order polynomial regression means there are a minimum of three points used to generate the regression line.

In regression, the R^2 coefficient is a statistical measure of how well the regression line approximates the 'real data points'. In this case a measure of the correlation of the regression line about the two measured sound level variables L_{A90} and $L_{Aeq.}$ It is important to note that the R^2 *is not* a direct measure of the relationship or correlation between the measured data, but an approximation of the regression line about the data set.

A perfect relationship or fit of the regression line about the data set would relate to an R^2 value of 1. An R^2 of 1 indicates that the regression line perfectly fits the data while an R^2 closer to 0 means no fit. In general terms an R^2 equal of 0 would mean there is no way to predict the sound level difference between the two sound level descriptors beyond the data set limits collected. One would view an R^2 of 1 or close to it meaning there is a very strong connection in terms of the regression line about the two measured sound pressure levels.

For the purpose of this study an R^2 between 0 and up to R^2 0.2 is viewed as 'low' with many exceptions to the variability between the trend and data. While R^2 0.2 to R^2 0.5 is viewed as 'modest' with quite a few exceptions to the trend in variability between the data. An R^2 of 0.6 upwards would be viewed as a strong trend with less variability between the two variables. In terms of the variability of the data this refers to the spread of data about the regression line.

Data Set M was the data set pre-Data Set N and is similar in filtering however does contain non-wind turbine sound. Data Set M has an R^2 value of 0.9 [when graphing regression line for L_{Aeq} versus L_{A90} sound pressure level]. An R^2 value of 0.9 would be described as having a high level of 'accuracy' or good fit around the regression line with few outliers. Data Set N however for the same data with additional filtering [removing non wind turbine noise] produces a lower R^2 value of 0.6.

As noted above If we simply relied on the descriptive statistics such as the R^2 values this would lead to the assumption that the connection between the two sound level descriptors are stronger than they actually are. As shown the data has a high R^2 for Data Set M however we know this sample includes a high proportion of non wind turbine sounds and hence is not representative of data for wind turbine sound only [the focus of this study]. It can therefore be concluded that the R^2 value is not incorrect for the descriptive statistics and analysis yet the results must be applied so as to not permit false assumptions to be made when assessing only wind turbine sound. If we simply relied on the descriptive statistics without the field observations and analysis we would return what is known as 'false positive' results when looking to review wind turbine sound only.

The analysis here again highlights why [field] observations as part of the study or any scientific experiment are so important. What is key to Data Set N results is that we know the measurement levels are *valid* as the data is from wind turbine sound only and hence is accurate.

Spearman's and Kendall's Rank Correlation Coefficients – A Measure of Association between L_{A90} and L_{Aeq}

In statistics there are various methods to test the correlation between data sets. The study here has up to this point only discussed polynomial regression. A polynomial regression is a straightforward form of linear regression analysis. The polynomial regression and the R^2 values have been calculated to provide a measure of the 'global fit' of the data around the regression line. The R^2 values relate only to the regression line and are therefore not a true or accurate test for the correlation between the valid measured sound level variables L_{A90} and L_{Aeq}. Despite this the linear regression and R^2 values have been used in the study because polynomial models provide a quick and simple form which are well known and computationally easy to use, that is the polynomial regression line has been fitted to a number of the graphs [including in the appendices] to provide a visual tool for the filtering process and analysis i.e. the spread of data and fit of data. Polynomial regression is also the foremost method used in NZS6808 for analysis of data.

In terms of the study the data would be described as linear if every single item is related to its previous and next item, while non-linear is when every item is related to other items in specific ways to reflect general relationships.

As the data in the study is nonlinear the confines of the linear regression analysis must be noted. These limits include the fact that linear regression analysis may provide good fit within the range of data, but will frequently depreciate rapidly outside the min and max range of the data. This makes accurate and precise extrapolation beyond the data set no simple task. Therefore the principal confine for the data set is the fact that the data collected for the study is nonlinear and hence the use of the polynomial model is merely useful up to this point.

Because the data is nonlinear further statistical tests have been applied to measure the actual correlations between the two measured sound level variables. In statistics there are a number of methods which can be applied to test the correlation between two samples. Such tests examine the association between two data sets and are referred to as 'rank correlations' where the relationship between two different sets of data are assessed to measure the correlation.

There are three common rank correlation coefficients readily used in statistics being Goodman and Kruskal's [Gamma Test], Spearman's and Kendall's. These tests are viewed as being 'robust' measures of association between actual variables and are viewed as being more sensitive when compared to linear tests such as the Pearson's Correlation Coefficient which is viewed as an acceptable model for true linear data testing.

The Spearman Rank Correlation Coefficient is a close 'relative' to Pearson's Correlation Coefficient however the Pearson's Correlation Coefficient works based on two parameters; 1] being cardinal numbers (a number used to indicate *magnitude* but not *order*) and 2] a true linear relationship. The Spearman Correlation Coefficient does not rely on a linear relationship of the data set and uses ordinal numbers, that is a number indicating relative position in a sequence or the rank.

One reason rank correlations are viewed as robust for nonlinear data sets is that they use rank as opposed to actual values and hence the method is said to be less sensitive to bias due to the effects of outliers, that is to say outliers get treated as a one-rank difference. As experience has shown with the analysis for the study rank correlations are somewhat computationally tedious. Even with the help of modern computing the calculations and assessment required are complicated and can be time consuming for non-statistical experts. Regardless the rank correlations are computationally superior to polynomial models providing a robust method to test the actual correlation between the two measured sound level variables for nonlinear data sets.

In terms of the study two specific rank correlation methods have been assessed, these are the Kendall tau Rank Correlation Coefficient and Spearman Rank Correlation Coefficient. The assessment is discussed further below.

Kendall's Rank Correlation Coefficient

The Kendall tau Rank Correlation Coefficient tests the correlation between two measured data sets. Kendall's tau is a measure of correlation. Kendall's tau [denoted τ] measures the strength of the relationship between the two variables. Like the Spearman Rank Correlation Coefficient, the Kendall's tau is carried out on the ranks of the data.

The Kendall's tau test provides an output range of $-1 \leq \tau \leq 1$. Where a value of $\tau=1$ is returned, this means a *perfect* positive correlation between the data sets i.e. the two values are exactly the same i.e. $L_{A90} = L_{Aeq.}$ Where a value of $\tau=0$ is returned, this means the data is completely independent i.e. self-determining and unrelated. A value of τ=-1 [minus one] means one variable is the 'reverse' of the other.

The main advantages of using Kendall's tau is the distribution of Kendall's tau has enhanced statistical properties which includes the fact that the interpretation of Kendall's tau in terms of the probabilities of observing the agreeable [concordant] and non agreeable [discordant] pairs is very direct.

An analysis of the Kendall's tau has been undertaken taken for the final Data Set N [n=39]. The analysis was carried out using Microsoft Excel [with add-in statistic package] and validated against the computational web based statistical software model [[100]]. Both assessments returned the exact same value of τ=0.64. A value of τ=0.64 illustrates a strong positive correlation between the two measured sound level variables for the final data set including only wind turbine sound. What this value means in terms of the study is that it confirms there is a strong correlation between the measured data for the L_{A90} and L_{Aeq}.

In the case of our data an increase in sound levels from wind turbine sound only is a function of wind speed increasing at hub height hence a positive τ value would always be expected. If a negative τ value were obtained this would mean the reverse i.e. we would expect sound levels to *decrease* as a function of wind speed increasing, which we know does not occur in real life for wind turbine sound. This is because aerodynamic sound increases with rotor speed such that sound generated by the blades increases with blade speed proportional to this fifth power of the velocity. A negative τ value would imply as wind speeds increase and hence rotor speeds and aerodynamic sound output increase as a function of blade tip speed, sound levels at offsite receiver locations decrease. This cannot occur as a true measure of wind turbine sound only.

Spearman's Rank Correlation Coefficient

A second rank analysis using the same calculation methods and software as above [[100]] has been under taken using the Spearman Rank Correlation Coefficient. This method assesses how well the relationship between two variable can be described using a monotonic function. Monotonic functions are functions that move in only one direction as x increases. In other words the two variables should either increase or decrease in value together.

One main advantage for the Spearman Rank Correlation Coefficient is that it can be used when the data is based on ordinal number and/or when the data is not strictly linear. It provides a robust measure of correlation when measuring the relationship between two variables that *are* related but not linearly.

When a Spearman Rank Correlation Coefficient of 1 is returned it is said that the two variables are monotonically related, even if their relationship is not strictly linear [as is the case of our data set for final Data Set N].

An analysis of the Spearman Rank Correlation Coefficient has been undertaken taken for the final Data Set N [n=39] and has yielded a value of 0.8. A value of 0.8 illustrates a very strong correlation between the two measured sound level variables.

Table 37 below sets out the analysis results for the Spearman Rank Correlation Coefficient [SRCC] and Kendall tau rank Correlation Coefficient [KRCC] for Data Set B [all raw data where n=8,623], Data Set M [n=1,174] and final Data Set N [n=39].

Data Set B has been chosen as it provides a large set of data; however the majority of this data is non wind turbine sound. Similarly Data Set M is selected for the analysis as it too includes non wind turbine sounds but unlike Data Set B has a very high level of filtering being only one filter set away from the final data set. Data Set N is selected as it is the final data set and is wind turbine sound only. The results are as follows in **Table 30**:

	All data	**Data Set M**	**Final Data Set N**
SRCC	0.84	0.94	0.81
KRCC	0.71	0.84	0.64

Table 30: Calculated Spearman Rank Correlation Coefficient [SRCC] and Kendall tau Rank Correlation Coefficient [KRCC] for all data [Data Set B], Data Set M and Data Set N [[100]]

Figure 111 and **Figure 112** illustrate scatter plots of the ranks for Data Sets M and N respectively using Spearman Rank Correlation Coefficient.

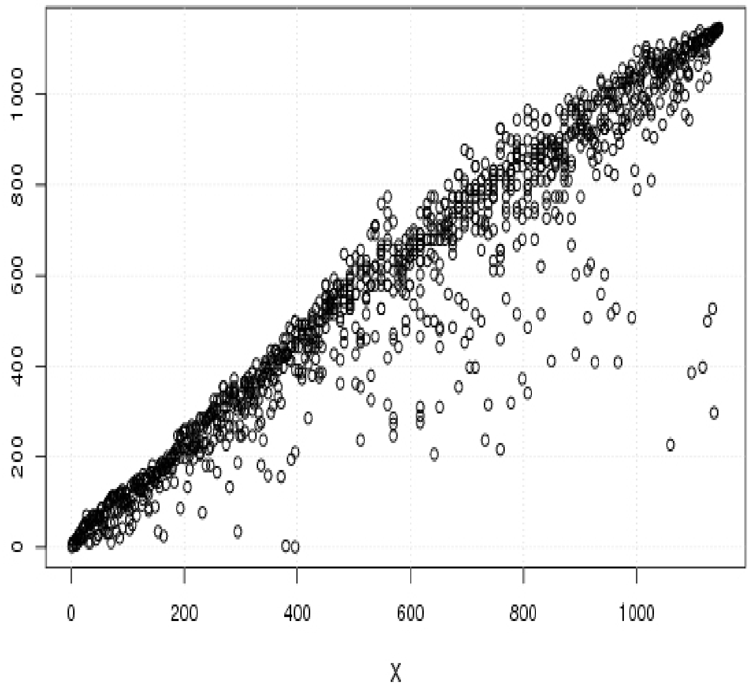


Figure 111: Scatter graph of rank [Data Set M] using Spearman Rank Correlation Coefficient [[100]].

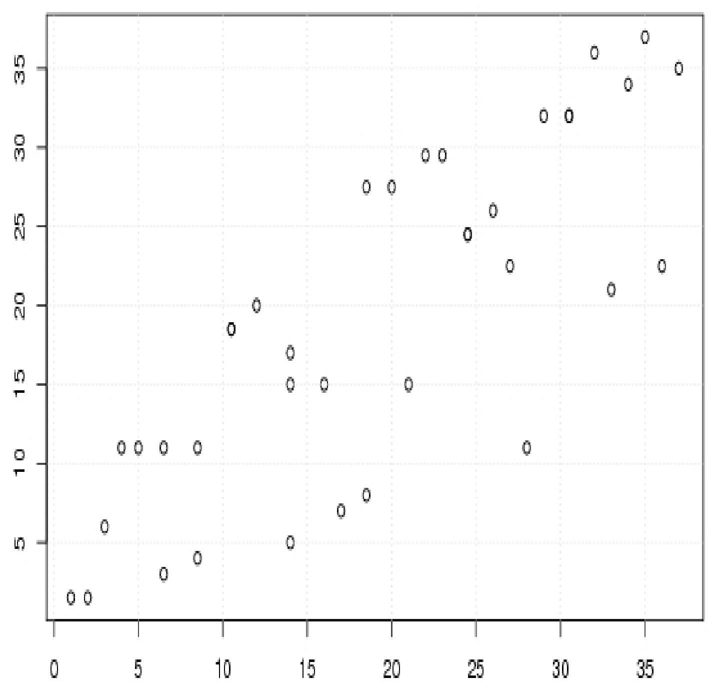


Figure 112: Scatter graph of rank [Data Set N] using Spearman Rank Correlation Coefficient [[100]]

What can be concluded from the data using the Spearman's analysis? Overall [in the case of the study data sets] the interpretations of Kendall's tau and Spearman's Rank Correlation Coefficient are very similar and thus have invariably lead to the same conclusions i.e. a strong positive relationship exists between the two measured sound pressure levels for wind turbine sound only.

In terms of the final Data Set N [which we know is wind turbine sound only] the Spearman Rank Correlation Coefficient was 0.81. This value is higher than the Kendall tau Rank Correlation Coefficient of 0.64 leading to the conclusion that the Spearman Rank Correlation Coefficient provides a more robust analysis in terms of outliers in the data sets.

This is simply due to the fact that although Data Set N has a high level of scatter the Spearman Rank Correlation Coefficient accounts for this in its analysis method, that is to say the Spearman Rank Correlation Coefficient method is less sensitive to bias due to the effects of outliers and hence due to the large spread of the final data less weighing has been provided for outliers. Regardless both methods illustrate a correlation exists between the two sound level variables for the final data set for wind turbine sound only.

As discussed above we know that there is a direct positive relationship between the two sound level descriptors. As discussed at length above Data Set M is closely aligned with Data Set N however If we simply relied on the statistical analysis this would lead to the incorrect assumption that the relationship between the two sound level descriptors are stronger than they actually are for Data Set M in terms of wind turbine sounds only as we know Data Set M contains extraneous noise. That is not to say that there is not a strong association between the two sound level variables for Data Set B and Data Set M but this association does not apply to wind turbine sound only. The rank analysis for all three data sets returns a strong association, however the fact remains only Data Set N is wind turbine sound.

It can therefore be concluded that the analysis again highlights why field observations and filtering as part of the study have been so important as we know the measurement levels for Data Set N only contains wind turbine sound and therefore by performing the rank coefficient analysis this confirms the fact that there is a significant correlation between the actual measured data for the two sound pressure level values for wind turbine sound only. We can also conclude there are strong positive relationships between the two sound level descriptors for all sound which includes unwanted extraneous noise.

Overall the rank analysis validates the statements that there is a strong relationship between the measured sound pressure levels for wind turbine sound only.

Statistical Significance using Spearman's & Kendall's Rank Correlation Coefficients

It is possible to carry out the hypothesis testing using rank analysis coefficients to assess the 'statistical significance' of the data i.e. a statistical significance test [p-value] can be undertaken in deciding whether a correlation exists at all. A statistical significance test [using the p-value] can be used to assess a proposition [null hypothesis] for the two data sets. When the p-value is less than the significance level the null hypothesis is rejected leaving the alternative hypothesis to stand. It is however noted that the p-value is *not* a measure of any correlations or strict association between the two measured sound level variables; it merely provides support in deciding whether an association exists. Hypothesis testing is outside the scope of this study.

Data Sample Size

A large sample size is generally considered to be more favourable than a smaller sample size. This is because a larger sample size theoretically is said to more closely approximate the wider 'population'. This is however a general observation and hypothetically depends upon what is being tested or how a study is designed.

In the case of the study we know the measured sound levels in final Data Set N are from wind turbine sound only. While a larger sample size may be ideal, for a study of this type actual and precise measurement results from wind turbine sound only is deemed to be key to the design of the testing. It is noted that a larger sample size does not necessarily mean more accurate or functional results, that is to say there is no point using the raw data with over 10,000 samples when it contains a high level of extraneous noise.

The study design ensured non-wind turbine noise sources are removed first and foremost so as to isolate wind turbine sound only. Without being able to sample the basic level and character alone can lead to various misinterpretations.

New work is emerging such as that by Bigot [[101]] which leads to the conclusions from actual measurements and statistical analysis that longer term measurement and hence more samples in the order of 20 days or more is a way to minimise measurement uncertainties. This work shows that there are lower values for the standard deviation, which apparently meant more accurate measurements emerged leading to a better understanding of measurement trends. This appears reasonable *if* the measurements are from wind turbine sound only, however from the experience of this study accurate measurements are not directly related to the absolute sample size.

In summary caution must be used in order to infer the actual meaning within the context of the study and observations, especially when attempting to extrapolate data measured on site from wind turbine sound at any distant location or at any other site. The study here provides a number of values, including descriptive statistics which due to various factors such as small pervasive data set spread have produced results which can be at best misleading when taken at face value. Overall a larger data set of wind turbine sound only would be preferred if wind turbine sound only however a larger data set with extraneous noise would not be purposeful to the study question.

Variability and Data Spread in Results as a Function of Wind Turbine Generator Design, Surrounding Environment and Operating Mode

The sound pressure level difference between the L_{A90} and L_{Aeq} results in terms of wind turbine acoustics is a product of the variability in received sound levels as a function of variations in wind turbine operating mode, wind turbine design, wind turbine operating environment and the variability induced by sound propagation effects between source and receiver locations.

To what degree such differences actually occur in practice also depends on the relative temporal variations of the wind turbine generator and the background noise environment at the receiving position. It is therefore clear that acoustic measurement of environmental sound [including from complex situations such as wind farms] is no easy feat.

The acoustic output of a wind turbine generator is complex and depends on various factors such as the turbine design itself, surrounding environment and acoustic parameters pertaining to the acoustic measurement.

Further complexity is added with the ever changing seasons and environment for which wind turbines operate and the environment in which sound is received at distant residential locations. In addition changes in the technology of the wind turbine design and evolution also play a key role in overall acoustic output and hence sound levels received not only as overall level but characteristics of the sound.

There are numerous reasons why the measure of spread of data is important one of the chief reasons is that the measure of spread about the regression line provides an idea of how well the mean represents the data, that is to say that if the spread of values in the data set is large then the mean will not be as representative of the data compared to a spread of data that is small. The reason for this is because a large spread indicates that there may be large differences between the two sound level descriptors which would generally indicate extraneous noise is present compared to a small spread of the data which would generally point to wind turbine sound only or at least wind turbine sound with a lower degree of extraneous noise present.

In terms of the study the spread of data for all the data sets is a function of the filtering and various intervening variables such as the surrounding environment. **Figures 113, 114 and 115** illustrate Data Set B, Data Set M and final Data Set N respectively in terms of regression line for L_{Aeq} versus L_{A90} sound pressure level.

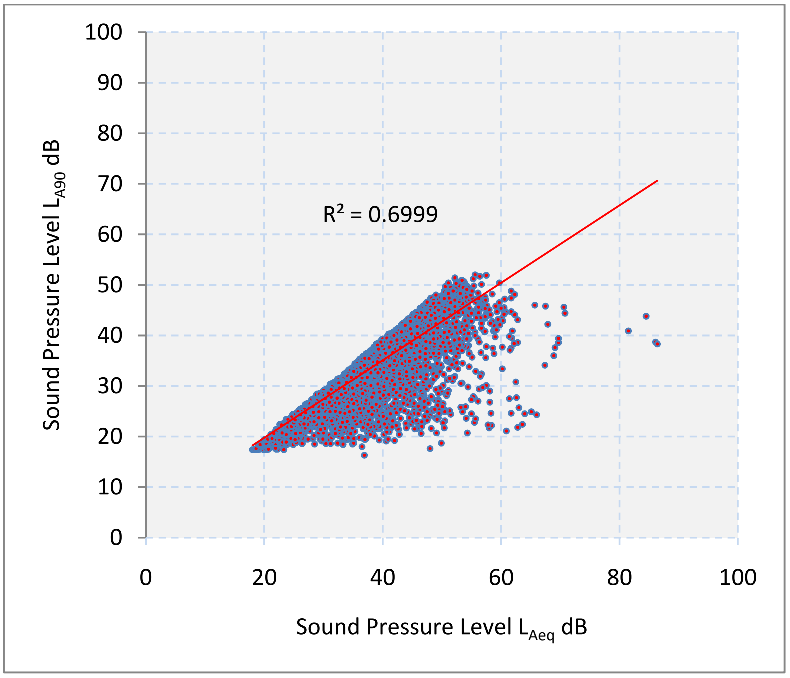


Figure 113: Scatter graph of L_{A90} versus L_{Aeq} for Data Set B.

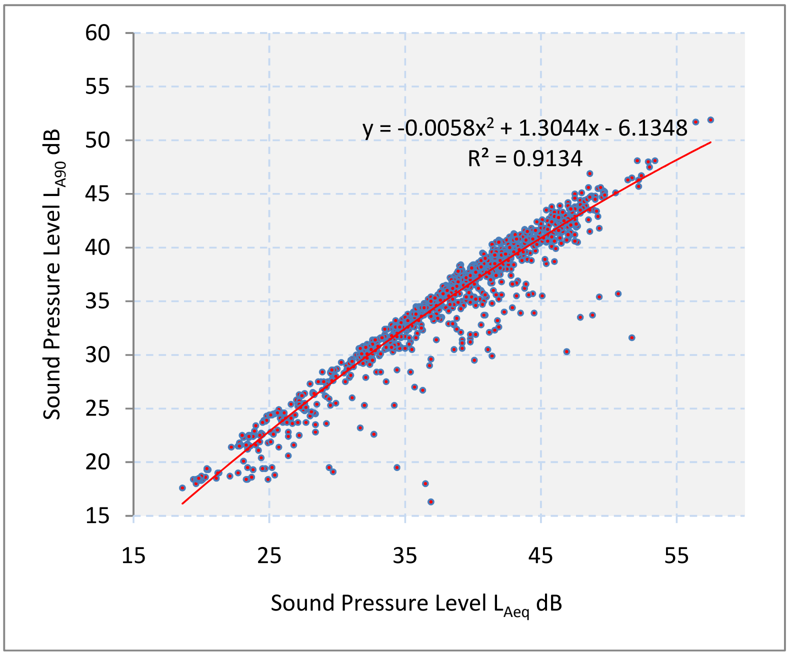


Figure 114: Scatter graph of L_{A90} versus L_{Aeq} for Data Set M.

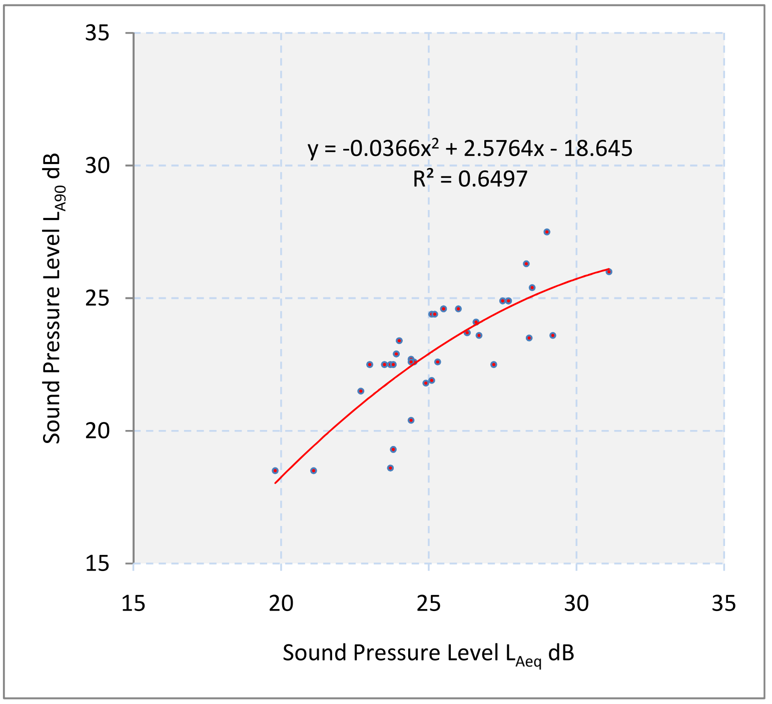


Figure 115: Scatter graph of L_{A90} versus L_{Aeq} for Data Set N.

Figures 116, 117 and 118 illustrate Data Set B, Data Set M and final Data Set N respectively in terms of L_{Aeq} and L_{A90} sound pressure level versus wind speed at hub height

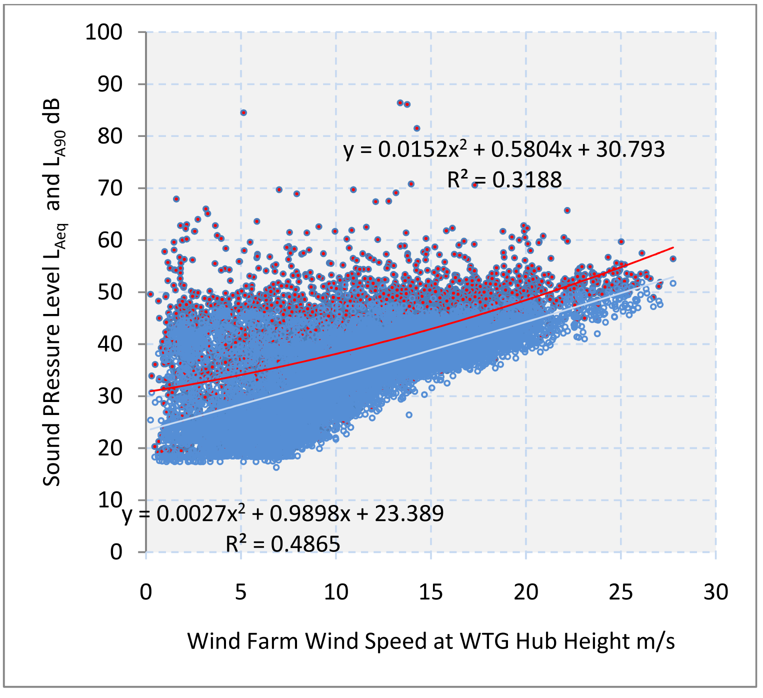


Figure 116: Scatter graph of L_{Aeq} [redline, with red dots] and L_{A90} [blue line with blue dots] versus wind speed at hub height [m/s] for Data Set B

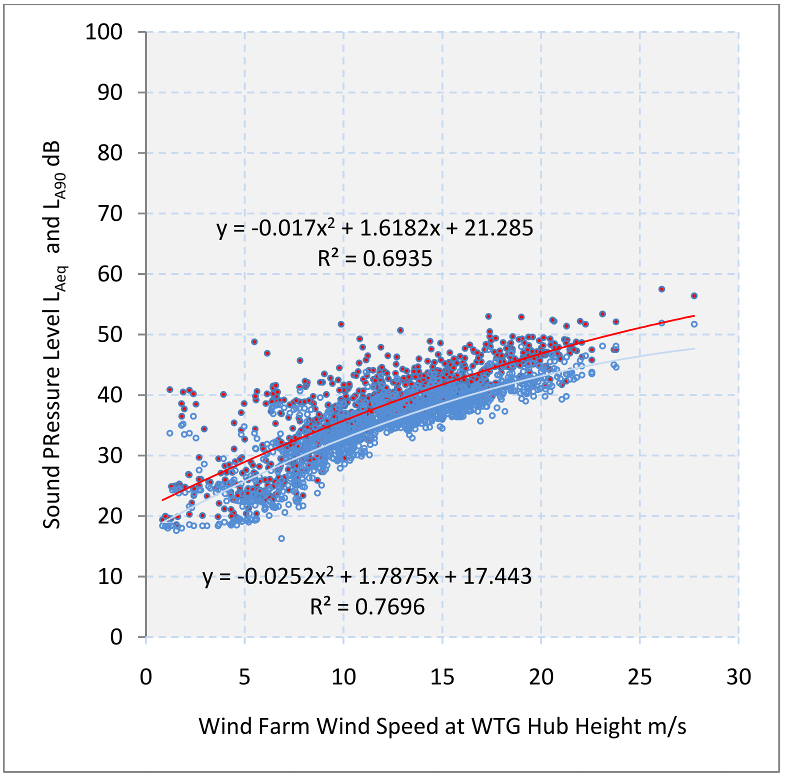


Figure 117: Scatter graph of L_{Aeq} [redline, with red dots] and L_{A90} [black line with blue dots] versus wind speed at hub height [m/s] for Data Set M

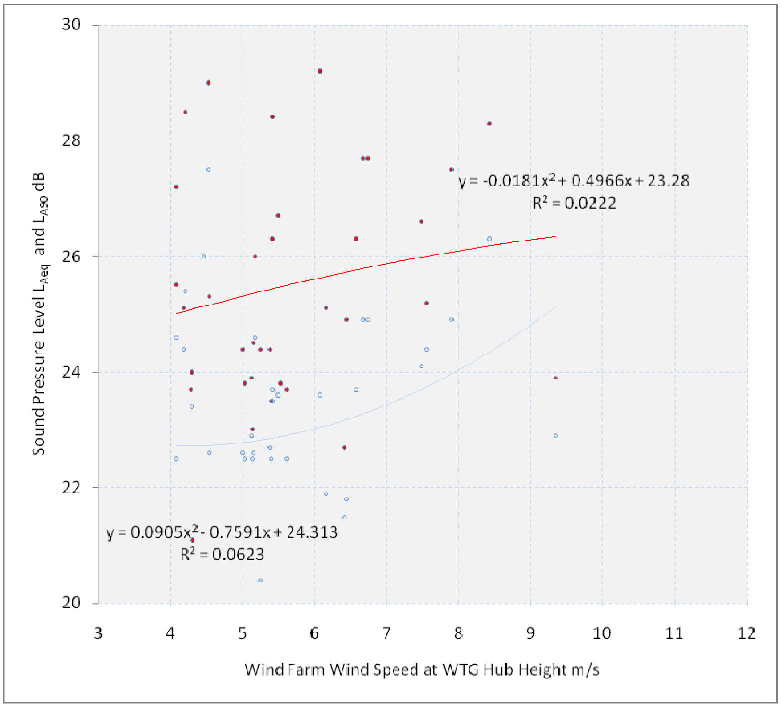


Figure 118: Scatter graph of L_{Aeq} [redline, with red dots] and L_{A90} [black line with blue dots] versus wind speed at hub height [m/s] for Data Set N.

In terms of the data sets shown above in **Figure 116 to 118** one common thread is as wind speeds increase at hub height [and at the 10m mask] the sound pressure levels increase. The general trend is a positive tendency where an increase in x equals an increase in y [a monotonic function]. This aligns well with site observation that is to say as the sound output from a wind turbine generator increases with wind speed so do sound levels increase at the subject site albeit from wind turbine sound or a mixture of wind turbine sound and extraneous noise.

The spread of the data in final Data Set N has the lowest spread around the regression line being approx 5 dB total or approx +/- 2.5 dB above and below the regression line. Data Set B and Data Set M have a much larger spread about the regression line being around 20 dB in total [above and below the line]. The largest outliers are generally at high or low wind speeds.

In regards to spread of data as a function of wind speed it can be seen that due to the filtering process Data Set B and Data Set M have far more outliers than Data Set N at the wind speed extremities that is at low and high wind speeds.

These outliers usually lie in the range outside what wind turbine sound could physically be received at number 403 Makara Road. For example Data Set M has L_{Aeq} levels over 40 dB at wind speeds of around 2 m/s. Data Set M also has L_{A90} and L_{Aeq} sound levels in excess of 50 dB at wind speeds over 25 m/s. Clearly these sound levels are at wind speeds outside operating wind speed range for the wind turbine which means the wind turbine is not turning and hence not producing any sound. Therefore one can conclude with absolute certainty these sound level points on the scatter graphs are not from wind turbine sound alone when outside the operating range of the wind turbine generator. One can also conclude with reasonable certainty that outliers above sound pressure level of 30 dB are also extraneous noise. This consideration is based on the measured, predicted and calculated wind farm sound pressure levels at 403 Makara Road.

As shown below in **Figure 119** wind turbine sound pressure levels have been predicted [based on the prediction methods of NZS 6808:2010]. The top graphic is 2d while the bottom graphic is 3d and shows the complex terrain and contour overlaid. The acoustic prediction shows expected sound pressure levels in terms of L_{Aeq} are less than 30 dB. These predicted sound pressure levels are based on a representative sound power level of L_{wA} 106 dB using a hub height of 67m above local ground level.

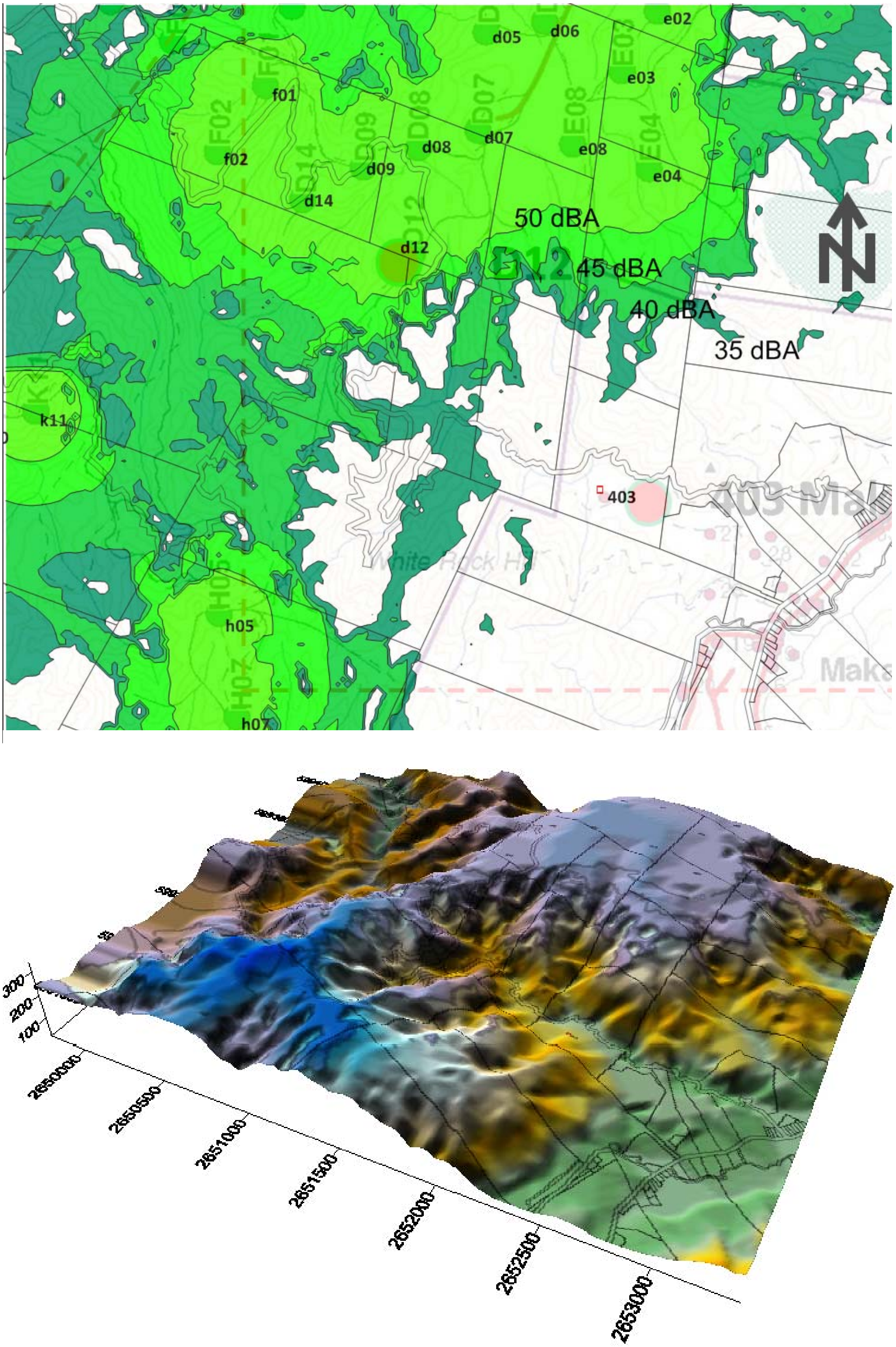


Figure 119: [Top] 2D [Bottom] 3D - Prediction of sound pressure level for 403 Makara Road. Contours of equal sound pressure levels between L_{Aeq} 35 and 50 dB.

Comparison and Analysis of Sound Level Descriptors [L_{A90} and L_{Aeq}]

The following discussion is based around concepts and how these physical parameters may have potentially altered the measured sound pressure levels, noting that in terms of the intervening variables within the study most were unable to be altered.

Given that the key purpose of sound level measurements at the receiving environment is usually to determine compliance with Resource Consent or similar noise limit requirements, the sound level descriptors measured, analysed and reported are important to correctly measure and understand, so are any limitations or pitfalls.

In order to understand the study results it is critical to understand the two sound descriptors which the measured sound pressure levels are based and how the sound level meter processes the measured sound pressure level energy signal. At this point it is key to understand a sound level meter cannot differentiate between sound sources as it only measures the sound levels and then processes these signals to derive the sound level descriptors.

There is debate and discussion around the fact that two different sound descriptors are used in NZS6808, including the fact that descriptors such as L_{A90} should not be used at all. It is not uncommon for lay persons to ask why not just use the same two sound descriptors and be done with it? Some professionals also believe only the L_{Aeq} sound descriptor should be used for wind turbine assessment.

The unit used in NZS6808: 2010 is the A-weighted noise descriptors for L_{A90} and $L_{Aeq.}$ A sound level at any location is never entirely unvarying to some quantity. The L_{Aeq} [which stands for A-weighted equivalent sound level] is defined as the steady [constant] sound level that has the same total acoustic energy as the actual time-varying sound level. Essentially this sound descriptor ensures that <u>all</u> sound sources near and far are taken account of over the entire measurement period and hence the sound level meter acts as a 'sponge' absorbing all sound over the selected measurement period.

Figure 120 illustrates the concept of L_{Aeq} and how mathamatically it accounts for all sound energy during the total measurement sample period regardless of level. What is important with the L_{Aeq} sound descriptor is the sampling period. **Figure 120** shows two sound level events with two very different instantaneous time varying sound traces which have the same total average L_{Aeq} sound level.

The first event [Event 1] is a high level sound event reaching a maximum sound level of 88 dB. Event 1 occurs over a short period of time [approx 13 seconds], with the remainder of time duirng the total 30 second sample time containing no sound energy.

The second event [Event 2] is a much lower sound level event reaching a sound level of no more than 83 dB over a longer period of time [approx 22 seconds], with the remainder of time during the total 30 second sample time containing no sound energy.

In terms of both events the total L_{Aeq} is calculated over the entire measurement period as being 30 seconds for both events, mathematically the sound energy is proportional to 10 raised to the [L/10] power, that is $10^{[L/10]}$.

The graph shows that both "energy" exposures are exactly the same although the time traces are very different. It should be noted that the grey shaded zones in the two samples have equal arithmetic areas. The graphs illustrate that because the two events contain the same exact amount of sound energy for the same sample measurement period of 30 seconds the L_{Aeq} for both events is exactly the same being $L_{Aeq\ [30\ secs]}$ 89 dB [102].

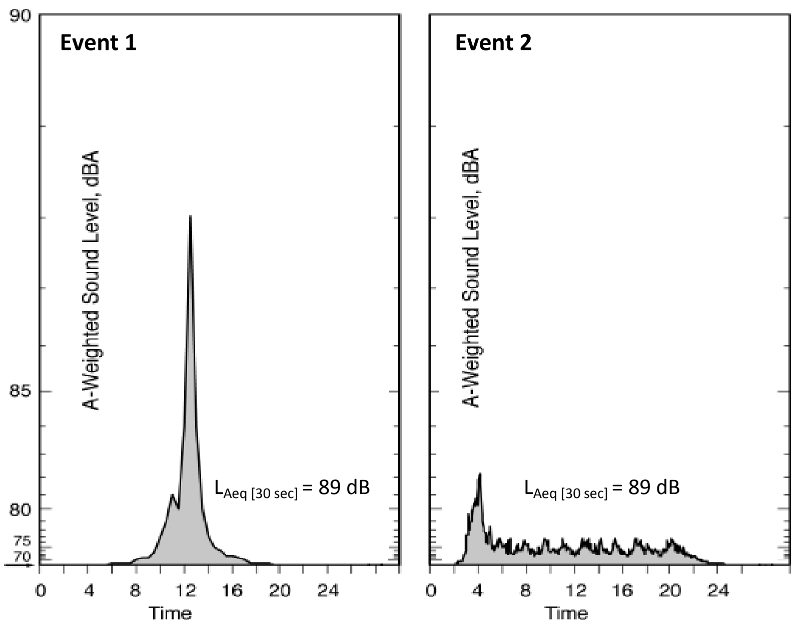


Figure 120: Graph of measured instantaneous time varying sound pressure level for 30 second measurement period with the same L_{Aeq} sound level [102].

The L_{A90} is a statistically defined sound level descriptor, that is to say it only accounts for sound sources that exceed the 90% time interval window. In critical terms the L_{Aeq} is an energy average of all sound and L_{A90} a mean minimum sound descriptor of the sound energy that is exceeded 90% of the selected time interval.

It is noted that the suggested remedy in the latest 2010 wind turbine standard is to treat any difference between the L_{Aeq} and L_{A90} descriptors as the same where direct comparison is needed to be made, that is field monitoring versus expected future sound pressure levels from the developed wind farm. This is compared to the 1998 standard which was to add the 2.5 dB back to the L_{A90} measurement to arrive at the L_{Aeq}.

This adjustment in itself is open to debate as any assumption that implies a blanket statement such as L_{A90} is 2.5 dB below the L_{Aeq} level when comparing the L_{A90} sound descriptor calculated on a *statistical distribution* compared to the L_{Aeq} sound descriptor which is calculated and derived by a totally dissimilar method, should be treated with caution and understanding as to why the standard make such statements for wind turbine sound.

Hence to treat the two sound level descriptors as the same for the purpose of the standard removes any indecision between the two sound level descriptors.

Figure 121 illustrates a time varying graph of common sound descriptors used in environmental measurement including the L_{A90} and L_{Aeq}. The graph is described as a fluctuating sound level graph over time. This graph is an example of instantaneous [un-weighted [dB]]] fluctuating sound of background noise of many sources [grey line].

Section 5.4.5.1 of New Zealand Standard NZS6801: 1991 *Measurement of Environmental Sound* describes fluctuating sound as '*varying randomly over a range of more than 5 dB and having no obvious model tendency during a time interval of interest*'. In terms of the study, fluctuating sound levels would best represent the raw data sets collected at 403 Makara Road which until filtered included both background noise and wind turbine sounds.

Key to the graph in **Figure 121** is noting the overall hierarchy of the sound descriptors for this particular measurement i.e. L_{min}, L_{90}, L_{50}, L_{eq}, L_{10} and L_{max}. These sound descriptors are calculated over the *entire* measurement period from the measured instantaneous sound level [grey line]. Note the overall difference in between L_{A90} and L_{Aeq} for the total measurement period and sample is around 7-8 dB for this general environmental sound.

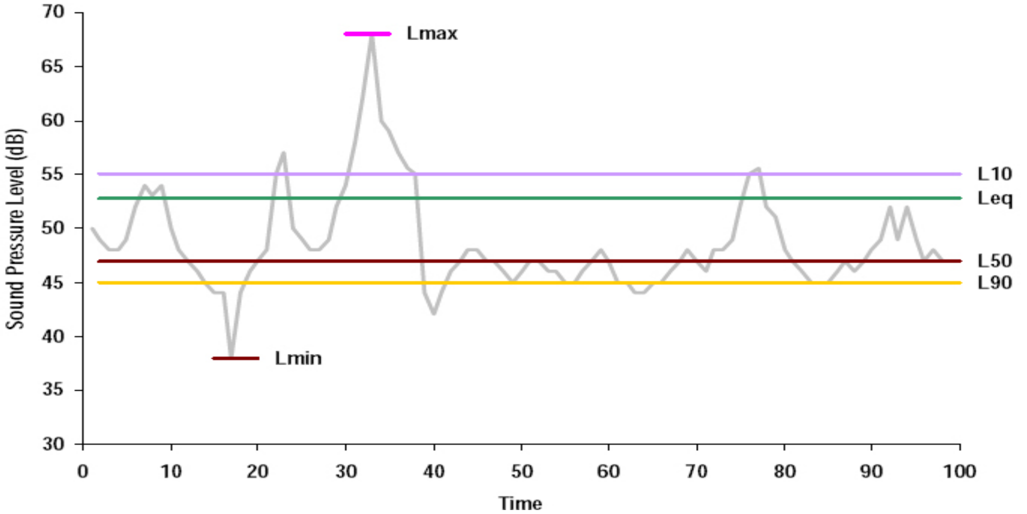


Figure 121: Graph of measured instantaneous time varying sound pressure level and noise descriptor relationships.

Figure 122 illustrates an actual time varying graph of raw data collected during the survey at 403 Makara Road including only the L_{A90} and L_{Aeq}. This graph would also be described as fluctuating sound. Note how the transitory high energy effects the L_{Aeq} levels but not to the same degree with the L_{A90} level.

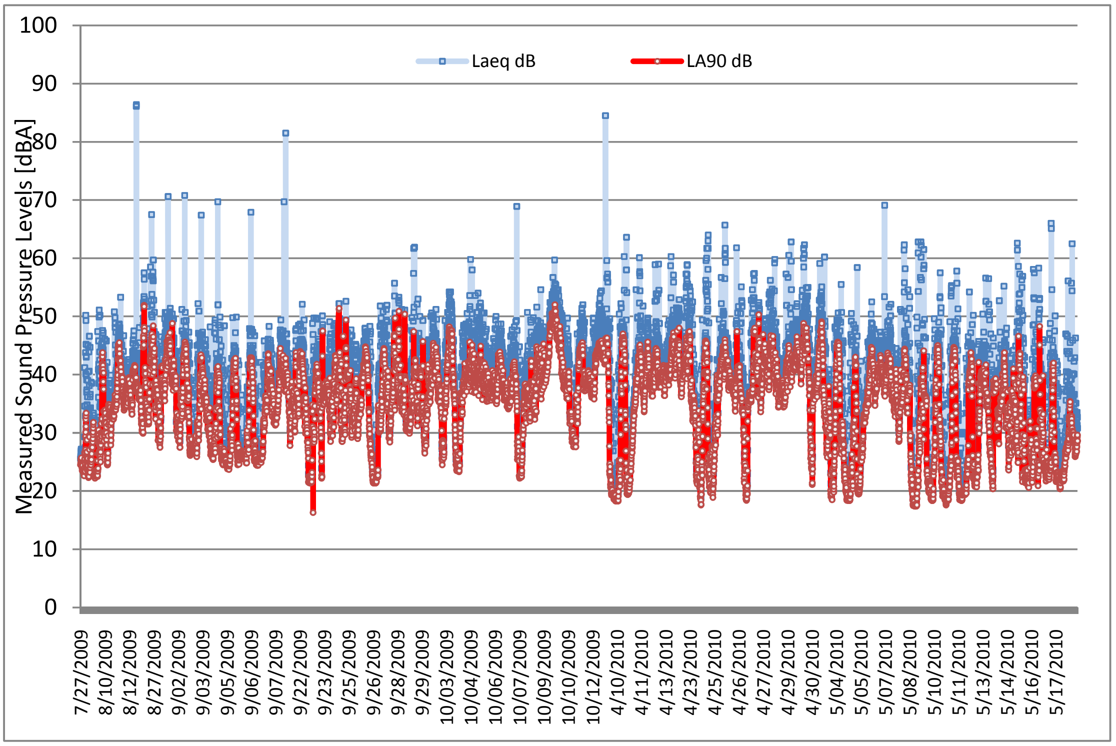


Figure 122: Graph of measured instantaneous time varying sound pressure level from non-filtered raw data [L_{Aeq} and L_{A90}] at 403 Makara Road.

In clear-cut terms the use of L_{A90} over L_{Aeq} for background noise sample before the wind farm is developed is said to be preferred by most experts as transitory high energy effects such as wind noise and wind gust upon the measurement microphone would artificially increase the measured L_{Aeq} [if used] making the background noise levels higher and hence allowing for a higher design limit i.e. potentially allowing wind turbine sound to be greater in situations where the background measured L_{Aeq} is higher from such short term transitory events.

However the use of L_{A90} is preferred over L_{Aeq} for background noise level sampling and setting of wind farm [turbine] design limits as in such cases where high level transitory events occur these are viewed as not being a component of the *natural* background noise [for example an aircraft overfly]. Although the fact that aircraft or other events which occur off site is questionable as to if these event should, or should not be included as part of the sound environment. This is outside the scope of the work here.

The L_{A90} can also be viewed as a measure of the lowest 10% window of the total measurement sample period. In regards to a 10 minute sample period this 10% window equates to the lowest 60 seconds during the 10 minute period of 600 seconds in total. Work has been conducted by Botha [103] and others which illustrates what can be viewed as the bias to a statistical descriptor windows used to measure sound [including wind turbine sound] compared to non statistical descriptor such as the energy average.

The following work as undertaken by Botha [103] illustrates a number of time varying graphs showing an instataneous L_{A95} sound descriptor. The samples illustrate the bias for short term transient events such as an aircraft overfly for example over a 10 minute period. Although the samples are for L_{A95} this effectively illustrates the same bias as an L_{A90} however with the L_{A95} the averaging period over 10 minutes is 30 seconds not 60 seconds as is the case for $L_{A90.}$

Time Varying Graph A

A sound source having *less* than 9 ½ minutes at 50 dB and 30 seconds *or more* at 25 dB. Under this situation the total overall L_{A95} is 25 dB.

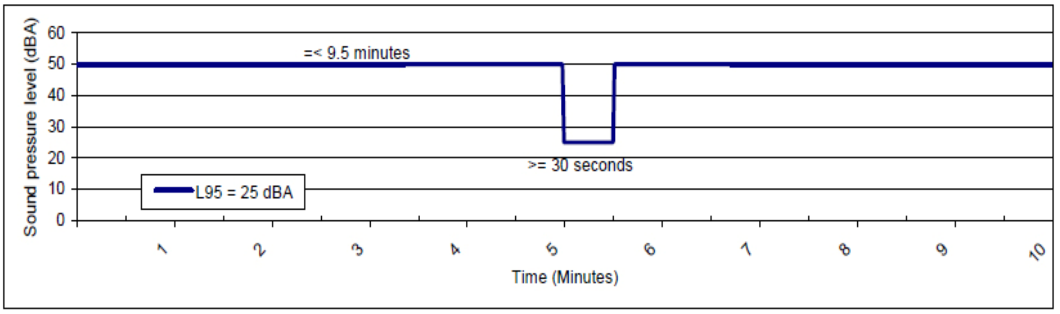


Figure 123: Time varying graph L_{A95} dB Sample A [103].

Time Varying Graph B

A sound source having *more* than 9 ½ minutes at 50 dB and *less than* 30 seconds or more at 25 dB. Under this situation the total L_{A95} is 50 dB.

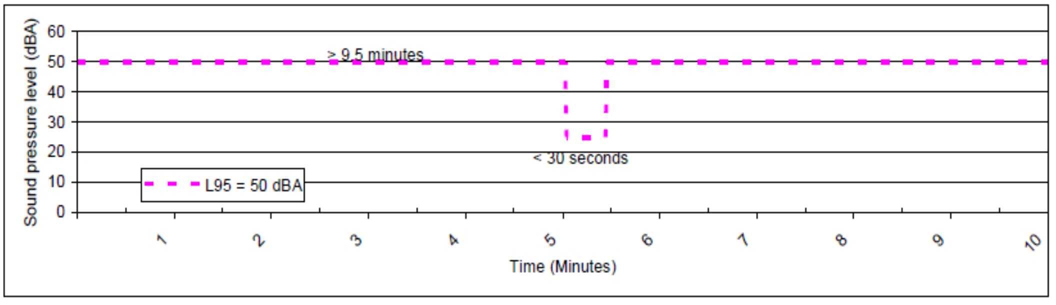


Figure 124: Time varying graph L_{A95} dB Sample B [103].

In terms of the above two graphs the equivelent instantaneous sound levels using the L_{Aeq} sound descriptor i.e. $L_{Aeq\ [10\ minutes]}$ would be greater than L_{Aeq} 49 dB for both cases while the

L_{A95} is 25 Graph A and 50 dB [Graph B]. The sound level difference beween the L_{A95} and L_{Aeq} is therefore approximately 24 dB.

Time Varying Graph C

A sound source having *more than* 30 seconds at 25 dB followed by 30 *second bursts* at 50 dB over the 10 minute period. Under this situation the total L_{A95} is 24 dB.

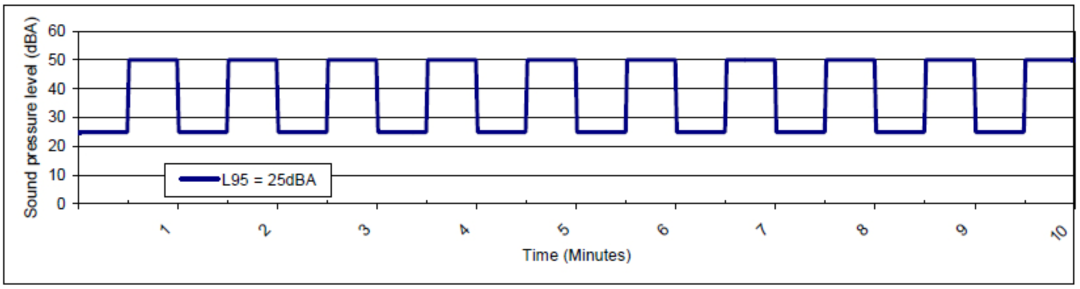


Figure 125: Time varying graph L_{A95} dB Sample C [103].

In terms of the above graph the equivelent instantaneous sound levels using the L_{Aeq} noise descriptor i.e. $L_{Aeq\ [10\ minutes]}$ would be L_{Aeq} 47 dB. The sound level difference beween the L_{A95} and L_{Aeq} is therefore approximately 22 dB.

Time Varying Graph D

A sound source having *six periods of 5 seconds* at 25 dB and the remaining time at 50 dB over the 10 minute period. Under this situation the total L_{A95} is 50 dB. In terms of the equivenlent instantious sound using the L_{Aeq} sound descriptor the $L_{Aeq\ [10\ minutes]}$ would be over L_{Aeq} 49 dB. The sound level difference beween the L_{A95} and L_{Aeq} is therefore approximately 24 dB.

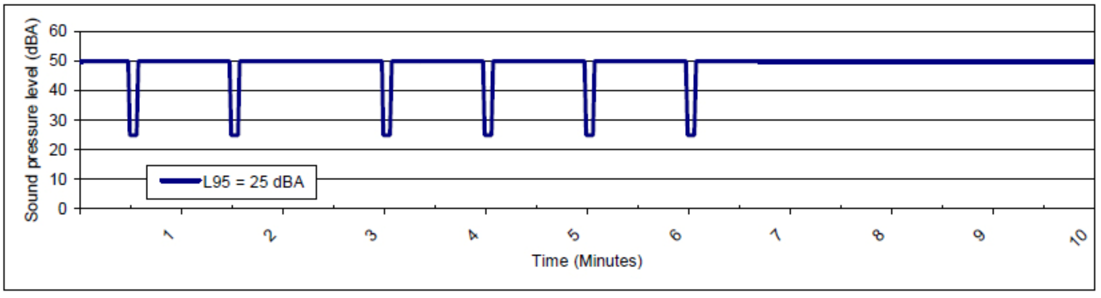


Figure 126: Time varying graph L_{A95} dB Sample D [103].

Time Varying Graph E

A sound source having *a total of 30 seconds* at 25 dB and the *remaining time* at 50 dB over the 10 minute period. Under this situation the total L_{A95} is 25 dB. In terms of the equivenlent instantious sound using the L_{Aeq} sound descriptor the $L_{Aeq\ [10\ minutes]}$ would be over L_{Aeq} 49 dB. The sound level difference beween the L_{A95} and L_{Aeq} is therefore approximately 24 dB.

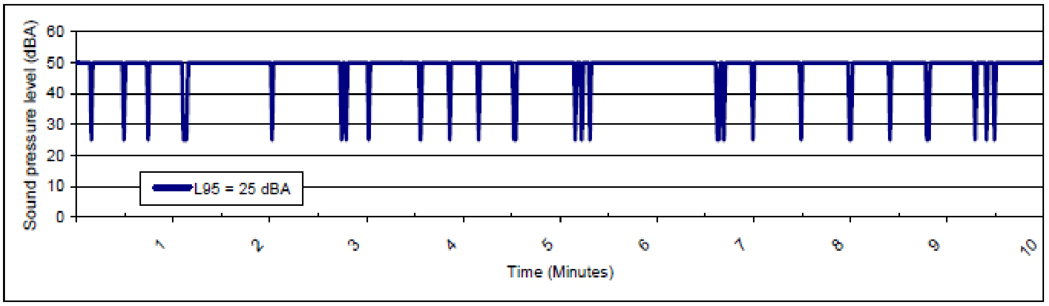


Figure 127: Time varying graph L_{A95} Sample E [103].

As shown in the above analysis by Botha if the L_{Aeq} was used for background noise level monitoring such events could potentially increase the L_{Aeq} and raise the wind farms design levels permitted at dwellings. However if the L_{A90} was used this is considered to be less affected by such short events. Hence using the $L_{A90\ generally}$ removes potential unnatural artificial sound sources and ensures measured background noise levels are not inflated.

Comparison and Analysis of Sound Level Meter Measurement Time Weighting and Sample Interval

Further to the measurement descriptor is the measurement sample time and measurement time weighting. All measurements at both wind farm sites were conducted using a 'Fast' time weighting or response sample time setting which is sampling sound every 125 milliseconds [i.e. 8 samples a second] which is short enough to allow for real time analysis]. A 'Fast' response is common for modern environmental integrating sound level monitoring. In addition to the time weighting is the sample period or measurement duration. In regards to the study at 403 Makara the L_{A90} or L_{Aeq} sound level descriptors were *logged* and *stored* every 10 minutes in duration in line with the requirements of NZS6808. When sampling over the 10 minutes the L_{Aeq} accounts for all sound during the entire 10 minute period [all 600 seconds] while the L_{A90} will only account for sound present for 9 of the 10 minutes [or 540 seconds out of every 600 second sample time]. That is to say the L_{A90} is the value the sound level was above 90% of the 10 minute sample time or the lowest 10% window of the total 10 minutes.

If L_{Aeq} were used with a shorter interval measurement time so as to be short enough to ensure a steady sound level during the sample interval [as experimented with at the R_o measurements location for part of the study] such as a 1 minute L_{Aeq} measurement [in line with IEC-61400-11 used for turbine noise output] this interval or any other shorter time interval would require an anemometer that is capable of providing wind data at the same interval rate. There are issues around shorter sample periods less than the 10 minutes regarding collection of wind data. Noting of course that the 10 minute period used is so to align with wind measurement data [speed, direction] and hence provides the challenge of ensuring it is wind turbine sound being sampled when using a 10 minute measurement period.

As expected measuring sound at 1 to 10 second samples allows for good uncontaminated samples as this short time period generally allows for exclusion of non wind farm noise or removal of non turbine sounds if able to be discernible. Longer sample periods of say 1 to 10 minutes may also allow for the exclusion of non wind turbine noise but longer time internals start to introduce higher probability that wind noise or extraneous noise issues may arise - this is not to say wind noise or gust may not be an issue for shorter periods due to the fact that it would be less problematic to note and remove for example in shorter sampling].

When a statistical descriptor L_{A90} is used the averaging time for each interval is 10 minutes to eliminate effects of contaminating events and outliers. As some studies have shown amplitude modulations present in the noise signal from the turbines themselves, there is a risk that the L_{A90} sound descriptor of even a 10 minute interval with no contaminating events may miss report the noise contribution from amplitude modulations. However when conducting measurements such as in durations of seconds caution must be used as for example a 1 second L_{A90} has no use or meaning compared to a ten minute sample interval. All final samples were at night when background sound is at its lowest and many activities present during the day are not operating. All these samples were also when wind speed levels were very low hence removing extraneous wind noise or noise produced from wind related functions i.e. rustling long grass.

In summary there is always going to be issue with whatever sample period is elected with a shorter sample time generally allowing for cleaner samples however if the samples cannot be related back to wind speed and direction data then the samples are of no use. The fact also remains that shorter L_{Aeq} samples may be acceptable however shorter L_{A90} samples are of limited value. As shown in the study less than two percent of the total samples at 403 Makara contain wind turbine sound over the 10 minute sample periods. That is around 6.5 hours of the sample was from wind turbine sound only for every ten minute sample interval compared to the total larger sample of nearly 1700hrs that is around a quarter of a day from wind turbine sound versus around 70 days total sample time.

Comparison of Sound Level Meter Signal Processing for L_{A90} & L_{Aeq} Sound Level Descriptors

The sound level meter receives the precise identical sound signal when measuring sound sources however the course of action taken by the sound level meter to calculate the L_{A90} and L_{Aeq} descriptors is different. The process is discussed as follows.

The wind turbine generator rotor blades produce vibration disturbance in the air which results in the presence of sound waves. These sound waves propagate through the air being affected by the surrounding environment travelling from the wind turbine generator over a long distance of hundreds of metres until they reach the integrating sound level meter. Once the sound waves are at the sound level meter, the sound level meter transducer [microphone] then 'sensors' the sound and converts the sound wave which is a fluctuating pressure signal into electrical voltages. The sound level meter then processes the electrical signals. Part of the process the signal goes through is to pass through the A-weighting filter providing a response characteristic to the measured sound level as a function of frequency [from 16 Hz to 16 kHz]. The resultant signal is amplified, and the Root Mean Square [RMS] value determined. The RMS is important in sound level measurement because it is directly related to the energy of the sound being measured.

The sound level meter takes the signal and computes, stores and displays a variety of powerful sound level descriptive parameters relating to the measured sound. There are numerous sound level descriptors that can be calculated using the 2260 sound level meter, in our case the L_{A90} and L_{Aeq} are of interest. Although the sound level meter receives and processes the same sound wave produced by the wind turbine generator the resultant signal which is processed calculates the L_{A90} and L_{Aeq} using two different methods.

The L_{Aeq} is a log average. Because the wind turbine generator sound energy fluctuates over a given time the sound level meter samples the entire fluctuating signal over the relative sample duration of 10 minutes and then produces an A-weighted time average sound level which is deemed to be the equivalent steady state sound level that has the same acoustic energy as the actual fluctuating sound. That is if the wind turbine generator produced a constant tone the L_{Aeq} would simply be the same as that constant tone being produced. What is principal to the sound level meter when calculating the L_{Aeq} is that *all* sound energy is integrated over the measurement duration so as to produce a time average sound over the total 10 minute period.

In regards to the L_{A90} the sound level meter does not ultimately take account of all sound energy over the sample duration. This is to say because the L_{A90} is a statistical sound level, the L_{A90} is based on the statistical distribution of A-weighted sound levels measured over the sample duration being a value above 90% of the 10 minute sample time.

Bruel and Kjaer, the producers of the 2260 sound level meter used in the study, state that the L_{A90} level statistics analysis of the signal is carried out in a number of discrete incremental steps. The sound level is sampled over the 10 minute sample duration, the sample is then divided into small sections called classes [such as 1 dB] and every time a sound sample falls within each class, a counter is incremented. A resulting curve is produced which is a percentage of the total number of samples [counters] known as the level distribution [curve] of the sound. The level distribution is then used to create a cumulative distribution [curve] by taking the contents of each class from the top of the measurement range and working downwards, adding the results. This result is a series of percentile levels at which point the sound level meter calculates the L_{A90}. That is to say a value above 90% of the 10 minute sample time. **Figure 128** is an example of the percentile level graph produced from the associated cumulative distribution curve in which you can see that the sound signal was above 40 dB for 10% of the time, above 35 dB for 50% of the time and above 30 dB for 90% of the time.

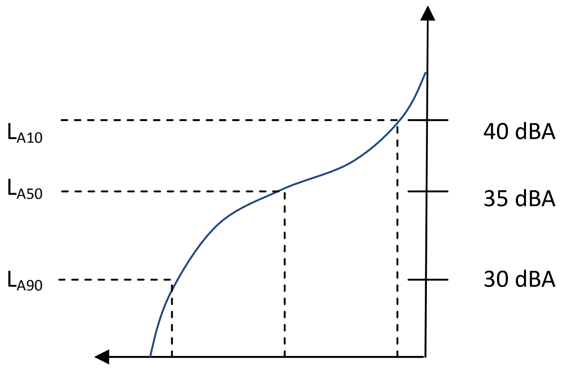


Figure 128: Percentile levels. [[104]].

The 2260 sound level meter has real time analysis sound level distributions output screens and percentile level output screens which are able to be viewed during field measurements from real time signal. These screens are very powerful real time analysis tools. The screens were used in field work for the study, for example when viewing the sound level distribution curve screen a restricted spread in sound levels results from dominate 'steady' wind turbine sound only, compared to environmental noise from non wind turbine sound which generally shows a much larger spread in sound levels due to a high fluctuation in level. Furthermore being able to analysis the percentage of sound within each sound interval is also very powerful. This is because a very high percentage of the total sound signal is present during a restricted interval of sound for constant type sounds or dominate type sound such as wind turbine sound only. This restricted interval is generally within a few dB.

Figure 129 illustrates two schematic graphs for the sound level distribution curve which would be similar to that found on a 2260 sound level meter. The graph on the left hand side is for common environmental sound samples with a wide sound level range between 30 to 50 dB. The graph on the right is from wind turbine sound sampling where the highest percentage of the sound signal is between a range of 28 and 30 dB. It is clear the schematic graph on the right is from a steady sound within a limited range which dominates for the highest percentage of time.

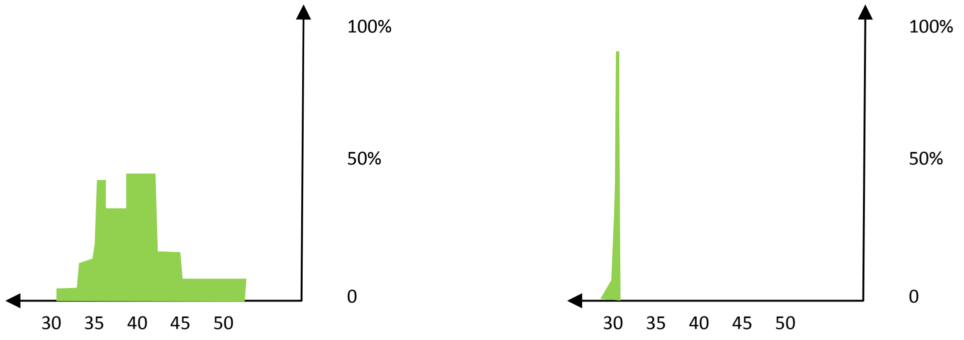


Figure 129: Sound level distribution curves.

Mechanisms and Intervening Variables Relating to Measured Results

In terms of the results received the key research question relates to the difference in the sound descriptors. It can be seen from the results that the relationship between the two sound descriptors is influenced by a number of intervening variables including:

- Noise source;
- Sound transmission path [including weather effects];
- Receiver environment.

The above topics are extremely detailed areas of acoustics in their own right. Many people have spent a life time studying these individual areas and are outside the scope of the study. What is important to note in terms of the study is that the sound level produced at source and finally received at the sound level meter, albeit at a close range or hundreds of meters away is greatly influenced by the sound source, sound propagation across the terrain, intervening weather and receiver environment. Regardless of the overall effects of intervening mechanisms the sound level meter receives the same identical sound signal when measuring sound sources it is how these sources are processed which is important to the study.

Measurement Uncertainty

Every experiment has a level of uncertainty which needs to at the very least be understood and noted in terms of the scientific results. ISO Standard 61400 – Part 11 *Wind turbine generator systems – Acoustic noise measurement techniques* outlines possible values for acoustic measurement uncertainty from wind turbine generator measurements. **Table 31** sets out uncertainly levels as set out in IEC 61400.

Component	Possible typical range	Possible typical standard uncertainty	'Possible worst case' standard uncertainty
Calibration	±0,3 dB	0,2 dB	0,3 dB
Instrument	±0,3 dB	0,2 dB	0,4 dB
Distance	±0,1 dB	0,1 dB	0,2 dB
Impedance	±0,2 dB	0,1 dB	0,3 dB
Turbulence	±0,7 dB	0,4 dB	0,9 dB
Wind speed, measured Wind speed, derived	±1,5 dB ±0,3 dB	0,9 dB b 0,2 dB b	3,3 dB [a] 0,6 dB [a]
Direction	±0,5 dB	0,3 dB	0,6 dB
Background	Equals the applied correction	Example: 0,1 dB	0,8 dB

Table 31: Examples from *IEC 61400-11: Wind Turbine Generator Systems Part 11: Acoustic Noise Measurement Techniques* of possible values of uncertainty components relevant for apparent sound power level measurements [[48]].

As illustrated in **Table 31** there are various uncertainties in the measurement of sound from wind turbine generators. Where possible all best practise has been undertaken to ensure the uncertainties are adequate, that is to say for example ensuring that basic hand held calibration is completed before and after all measurements when possible or ensuring correct set up of the equipment. These are items which can be controlled however uncertainties due to intervening variables such as distance for example or wind speed are outside the control of the study other than to note they exist and if others were to use the results beyond the study scope should careful ensure such uncertainties are accounted for in their analysis.

It is further noted that within each of the discrete categories in **Table 31** there are numerous details sub categories. For example **Table 31** includes 'instrument' uncertainty which among other things also covers the 'noise floor' of the sound level meter. Due to study here conducting sound level measurement of low level wind turbine sound at great distances during night time the 'noise floor' became an important issue to consider with the field work.

In a paper by Halstead and Wood [[105]] a discussion is presented on measurements of environmental sound levels in terms of the measuring equipment and their 'noise floor' [also referred to as 'inherent noise levels']. The concept of the sound level meter's noise floor is commonly branded as the lowest level the instrument can measure down to [this is however only a partially accurate description of the noise floor concept as accuracy also relates to the linear level of the instrument].

Most modern sound level meters will report sound pressure levels down to the inherent noise level being the sum of microphone and electronic noise. Also advised this is the minimum level within the linear operating range, being the range within which an instrument conforms to its 'type' requirements for precision in the case of the study generally Type 1 precision.

Halstead and Wood investigated typical noise floor levels for commonly used sound level measurement instrumentation with a specific focus on the potential effects of the measuring equipment's noise floor on wind farm sound level measurements. In specific the paper recognises that sound level meters with a low noise floor may be required for wind farm measurements in the *field*. This is an accurate and valid statement in terms of the study findings.

In the case of the study here the best practise has been followed by choosing to use a sound level meter which was viewed as appropriate for the particular study circumstance such as ensuring the selected equipment had a low linear operating range [or at least as low as possible for field measuring equipment which has to meet other criteria].

Halstead and Wood accurately tell us that modern sound level meters cover a wide dynamic range, so that in day to day use it is often not necessary to consider the influence of the instrumentation on the result, however when assessing very low sound levels [as is the case for the study here in the context of a rural residential test site] the total noise contribution of the microphone, amplifier and other components can influence the measured sound levels such that results may need to be 'adjusted' or 'corrected' for any possible known errors. In regards to the study here the following data are provided regarding the 2260 sound level meter [the main sound level meter used in the study here]. This is based on the manufacturers [Bruel and Kjaer, Denmark] stated inherent noise levels and minimum linear operating levels are listed in **Table 32.**

Instrument	**Noise Floor Inherent Noise Level [dBA]**	**Minimum Linear Level [dBA]**
B&K 2260 SLM	17 dBA	24 dBA

Table 32: Inherent noise level of 2260 Bruel and Kjaer Sound Level Meter [[105]].

Figure 130 below illustrates a scatter graph from the study which illustrates the two sound level descriptors versus wind speed at hub height. The boxed area illustrates the 'noise floor' of the measurement – note how the 'floor' produces a relative straight line when joining the dots hence the concept of noise 'floor'.

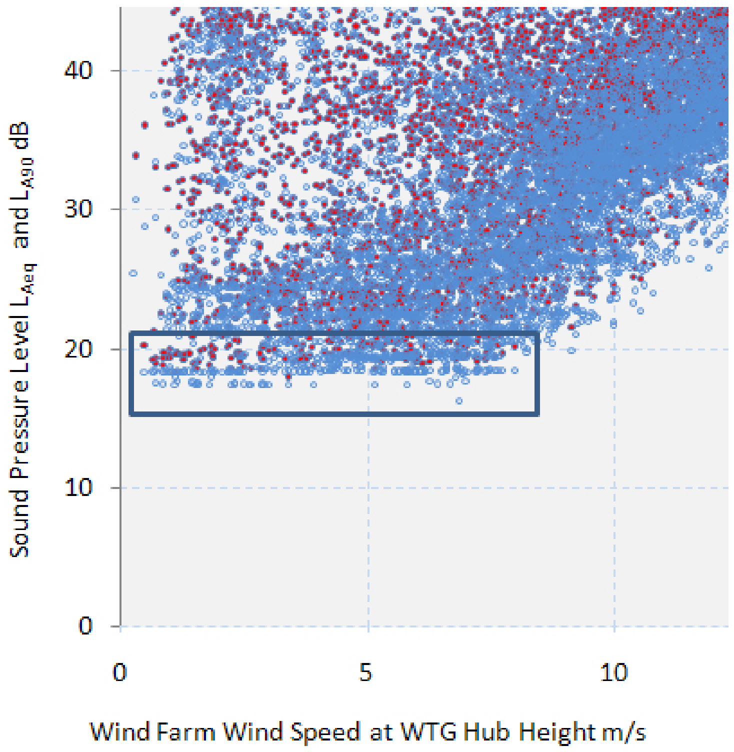


Figure 130: Example of noise floor in study measurements.

Halstead and Wood state a Class 1/Type 1 instrument has a stated level linearity error of less than +/- 1.1 dB this level is typically 7–8 decibels above the inherent noise level. This means that above this level, the contribution of inherent noise is *not* expected to cause the instrument to over-estimate the actual sound levels by an amount exceeding this tolerance. If however the inherent noise of an instrument is precisely known, it is possible to correct measured sound levels below the minimum linear operating range by subtracting, on an energy basis, this self-noise level from the measured value. Halstead and Wood state however the accuracy with which we know this value at a given time limits the accuracy of this correction. As a general rule, this correction can be made when the measured value is at least 3 decibels higher than the inherent noise level.

For the reason set out above correction for instrument noise and any contribution should be made where it is permissible to do so.

In regards to the purposes of this study no such corrections or adjustments have been attempted as this is outside the study scope. It is also the fact that known value at a given time has limited the accuracy of any such correction. Regardless in terms of the assessment here actual background noise levels and wind farm sound levels were very low or in some cases wind farm sound levels lower than what may be measured with the use of Class 1/Type 1 precision grade sound level measurement equipment.

The use of a Class 1/Type 1 sound level meter for the majority of this study represents suitable equipment for environmental noise evaluation which limits error suitable for the purpose of this study.

Recommendations and Further Work

A great deal of work has been undertaken by many people, parties and organisations relating to wind turbine generator sound measurements, assessment and potential health effects. The bulk of this work is however based overseas in Europe where terrain is commonly flat or undulating. What this means is that due to New Zealand's complex terrain one cannot necessarily apply the results from one wind farm to another without knowing all the intervening variables, conditions and uncertainties around the measurements.

This research has the early development stages of providing some basic data around wind turbine sound from field measurements at far field receiver locations. However starting with 11,150 raw samples and ending up with only 39 samples of wind turbine sound has confirmed a number of important issues specific to wind farms in a real world situation.

One key issue learnt from the study is that it is incredibly challenging to capture a large number of wind turbine sound samples on their own and without extraneous data using the methods used here. Such issues like this are important as it's common for wind farm developments to have Resource Consent Conditions which require acoustic monitoring of the wind farm once established and operational so as to ensure compliance is achieved within the predicted design limits.

Based on time frames for the study and samples collected, future work could be based around analysis of larger sample sets. Larger samples of wind turbine sound only would allow for a preferred analysis and larger sample set. Additional work could also include and take account of as many intervening factors as possible in order to allow more understanding of actual measured data and surrounding operating environs. In addition work into current technology such as having robust measuring devices to be able to discriminate between measured background noise and wind turbine sound sources would be beneficial. Such work and research already takes place in the airline industry around airports where aircraft model can be tracked and correlations made regarding noise levels and movements in and out of airports.

The arrival of far field beam forming has allowed an opportunity to analyse noise sources such as wind turbines in the far field with comparatively little effort and high levels of accuracy. A commercial implementation of far field beam forming for noise source localisation was introduced by Christensen and Hald [106]. This technique uses an array of microphones situated throughout a circle on one plane surface. The channel count for such an array being relatively high allows for simultaneous digital acquisition.

Many long term sound monitoring systems and techniques are coming on line such as the remote web based systems which can be remotely accessed and controlled. One such system manufactured by Bruel and Kjaer, Denmark called ‘Pulse’ allows a suite of data including weather and noise. **Figure 131** illustrates a schematic of the pulse system.

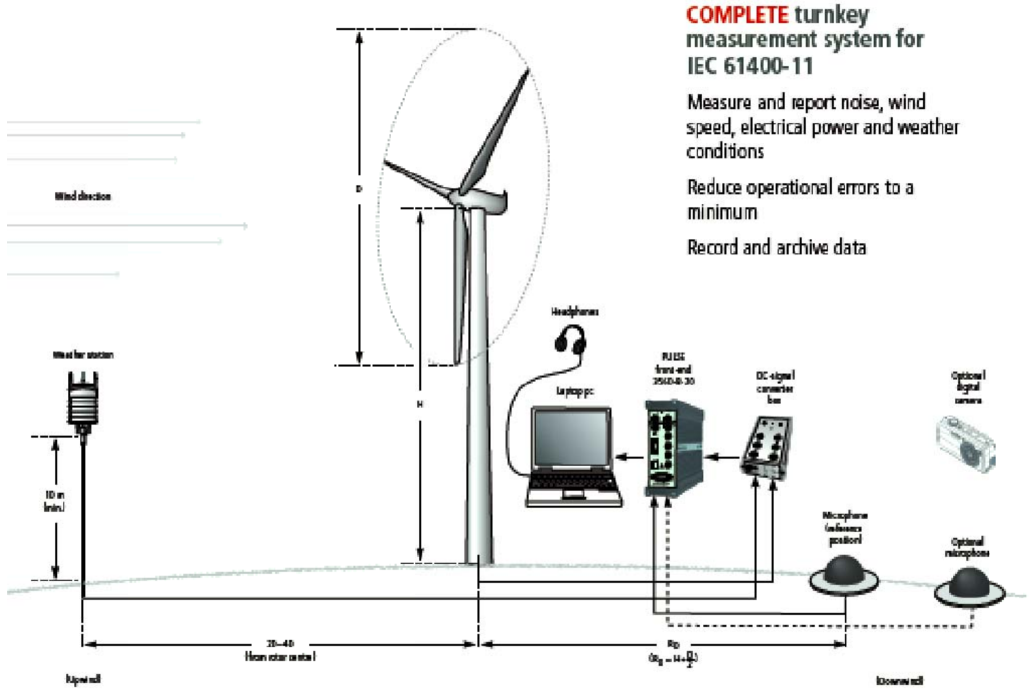


Figure 131: Bruel and Kjaer Pulse System [107].

What is important to note is current systems are incredibly costly and outside the scope of any academic study such as this purely due to cost of equipment alone, however such systems are used for many commercial applications including wind turbine generators and wind farms.

Even with a detailed quantitative analysis of sound levels being available, the best solution for measuring wind turbine sound still relies on the physical separation of background noise levels from wind turbine sound. Simple methods exist such as background noise being measured prior to the wind farm development [or measured once the wind farm is operating with turbines off] and then subtracting this from total wind turbine sound levels once operating. This indicates that long term accurate measurement will be readily available which is positive for further analysis.

Other work such as improved sound level meters with lower noise floors and decreased tolerances will also improve work off site. Overall there are literally hundreds of important issues relating to equipment, measurement methods and techniques which would allow for accurate measurement and hence enhanced assessment of wind turbine sound where people reside.

If time, resources and money were not an issue it would be of immense benefit to be able to conduct further basic studies in the complex terrain testing measurements simultaneously both on and off the wind turbine site at various distances including over 2 km. In some cases such testing could also be validated by a controlled noise source such as a loudspeaker producing a pure tone across a range of frequencies for example. Again if resources were not limited carrying out audio recording and/or manning the measurement locations to record notes would also be beneficial in an 'ideal study'. There are also a number of other simple tests which could be investigated around equipment. One such test would be increasing the height of the sound level meter microphone from the standard 1.2m height used in this study to heights above 4m and above to see if extraneous noise from grass or other extraneous noise sources could be reduced or removed. Although outside the scope of this work, measurement and assessment in terms of the effect on human health and amenity is also greatly needed in the wind industry.

This thesis if time allowed would have also benefited from investigated sound as a function of frequency as opposed to just overall sound levels. In summary being able to control and change as many variables as possible while measuring sound at various locations under various operating conditions represents all possible scenarios for future studies. It appears far greater work both on and off site would be beneficial including work relating to health and amenity issues.

Major Assumptions and Limitations to Body of Work

Key limitations have related to the collection of data from the wind turbine generators themselves, especially on the wind farm at Te Apiti. These limitations are due to the fact that wind turbine generators are a working commercial entity competing with other energy sources and providers and therefore information and data needed to complete this study have needed to be carefully presented.

There has also been the key issue to ensure that data collected both on the wind farm and in the receiving environment has been accurately measured in line with best practice and even more importantly that this data has been correctly interpreted and analysed so far as ensuring a clear distinction between wind turbine sound and other extraneous noise has been made i.e. it is all too common for a lay person to assume when they see a graph or measure sound with a sound level meter that this is purely from the source they are measuring. To this end the author has taken much care to try and ensure full details are provided to the method of study and interpretation. Including the fact that the study is

based on a very finite time frame based around the specific requirements for a masters level thesis and nothing else.
It is therefore critical that any person reviewing the work ensures they have read the thesis in its *entirety* and studies all the data sets, so that they understand what each and every graph and piece of data presented actually represents within the context of the study.

There have been various assumptions made in this work; these assumptions are typically in relation to field work and the operation of the turbines. Such assumptions are detailed above in the thesis. In terms of limitations these too are detailed in the body of the thesis and should be read within the context of the work.

Lindsay Hannah
December 2011

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Appendix A

Introduction

This appendix contains detailed information on wind energy conversion and the science of wind power from wind turbine generators in relation to wind turbine acoustics.

Sources of Wind

The origin of wind is a complex science. The movement of air masses in the atmosphere is perceived as wind and has various causes. Wind energy utilisation is an indirect form of solar energy heating the earth. Wind is a result of the movement of atmospheric air. Wind comes from the fact that the regions around the equator, at 0^o latitude, are unevenly headed more by the sun than by the poles [which receive less energy from the sun]. Thus the hot air from the tropical regions rise and moves in the upper atmosphere toward the poles, while cool surface winds from the poles replace the tropical airs.

These winds are also affected by the earth's rotation about its own axis and the sun. The cooler air from the poles twist toward the west because of its own inertia and the warm air from the equator tends to twist toward the west because of its inertia. The result here is a counter-clockwise circulation of air streams about low pressure regions in the northern hemisphere and clock wise circulation in the southern hemisphere [1]. This is known as the 'Coriolis Effect' [a force which deflects the air mass]. The same thing happens in smaller scale Highs and Lows. Instead of blowing straight out from a high the winds spirals outwards clockwise in the northern hemisphere and anticlockwise in the southern hemisphere [1].

Local wind systems are created by adjacent areas being unevenly heated by the sun. During the day as the hill, terrain or mountain slopes absorb sunshine the air directly in contact with them starts to rise as it becomes warmer, and therefore less dense and lighter than the valley air. Cooler air from the valley below rushes in to replace it, creating a breeze blowing up the slope.

At night the situation is reversed, with no sun to warm the air, cooling mountain slopes causes the increasing dense and heavier air above to "slides" down into the valley producing a breeze in the opposite direction. **Figure A1** shows a schematic of the Coriolis Force.

Coriolis Force

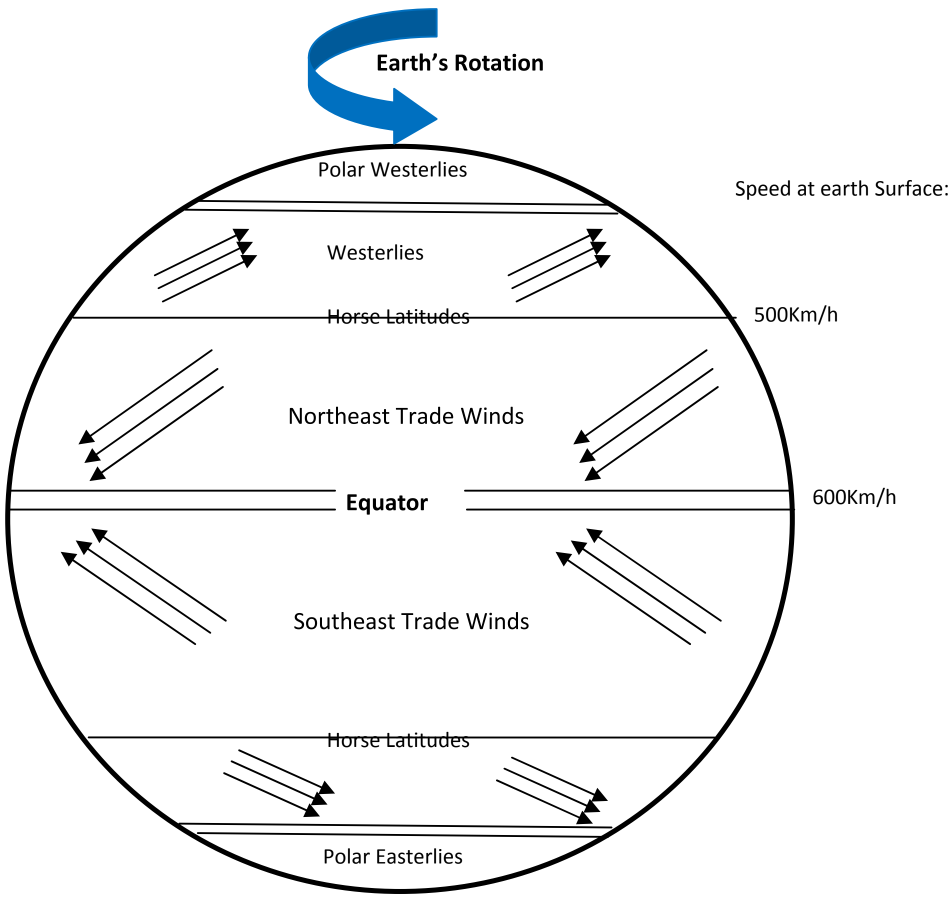

Figure A1: Coriolis Force [2].

In one of the simplest models for the mechanics of the atmosphere's wind motion, four atmospheric forces must be considered. These include pressure forces, the Coriolis Force [caused by the rotation of the Earth], inertial forces [due to large-scale circular motion] and frictional forces at the Earth's surface. The pressure force on the air [per unit mass] F_p is given by [3]:

$$\mathbf{F_p} = \frac{-1}{\rho}\frac{\partial p}{\partial n} \qquad \text{[Eq A1]}$$

Where:

ρ is the density of the air
n is the direction normal to lines of constant pressure

Where *p* is the density of the air, and n is the direction normal to lines of constant pressure. Also *op/on* is defined as the pressure gradient normal to lines of constant pressure [or isobars]. The Coriolis Force [per unit mass], F_c, a fictitious force caused by measurements with respect to a rotating reference frame [the earth] is expressed as [3]:

$$\mathbf{F_c = fU} \qquad \text{[Eq A2]}$$

Where:

U is the wind speed

f is the Coriolis parameter $[f = 2\omega \sin[\phi]]$.

ϕ represents the latitude and ω the angular rotation of the earth.

Thus based on the above formula the magnitude of the Coriolis Force depends on the wind speed and latitude. The direction of the Coriolis Force is perpendicular to the direction of motion of the air. The results of these two forces, called the geotropic wind, tends to be parallel to isobars [[3]]. **Figure A2** illustrates the concept of the geotropic wind and related wind forces.

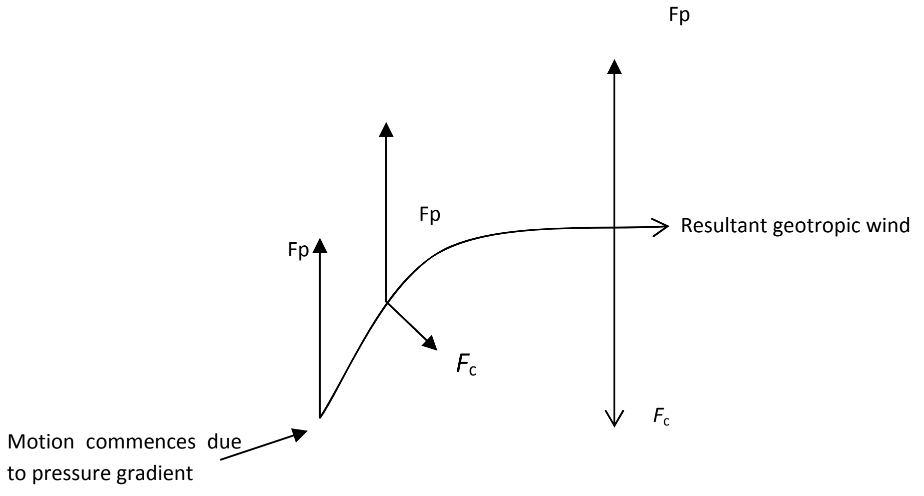

Figure A2: Illustration of the geotropic wind, F_p, pressure force on the air, F_p, Coriolis Force [[3]].

Solar heating affects land and bodies of water differently. Air over land warms and cools faster than over the sea. These temperature contrasts generate offshore breezes and onshore sea breezes.

Coastal regions [such as Makara [West Wind] Wind Farm] adjacent oceans have their own local wind systems. When moving air encounters mountains or other such barriers, it can do only one of two things. First it can flow around them and through the gaps between them, when funnelled into deep narrow valley airflow will speed up and cause the wind to blow from a particular direction. However in most cases the wind does not simply move around a barrier but goes up and over it. Conditions may then be right for what is known as the *Foehn Effect*. Although its impact will depend upon local weather conditions and whether the topography involves gentle slopes, steep hillside or mountains, these variable phenomena are often responsible for small scale weather patterns known as *microclimates*.

Most of the energy stored in these wind movements can be found at high altitudes where continuous wind speeds of over 160 km/h occur. Eventually, the wind energy is converted through friction into diffuse heat throughout the Earth's surface and the atmosphere.

Katabatic Winds are when the sun goes down; the air on top of the mountain, being at a greater height is cooler than the air at the bottom. Thus, on becoming denser and heavier, it flows down the mountain side into the valley; this flow is known as a Katabatic Wind.

Anabatic Winds occur in the morning, when the sun rises, the valley will warm more quickly than the mountain top. This warmer air, being less dense, will begin to rise up the slopes; this air flow is known as an A*nabatic Wind.* **Figure A3** below illustrates a schematic of the Katabatic and Anabatic Winds.

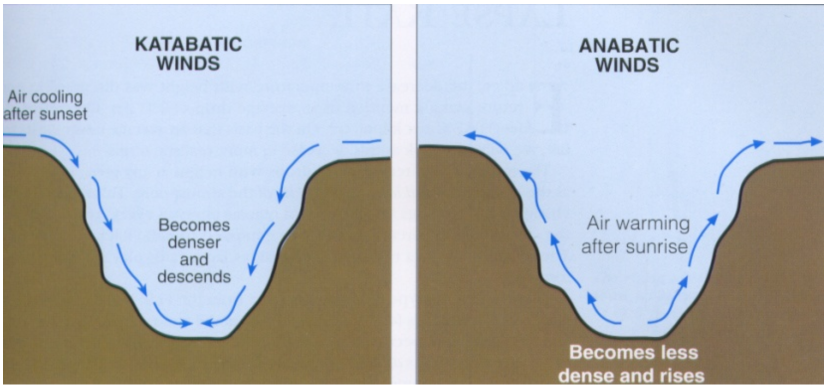

Figure A3: Schematic of the Katabatic and Anabatic winds [4].

Apart for global and local movement of air in the atmosphere wind is also influenced by small scale topographic situations for example mountain slopes as shown above. At greater altitudes the air moves along lines of equal pressure [isobars], this movement at altitudes above around 600m is called geotropic wind and this air flow can be considered free of the earth's surface influence. At lower altitudes the influence of the earth's surface can be felt. This part of the atmosphere is known as the boundary layer, the factors which influence this related to strength of the geotropic wind, surface roughness, Coriolis effects and thermal effects [being stable, unstable and neutral stratification].

Wind Scales

Local terrain conditions impact the local meteorology and thereby the resulting sound levels. In regards to local terrain conditions it is these conditions that dictate the wind profiles which produce electricity. Generally there are variations in wind scapes which include 'microscale' being a time scale of a few seconds to minutes generally only affecting individual turbines on the wind farm site.

The wind at this scale is chiefly turbulent and irregular and would affect the individual sitting of individual turbines on site viewed as a time scale in seconds or minutes. It is not uncommon to view several turbines side by side on the same wind farm site all having varying rotational speeds and times due to the varying microscale of the site.

A 'mesoscale' is viewed as a time scale of a few hours and includes the wind environment outside the wind farm. At the mesoscale scale modelling is used to forecast wind variations such as weather fronts and the like used for scheduling the wind resource for generation purposes.

The ultimate scale is the largest scale being the seasonal scale, which has a time frame of weeks and months. At this scale entire areas such as large areas of New Zealand become affected.

Wind Turbine Generator Available Wind Power

Atmospheric motions carry in both time [seconds to months] and space. **Figure A** below illustrates the time and space variations of atmospheric motion applied to wind energy development. Space variations are usually dependent on height above the ground and global and local geographical conditions. As illustrated in **Figure A4** one can determine the mass flow of air dm/dt, through a rotor disk or area *A*.

From the continuity equation of fluid mechanics the mass flow rate is a function of air density, *p*, and air velocity [assumed to be uniform], *U* and is given by [3]: $d_m / d_t = p\,AU$ [3].

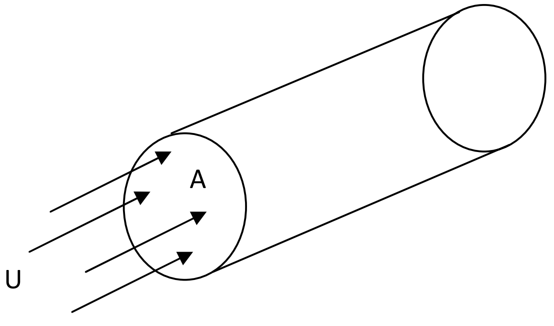

Figure A4: Flow of air though a rotor disk, *A* area *U* wind velocity [3].

The actual power production potential of a wind turbine must take into account the fluid mechanics of the flow passing through power producing rotor, and the aerodynamics and the efficiency of the rotor/generator combination. In practice, a maximum of about 45% of the available wind energy is harvested by the best modern horizontal axis wind turbine generators.

Table A1 shows the power available from steady winds illustrating that the wind velocity is an important parameter which has significantly influences on the power per unit area available from the wind turbine generator [3].

Wind Speed [m/s]	Power/Area [W/m^2]
0	0
5	80
10	610
15	2070
20	4900
25	9560
30	16550

Table A1: Power per unit area available from steady wind [air density = 1.225 kg/m3] [3].

Power Density Function

For the purpose of wind turbine generator design the wind vector is considered to be composed of a steady wind plus fluctuations about the steady wind. Both steady wind and fluctuating winds must be considered in wind turbine design, with the power and energy obtained from wind based only around steady wind speed.

Therefore based on this theory the power available in the wind varies with the cube of the wind speed. A common unit of measurement is the wind power density or the power per unit of area normal to the wind direction from the wind is blowing [5]:

$$\boldsymbol{P}\mathbf{w} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\varrho} \cdot \boldsymbol{\upsilon}_{\mathbf{W}}^{\mathbf{3}} \quad [\mathbf{W/m^2}] \qquad \text{[Eq A3]}$$

Where:

ϱ = air density at standard atmosphere [kg/m^3]

υ_{W} = wind velocity m/s

In relation to annual wind frequency distribution this can be obtained by:

$$\overline{\boldsymbol{P}}\mathbf{w} = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\varrho} \cdot \boldsymbol{\upsilon}_{\mathbf{W}}^{\mathbf{3}} \;\; \boldsymbol{f}[\boldsymbol{\upsilon}_{\mathrm{W}}] \qquad \text{[Eq A4]}$$

Where:

f [υw] is the wind frequency distribution a Weibull function.

Mean annual wind speed is usually not enough information to enable precise energy calculation information on frequency of individual wind speeds is also required. Such frequency from annual wind can be statistically expected.

The frequency distribution of the annual wind speeds can be derived from data measured at a given elevation. The mean values for ten minutes [being the time period used for wind turbine generator assessment] are commonly evaluated over at least one year and are then compiled in defined wind speed or bin classes.

To obtain reliable statistic for the site longer terms periods of several years are required, frequency distribution of annual wind speeds are generally specified as relative frequency distribution or cumulative frequency.

In practice the problem is frequently that insufficient data about the frequency distribution of the wind speeds at a particular location are available, in such a case there is no alternative but to either undertake actual field measurements or use a mathematical approximation for the distribution curve, a Weibull Function will provide an approximate[5].

The Weibull function is defined as

$$\boldsymbol{\Phi} = \mathbf{1} - \mathbf{e}^{-\left[\frac{v_w}{A}\right]^k} \qquad \text{[Eq A5]}$$

Where:

Φ = distribution function
e = logarithmic base [normally the natural log, $e = 2.781$]
A = scaling factor
k = form parameter

The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface. The Weibull distribution may thus vary, both in its shape, and in its mean value. If the shape parameter is exactly 2 [k=2] the distribution is known as a Rayleigh Distribution. Wind turbine manufacturers often give standard performance figures for their wind turbine generators using the Rayleigh Distribution [6].

Wind Shear and the Increase of Wind Speed with Height

Wind shear may be described as the rate at which wind velocity changes from point to point in a given direction. The shear can be speed shear [where speed changes between the two points, but not direction], direction shear [where direction changes between the two points, but not speed] or a combination of the two.

Figure A5 shows you how wind speeds vary in roughness class 2 [agricultural land with some houses and sheltering hedgerows with some 500m intervals], if it is assumed that the wind is blowing at 10m/s at a height of 100 metres. The fact that the wind profile is twisted towards a lower speed as we move closer to ground level is related to wind shear. Wind shear is important when designing wind turbines. Wind developers seek to avoid sites with features that might significantly slow down the wind or increase its turbulence. The impact of any obstacle will be determined by its height, its width and its porosity to the wind.

Obstacles can be natural, ranging from dense forests to scattered trees, or manmade such as windbreaks or buildings. Such artificial and natural structures can not only slow the wind down but they can also induce turbulence. 'Surface roughness' is a key factor to consider. Rougher surfaces slow down the wind and introduce turbulence into the air flow.

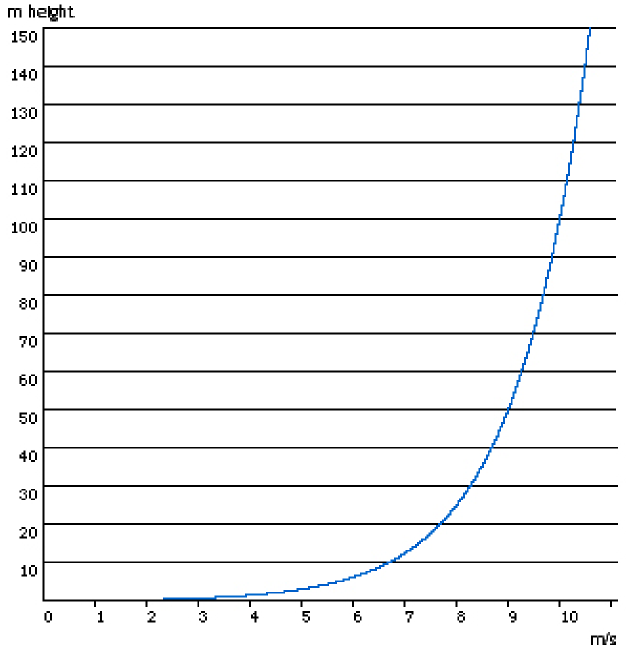

Figure A5: Wind Shear for wind speeds vary in roughness class 2 [6].

The conventional method for describing the increase in wind speed with height is given by:

$$\bar{\upsilon}_H = \bar{\upsilon}_{ref} \cdot \frac{\ln\frac{H}{z_0}}{\ln\frac{H_{ref}}{z_0}} \qquad \text{[Eq A6]}$$

Where:

$\bar{\upsilon}_H$ = mean wind velocity at elevation H [m/s]

$\bar{\upsilon}_{ref}$ = mean wind speed at reference elevation H_{ref} [m/s]

H = height [m]

H_{ref} = reference elevation [measuring elevation] [m]

ln = natural logarithm [base e = 2.7183]

The wind turbine generator source sound power level is determined by a recognised test methodology given in IEC 61400-11 - Wind Turbine Generator Systems Part 11, Acoustic Noise Measurement Techniques which results in sound power levels being provided for a range of 10m height wind speeds, usually from 6 m/s up to rated power, normally around 10 m/s.

The wind speed is given for 10 m height winds speeds, irrespective of the height of the turbine, such that the higher sound levels generated by a taller wind turbine generator, as a result of it experiencing higher wind speeds [wind speed increasing with height] will be reflected in its sound output specification.

Some manufacturers will, however, provide *warranted* sound power levels for the hub height of the wind turbine generator being supplied and this is the preferred approach to sound prediction and assessment. The sound pressure level is plotted versus the wind speed and the reference sound power level is determined. According to current measurement standards which either require or recommend [depending upon the test methods] the wind speed can be measured in front of the turbine at a reference height of 10 m.

For acoustic purposes prediction of the wind speed at hub height is based on the wind speed V_{ref} at the reference height for wind speed measurements [H_{ref} = 10m], extrapolated to a wind speed V_h at height h with the well known and widely used formula for the logarithmic wind profile. Research has shown however that for complex terrain such as in New Zealand and under other conditions there are potential issues

Wind Speed and Energy Variation with Elevation

Wind speed varies with elevation above sea level at a rate of approx 7 % per 100 m. The more elevated the site the higher the wind speed and hence why New Zealand with a high elevation with undulating terrain and position relating to latitude is a good area for wind resource. Wind speeds at 900 m elevation will therefore be approximately 80% greater than those at sea level. As an example, a 900 m wind speed of 7.0 m/s is equivalent to a sea level wind speed of about 3.8 m/s and while the wind speed is 80% higher, the energy output is almost 400% greater.

While wind speeds increase with elevation, the density of air decreases. Site elevation causes a decrease in air density which results in a reduction in energy. However, this energy reduction is generally very small; for example, an increase of 900m in elevation results in about a 4% reduction in energy which would be attributable to the lower air density. In summary, the energy yield from a wind turbine is therefore considerably more at elevated sites compared to ‘flat sites’ [[7]].

Roughness Classes and Roughness Lengths

Roughness of the terrain is referred to as ‘roughness classes’ or ‘roughness lengths’. A high Roughness Class of 3 to 4 refers to landscapes with many trees and buildings, while a sea surface is in Roughness Class 0. The term roughness length is really the distance above ground level where the wind speed theoretically should be zero [6].

The International Standard IEC 61400-11: Wind Turbine Generator Systems Part 11: Acoustic Noise Measurement Techniques sets out in **Table A2** the roughness length [Z_0]. The standard states that roughness length can be calculated from wind speed measurements of several heights or estimated according to **Table A2** as reproduced as follows:

Type of Terrain	Roughness length Z_0
Water, snow or sand surfaces	0,0001m
Open, flat, mown grass, bare soil	0,01m
Farmland with some vegetation	0,05m
Suburbs, towns, forests, many trees and bushes	0,3m

Table A2: International Standard IEC 61400-11: Wind Turbine Generator Systems Part 11: Acoustic Noise Measurement Techniques - Surface roughness length [8].

Surface roughness is a classification of the friction of the earth’s surface that slows the wind down. The higher the surface roughness the greater the friction and the more the wind is retarded. A city has a surface roughness of about 1.0 m while open farmland is classified as 0.03 m.

Topographic Effects on Wind Speeds

The most basic classification of terrain divides it into flat and non-flat terrain. Many authors define non-flat terrain as complex terrain [this is defined as an area where terrain effects are significant on the flow over the land area being considered]. Flat terrain [homogeneous] is terrain with small irregularities such as forest, shelter belts, etc.
Non-flat terrain [heterogeneous] has large scale elevations or depressions such as hills, ridges, valleys, cannons.

To quantify as flat terrain, the following conditions must hold. Note that some of these rules include wind turbine geometry [3]:

- Elevation differences between the wind turbine site and surrounding terrain and not greater than about 60m anywhere in a 11.5km diameter circle around the turbine site;
- No hill has an aspect ratio [height to width] greater than 1:50 within 4 km upstream and downstream of the site;

- The elevation difference between the lower end of the rotor disk and lowest elevation on the terrain is greater than three times the maximum elevation difference [*h*] within 4 km upstream;

Figure A6 illustrates a concept for the determinations of flat terrain.

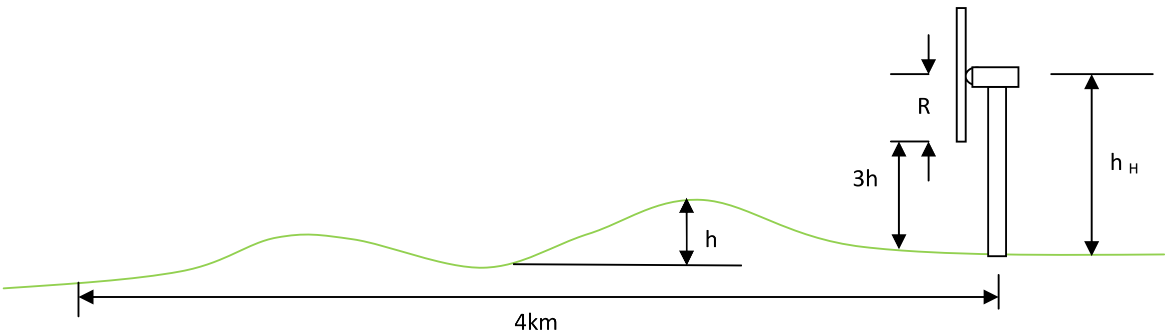

Figure A6: Determination of flat terrain [3].

Non flat or complex terrain consists of sub classifications such as isolated elevations or depression or mountainous terrain. Flow conditions is mountainous terrain is complex because the elevations and depressions occur in a random fashion, Thus flow is such terrain is further divided into two classifications being small and large scales. The distinction between the two is made with comparison to the planetary boundary layer, which is assumed to be about 1km. That is a hill of a height which is a small fraction of the planetary boundary layer [approx 10%] is considered to have small scale terrain features [3].

The Te Apiti wind farm site, in terms of the terrain between the wind turbine generator and sound level measurement location would be classified as flat terrain. Makara [West Wind] Wind Farm in terms of the terrain between the wind turbine generator and sound level measurement location would be classified as non-flat terrain or as referred to in the body of the study [complex terrain].

New Zealand is atypical of many wind farm sites compared to say European countries where the terrain is usually classed as flat, hence direct comparisons of many factors including acoustic measurements and modeling must be approached with awareness, especially if features from one type of wind turbine generator are to be applied from a flat site compared to a hilly site.

Ridges, hills and escarpments all have the ability to accelerate and decelerate wind speeds. Typically the wind speed accelerations occur at the top of a hill and decelerations are experienced in front of and behind the hill. The wind speed acceleration at the top of the hill is in addition to increases simply due to the increased elevation. Wind speeds at the tops of hills and ridges can be significantly accelerated due to the shape of the hill.

The fundamental effect of the change in wind speed with height above ground level is shown in **Figure A7**. The arrows represent the wind speed at varying heights above ground level. The wind speeds above the crest are significantly accelerated. Generally, zones of high wind speed have lower turbulence. Turbulence is a critical parameter for the design of wind turbines.

As the design of the majority of the components in a wind turbine is driven by fatigue, the turbulence regime in which a turbine operates is critical to its design. For larger diameter turbines, used in IEC Class II wind speed sites, the low turbulence intensity is beneficial in maximising the energy production.

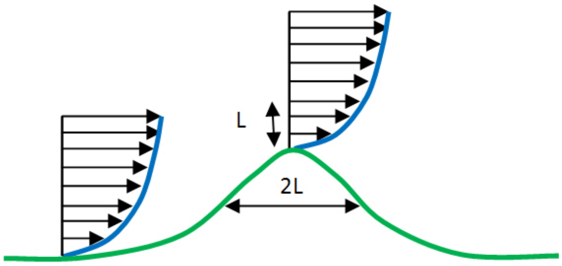

Figure A7: Illustration of increased wind speed at the crest of a ridge.

In real life situations the air flow over flat ground is multifaceted and therefore changing the terrain to hills makes the air flow even more difficult to understand.

To make the issue manageable researchers use 'smooth' mathematical functions such as the *Witch of Agnesi* z = h / *[1 + [x / L_h] 2]* for computational models or for wind tunnel experiments and have made field measurements at smooth, low-lying isolated hills such as the Askervein Hill in Scotland [9]. However hilly terrain is more complex than this model.

The study of the atmospheric wind flow over Askervein Hill is one of the greatest documented and most carefully executed projects on field experiments as well as wind-tunnel simulations.

Askervein Hill which is located in Scotland [approx location = 57° N, 7° W]. The hill resembles an ellipsoid with major and minor axes of approximately 2 km and 1 km, respectively. The hill height is about 116 m and the hill slope in the minor-axial direction is about 0.2. A photo of Askervein Hill is shown in **Figure A8** below.

Figure A8: Askervein Hill, Scotland [10].

Hills are characterised by the height, *h*, and the half-width at half height L_h. The flow over the hill can be divided into three layers. Adjacent to the ground is the inner layer, with a thickness up to 10 m, where turbulent friction is significant. Above this layer is the middle layer within which the flow is essentially inertial with no direct interaction with the surface [11].

However, vortices due to the hill must still be taken into account. The height where the hill-induced velocity shear ceases to be significant marks the beginning of the outer layer. This height is given by $H_m = L_h \sqrt{l_n} [L_h/z_o]$ where Z_0 = length scale of the surface roughness. Like an aerofoil a hill or a ridge will cause changes in the velocity of the air flowing over it. In the middle layer above the crest, a speedup occurs which varies according to the terrain: 1.6 h/L_h for a-symmetric hills, 0.8 h/L_h for two dimensional escarpments, and 2.0 h / L_h for two dimensional ridges [11].

Since for natural hills the height-to-width ratio is ~0.1, a speedup of 10 to 20% occurs. The region of speedup extends for ~$2L_h$ upwind and downwind from the crest. These relations describe the situation where flow separation does not occur. Separation occurs when the streamlines of the flow next to the ground decelerate as they flow down the hill and reverse direction forming an eddy in the flow [11].

For ridges this separation bubble will extend two or three ridge heights horizontally from the summit. Empirically it is known that separation occurs when the slope of a two dimensional ridge is greater than 18^o for a smooth surface or 10^o for a rough surface. The corresponding angles for a hill are 30^o and 20^o [11].

Downwind from the crest of the hill is a wake, a turbulent region in which the wind velocity is reduced compared with the wind velocity profile upstream. The wake is an extensive feature since it can be detected several tens of hill heights downwind. If separation has occurred, the wake extends even further. In the wake, although the velocity is reduced, the variance is increased since it is a turbulent region. This is the most lasting effect of the ridge or hill since the standard deviation is increased up by a factor of 2 or 3 for about ten hill heights downwind from the crest. This can be seen with the standard deviation ratios near the ground: σ_u / σ_w = 3.8 and σ_u / σ_w = 3.2. The ratios are larger than for flat terrain because σ_w is insensitive to surface roughness whereas σ_w and σ_v are. As with flat terrain, the ratios approach unity at high altitudes [11].

The definitions of z, h, L_h, u_o are effect shown in **Figure A9.**

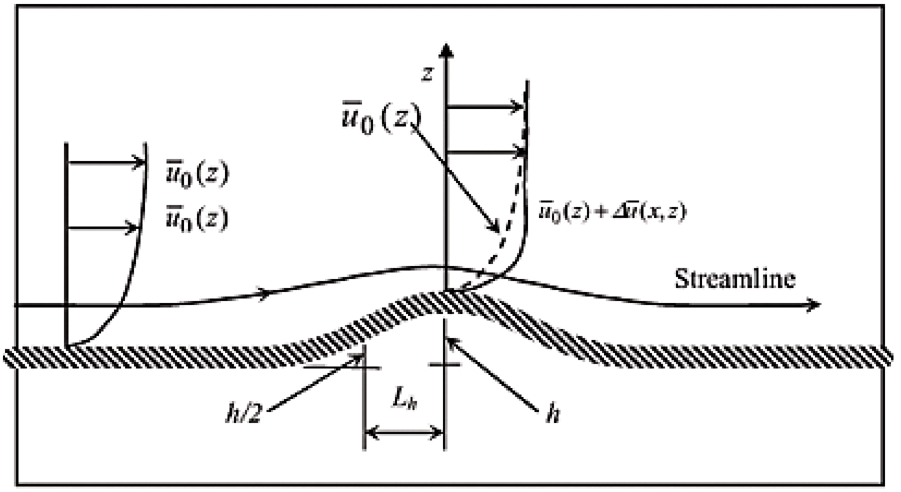

Figure A9: Definitions of z, h, L_h, u_o [12].

Measured results of flow over a hill are shown in **Figure A10**. The horizontal axis represents distance from the top of the hill. The vertical axis represents the relative speed-up. The solid dots represent actual measurements. There is an 80% increase can be seen at the crest of the hill.

A 20% reduction in wind speed was measured up wind of the hill and a 40% reduction in wind speed was measured downwind of the hill. It is noted that numerical models tend to over-predict the wind speeds in the lee of hills [7].

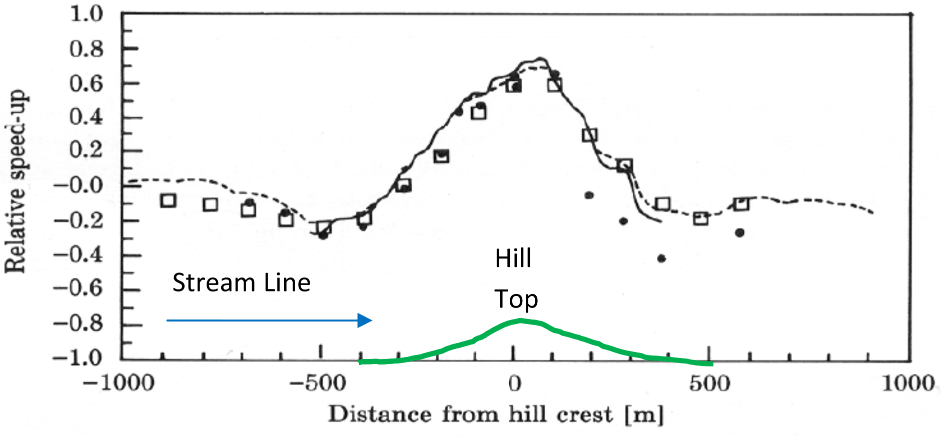

Figure A10: Speed up over Askervein Hill [13].

Modelled Wind Speed

To examine the local topographic effects wind flow over a site using a numerical wind flow software package can be modelled using computer programs. Such software can also be used to determine wind speeds due to terrain variation in applications such as transmission line design. One model is the Wind Atlas Analysis and Application Program [WAsP] modelling package is able to model wind speed variations over a particular area.

This model is capable of modelling wind speeds at different heights above ground level. The inputs to the model include:

- o Digital terrain model;
- o Surface roughness information;
- o Wind speed data [in the form of a speed and direction frequency table], and;
- o Description of any obstacles in the vicinity of the wind measurements.

The results of the numerical flow modelling from WAsP have been represented in graphical form in **Figure A11.**

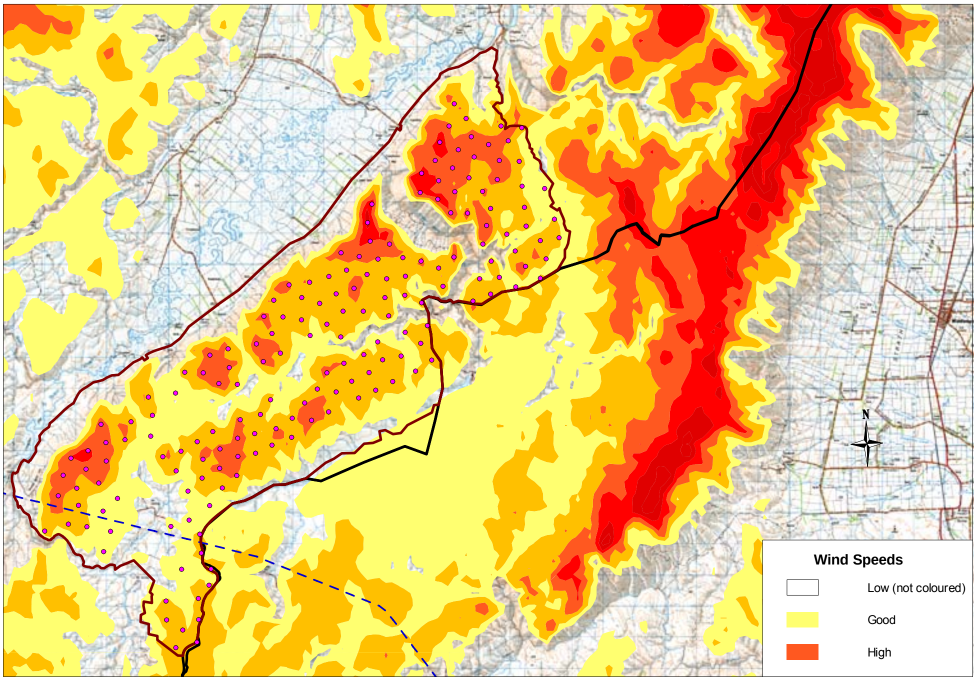

Figure A11: Numerical flow modelling map using WAsP [7].

Figure A11 shows the areas in orange and red have higher wind speeds and those in yellow, slightly lower, while those not coloured have the lowest wind speeds and represent the lower land typically in the valleys. The wind speed map is shown superimposed on a 1:50,000 topographical map and the turbine locations are also shown. The 3D topographical map used for the wind speed modelling has 5 m contours and is based on aerial survey information obtained for this project [7].

Wind Direction

Wind is reported in and expressed in terms of direction from which *it blows* in relation to the points on a compass, or in degrees from 001 to 360 [note 360 degrees is the same as 000 degrees].

Direction is generally given by a wind vein or a windsock. Wind which blows from the north [360 degrees] is known as a northerly. To illustrate information about the distributions of wind speeds, and the frequency of the varying wind directions, one may draw a wind rose on the basis of meteorological observations of wind speeds and wind directions.

A wind rose is generally divided up into 12 sectors; each gives the relative frequency of each of the 12 wind directions, i.e. per cent of the time the wind blows from that direction. The second wedge on the wind rose diagram gives the same information, but multiplied by the average wind speed in each particular direction. The result is then normalised to add up to 100 per cent. This tells you how much each sector contributes to the average wind speed at our particular location. A sample of a wind rose is given in **Figure A12.**

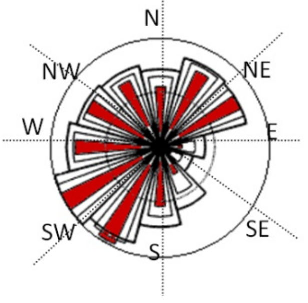

Figure A12: Sample of a wind rose diagram used for a wind turbine generator project.

Figure A13 below is an example of a site which has a dominant north-west wind direction followed by a south-east direction being a secondary direction.

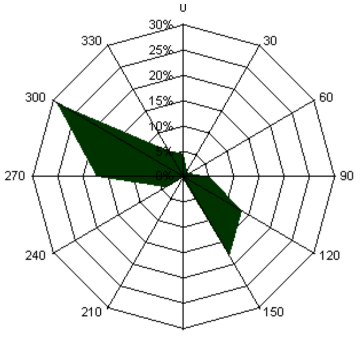

Figure A13: Example of a wind rose for a wind farm site which has a dominant north-west wind direction for the greatest percentage of time.

Wind Speed

Wind speed may be expressed in metres per second per the SI system of units. Wind speed is measured with an *anemometer.*

New Zealand Wind Capacity

New Zealand is ideally situated to generate significant amounts of electricity from the wind. Our location directly across the path of the prevailing westerly winds provides an excellent wind resource. A New Zealand Energy and Efficiently Conversation Authority reported in a study [14] 13 general areas of land around New Zealand that would be suitable for wind farming and of these most were on or near the coast. For a variety of reasons coastal winds are generally of a higher speed and consistency throughout the year and consequently coastal regions are often more suited for wind farms. Not all sites will have an appropriate wind resource and there will be other constraints such as turbulence, lack of demand, weak electricity grids etc. The New Zealand Energy and Efficiently Conversation Authority report noted that the total electricity generation potential, from wind, was 100 Terawatt hours [TWh] annually or approximately two and half times more than our current electricity consumption[15].

New Zealand has one of the greatest wind resources in the world, while sites such as those in Wellington and the Palmerston North Area are exceptional. The Brooklyn wind turbine based in Wellington has been operational for 14 years and is understood to be one of the world's most productive turbines for its size. There are a number of other excellent 'windy' locations ideal for wind energy generation throughout New Zealand

Figure A14 shows a world wind map. This clearly shows New Zealand is an area with significant *mean wind speeds*, greater than most other countries. This data set has been compiled by NIWA and represents the annual mean wind speeds at 10 m above ground level over New Zealand. A wind speed at 10 m agl has been represented as this is the internationally accepted measurement height used by meteorological organizations. While there is significant discussion on *mean* wind speeds, it is the energy output from a wind farm that is critical. The theoretical power available in the wind is proportional to the cube of the wind speed. As an example, a doubling of the wind speed gives rise to an eightfold increase in available power. Energy is the product of power and time. A small change in wind speed can therefore give rise to significant changes in power and consequently energy. The site *mean* wind speed is therefore one of the most important factors in selecting a wind farm site, followed by the choice of an appropriate wind turbine. The process of deriving the energy output at a site is related to the site's wind speed distribution curve combined with a wind turbine power curve to determine the site energy yield. The wind speed distribution combined with the power curve is used to calculate the energy distribution [6].

The map shown in **Figure A14** is a world, year-round *average* wind speed map. It is derived from 10 years of *GEOS-1* satellite data. Satellite data are the only wind data with global extent. The map illustrates that the largest wind resources are above the oceans and mid-continental plains of each of the major continents. The coastal oceans are of special interest because they have strong winds and, as seen by the earth at night, they are close to most of the world's population and electric use. According to the map New Zealand lies between a range of approximately 7.5 m/s and 9.0 m/s.

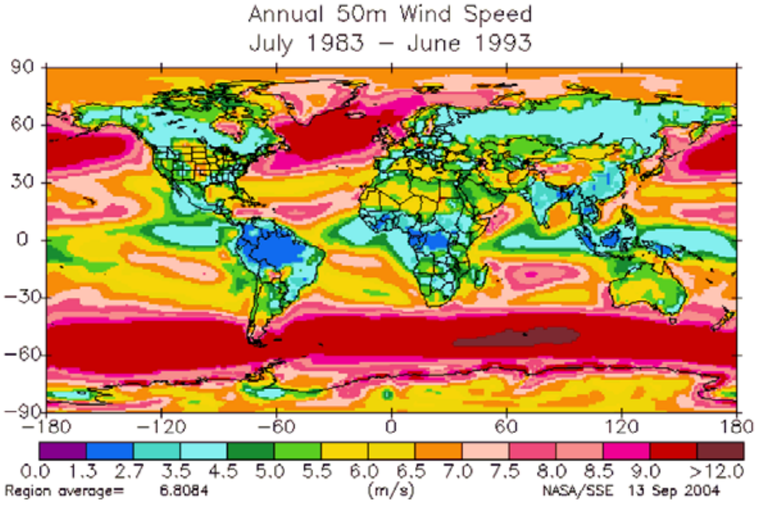

Figure A14: World year-round average wind speed map [16].

Aerodynamic Power Control in Wind Turbines Generators

The power captured from the wind will generally exceed the limits set by the design strength of the rotor and supporting structure. This is especially true of large wind turbine generators as the safety margins of the strength limits of the components become narrower with increasing turbine size. The driving aerodynamic forces can be reduced by influencing the aerodynamic angle of attack, by reducing the projected swept area of the rotor or by changing the effective free stream velocity at the rotor blades [5]. It is important to note that since wind speed cannot be influenced only changes to the rotor can be made.

The success of modern wind turbine generators owes much to the integration and control of complex dynamic systems. Aerodynamically efficient rotors depend upon pitch control to maintain optimum energy capture through a wide range of wind speeds. There is a yaw system to rotate the nacelle so the rotor always faces the prevailing wind. There is control of the variable speed rotor which is allowed to respond to gusts and load changes to reduce drive train loads. There is control of the output power from the generator in terms of frequency and power quality so that the wind farm's variable output has a benign effect on the electricity grid when synchronised.

Wind farms operate fully automatically, entirely unmanned and are monitored remotely, constantly logging data for machinery condition monitoring, technical performance, power generated.

The sound from a wind turbine generator naturally increases with wind speed, with a variable wind turbine generator varying by 10 – 12 dB. **Figure A15** provides an example of a control system and sequence control of a wind turbine.

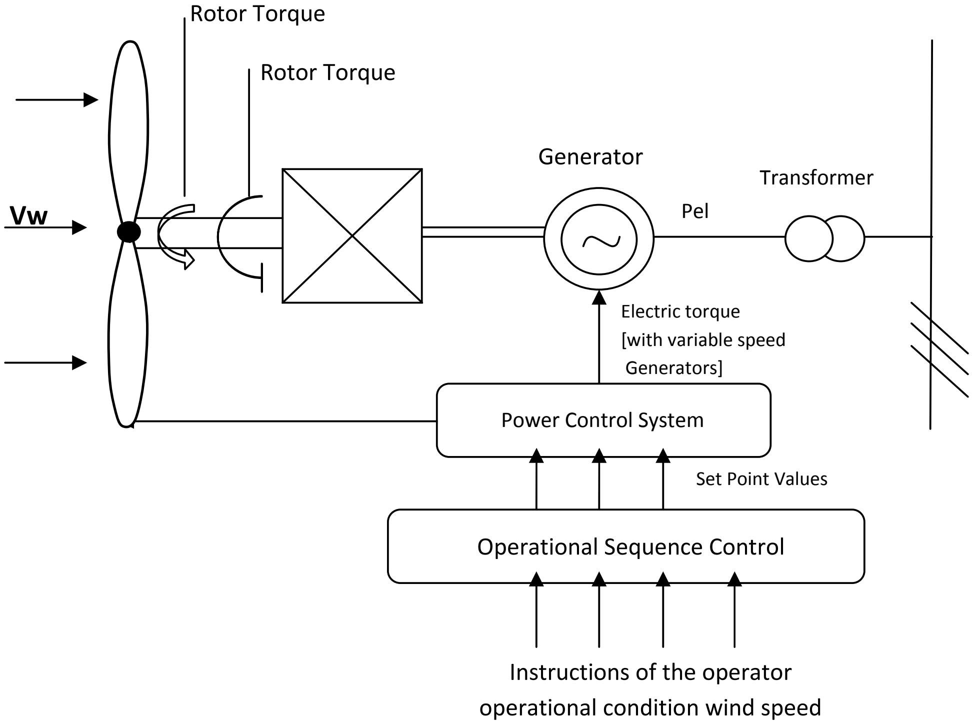

Figure A15: Tasks of the control system and sequence control of a wind turbine [[17]].

The control systems take care of the internal control process so there is a connecting link between the sequence controller and the mechanical and electrical components of the turbine and therefore must be matched to the operating characteristics of the turbine.

Early wind turbines were stall controlled and could not pitch their blades [i.e. had a constant pitch angle]. A further refinement of the stall controlled turbine is an active stall machine, with the biggest difference between these turbine types is the way that they control their power output in high wind speeds and the corresponding sound levels during these periods.

Nearly all the early wind turbine generators were fixed speed, fixed pitch stall regulated with mechanical brakes. Most turbines today are variable speed, variable pitch and have both aerodynamic and mechanical brakes.

Stall

A wind turbine generator under normal operating conditions with a stalled rotor blade would not be acceptable because the energy absorbed by the wind will decrease even to the point where no energy is absorbed. However under high wind conditions stall can be used to protect the wind turbine generator.

The wind turbine generator stalling mechanism works by increasing the angle at which the relative wind strikes the blades to induce drag. The stall characteristics can be designed as part of the wind turbine rotor blades so when a certain wind speed is exceeded the energy absorbed will fall to zero and hence protecting the equipment from exceeding mechanical and electrical ratings [[5]].

In stall designed wind turbine generator blades are fixed and the cross sectional area of the rotor blade have been aerodynamically designed to ensure that when wind speeds are too high it creates turbulence on the side of the blade not facing the wind. The stall therefore prevents forces which cause the blade to rotate. All of a sudden the lift from the low pressure on the upper surface of the blade disappears. This phenomenon is stall. The key advantage of stall control is that it avoids moving parts in the rotor blade itself and a complete control system, however stall represents a complex aerodynamic design problem and related challenges in structural dynamics of the whole turbines e.g. it was discovered that stalled blades can generate a large amount of stall-induced vibration [[5]].

There are two key types of stall being 1] passive stall control and 2] active stall control. Passive stall controlled wind turbine generators have the rotor blades bolted onto the hub at a fixed angle.

Active stall is similar to pitch controlled as the machines have pitchable blades.

The rotor blades are adjusted in operation over their entire length. The concept of stall with an blade is illustrated in **Figure A16 to A18** below.

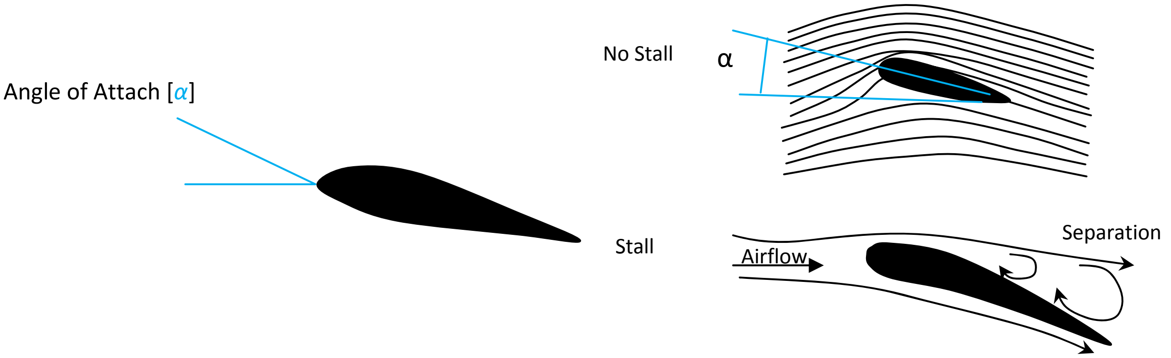

Figure A16: [left] Angle of attack on rotor blade. **[Right]** Fundamental concept of aerofoil stall [2].

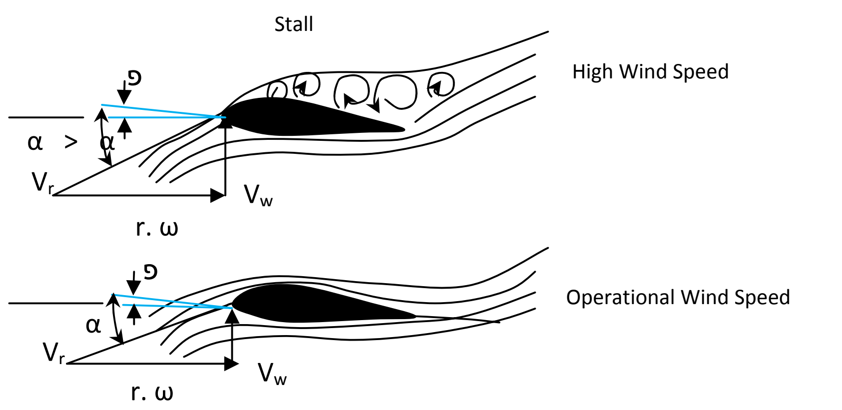

Figure A17: Aerodynamic stall at a rotor blade with fixed blade pitch angle at increasing wind velocity and fixed rotor speed. Stall occurs with increasing wind velocity and with the tangential velocity of the rotor kept constant [5].

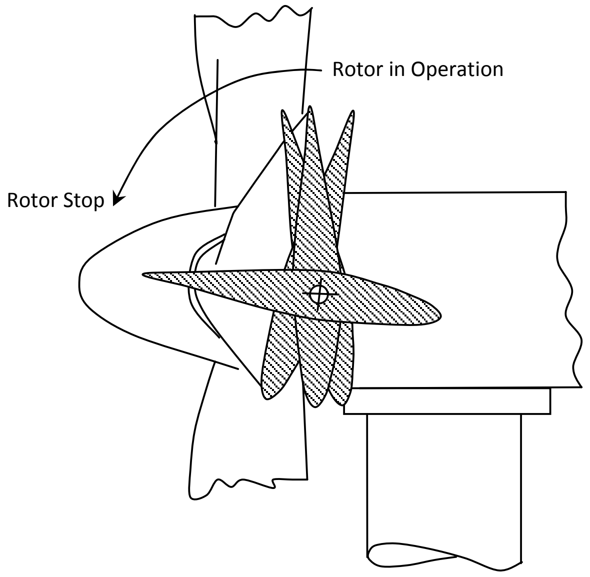

Figure A18: Active stall control at a rotor blade with a number of blade pitch angles in operation and in standstill mode illustrated [5].

Pitch

Pitch control is a method of controlling the speed of a wind turbine generator by varying the orientation, or pitch, of the blades, and thereby altering its aerodynamics and efficiency. On a pitch controlled wind turbine generator the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high the controller sends a signal to the blade pitch mechanism which immediately pitches [turns] the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops again.

On a pitch controlled wind turbine generator, the computer will generally pitch the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle in order to maximise output for all wind speeds. The pitch mechanism is usually operated using hydraulics [[18]].

In principle there are two key methods regarding power control being change of angle of attack of the rotor to a smaller angle to reduce power and conversely increase the angle of attack to increase power output. The concept of angle of attach is shown in **Figure A19** below.

Yaw

Yaw is the turning of a plane, or turning the rotor out of the wind [also knowing as furling]. The wind turbine generator yaw mechanism is used to turn the wind turbine rotor out of the wind direction when the wind speed exceeds the design limits. In this way the effective flow cross section of the rotor is reduced and the flow incident on each blade considerably modified [[18]]. Yawing the rotor with respect direction reduced wind velocity acting perpendicular to the rotor plane and therefore reduced the swept area in relation to the wind direction. **Figure A19** illustrates rotor input control by power pitching the blade toward feather or towards tall modes.

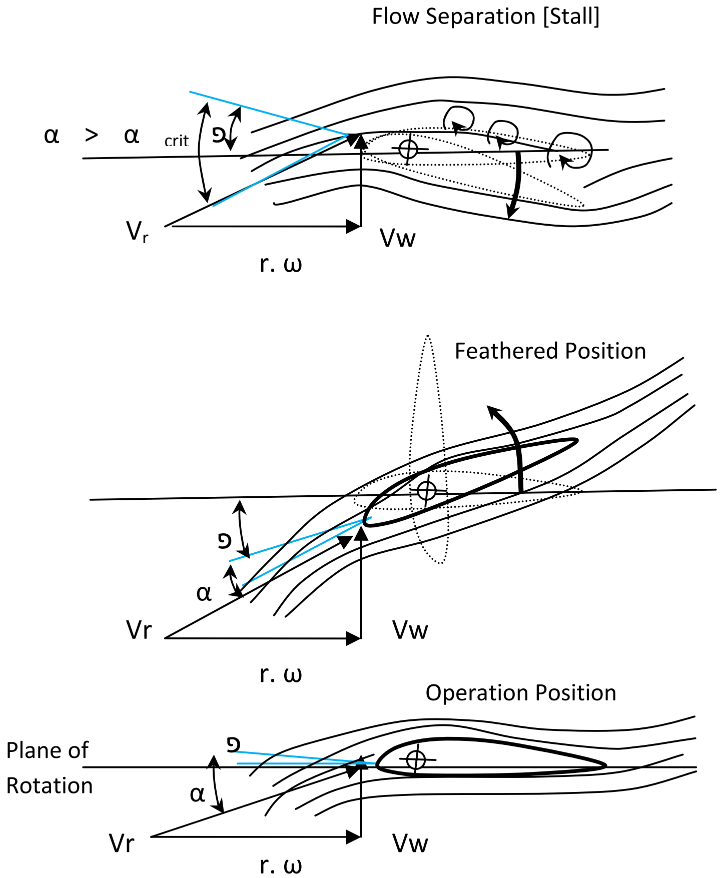

Figure A19: Rotor input control by power pitching the blade toward feather or towards tall modes [5].

Mechanical Power Extracted from Wind

The power extracted by the wind turbine generator in terms of total mechanical power output for a given tubines depend on the square of the rotor blade diameter and the cube of the wind speed, as described as:

$$P_t = \frac{1}{2}\rho A_T V_1^3 \qquad \text{[Eq A7]}$$

The area swept by a turbine's blades increases by the square of the rotor diameter. Therefore, doubling the length of a turbine's blades will quadruple the *theoretical* power output. The power in the wind is proportional to:

- The area of wind turbine being swept by the wind;
- The cube of the wind speed;
- The air density.

For a given wind turbine if the wind speed is doubled the output power will be multiplied by 8 times as much.

The Power Co-efficient

The power coefficient is a measure of how efficiently a wind turbine generator converts the energy in the wind to electricity. The wind turbine extracts energy by slowing or breaking the wind.

For the wind turbine to 100% efficient it would need to break 100% of the oncoming wind and hence the rotor would need to be a solid disk. However if this were the case then a solid disc would not be able to turn and hence no kinetic energy would be converted.

The opposite to the solid disc example is a single rotor blade which would mean the majority of the wind energy would not be broken and would therefore pass by the swept area by the wind turbine blade and hence the maximum available kinetic energy would be kept by the wind.

The ratio between the mechanical power extracted by the converter and that of the undisturbed air steam is called the 'power co-efficient' i.e. extractable mechanical power: power contained in air steam or the ratio of the actual power output compared to the theoretical available.

The following equation and **Figure A20** relate to the power co-efficient concept

$$C_p = \frac{p_r}{p_w} \qquad \text{[Eq A8]}$$

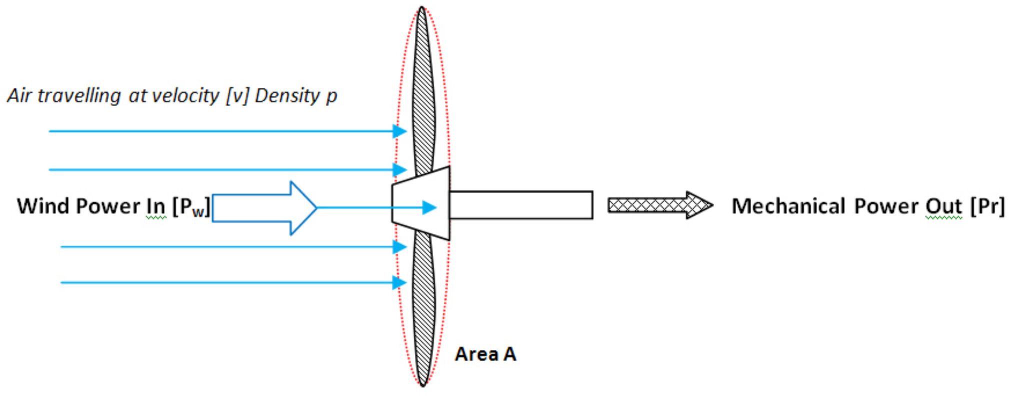

Figure A20: Power co-efficient concept.

There are physical limits to the amount of power that can be extracted from the wind. It can be shown that any wind turbine can only possibly extract a maximum of approx 59% of the power from the wind - this is known as the Betz Limit or Betz Factor.

Knowing the maximum ideal power coefficient is reached at v_2/v_1 = 1/3 the flow of velocity the required reduced velocity v_2 behind the converted can be calculated. With v_2/v_1 = 1/3 the maximum ideal power co-efficient becomes:

$$Cp = 16/27 \text{ i.e.} \sim 59\% \qquad \text{[Eq A9]}$$

The Tip Speed Ratio of a wind turbine generator is a key factor to how efficient the wind turbine will perform. The graph in **Figure A21** shows the relationship between tip-speed ratio and the power coefficient i.e. flow velocity ratio of the flow before and after the energy converted. It is also worth bearing in mind that a wind machine will only operate at its maximum efficiency for a fraction of the time it is running, due to variations in wind speed [5].

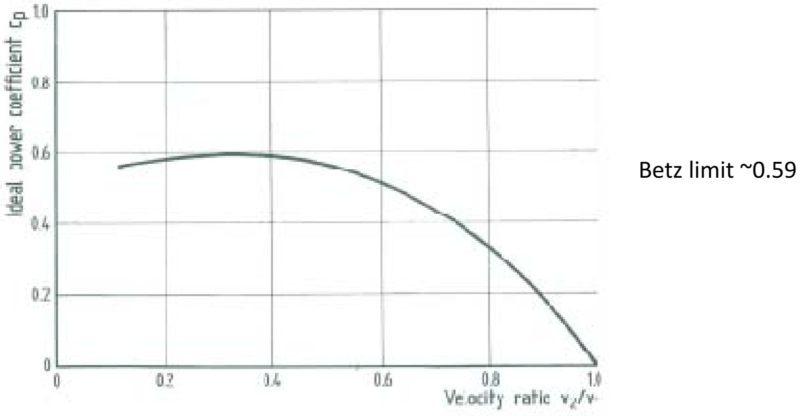

Figure A21: Power co-efficient versus the flow velocity ratio of the flow before and after energy converted [5].

Wind Energy Power Output Based on Wind Speed

The correct measure of economic value of a wind turbine is the energy yield based on the turbines power characteristics with a given wind regime not the rated power of the electrical generator i.e. Kw output.

Wind turbines utilise solar energy and therefore the utlisisation of such energy is chiefly determined by the size of the energy “collector” in the case of wind turbines being the rotor diameter.

The wind systems that exist over the Earth’s surface are a result of variations in air pressure. These are in turn due to the variations in solar heating. Warm air rises and cooler air rushes in to take its place. Wind is purely the movement of air from one place to another. The key design task is to maximise the wind turbines output over the wind speed range, with the rotors aerodynamic design, control, operation and generator being optimised as the overall design goal.

The electrical power output versus the wind speed [the so called power curve] is the result not only of the technical characteristics of the turbine but to certain extend also of the wind data forming the basis of the turbine design. Against the background of the "design wind regime", the optimum rotor speed and also the most favourable rated generator power can be selected. Considering this aspect, the wind turbine here, too, turns out to be an "environment-related" energy generation system the technical design of which must be adapted to its environmental conditions. This process results in the power curve, the relationship between electrical power output and wind velocity [5]. The power curve is the basis of the energy output under the specific wind condition.

There are several key areas of power optimisation for a wind turbine these relate to operating characteristics of the rotor [aerodynamics properties, which described power capacity and influence operating mode of the rotor]. Constraints which prevent the rotor from operating at full theoretical output are complex and relate to the electrical generator, loading and blade control [pitch etc].

A second area of optimisation related to power loses along the mechanical electrical drive train due to such things as efficiency of the gearbox, generator [electrical] and frictional lose of rotor shaft. **Figure A22** illustrates the energy flow through the mechanical electrical energy conversion chain at nominal wind speed for a WKA-60. The loss of energy from start [3046kW] through to grid output [2276 kW] is approx 770 kW, with small gradual loses being obtained throughout the chain [5].

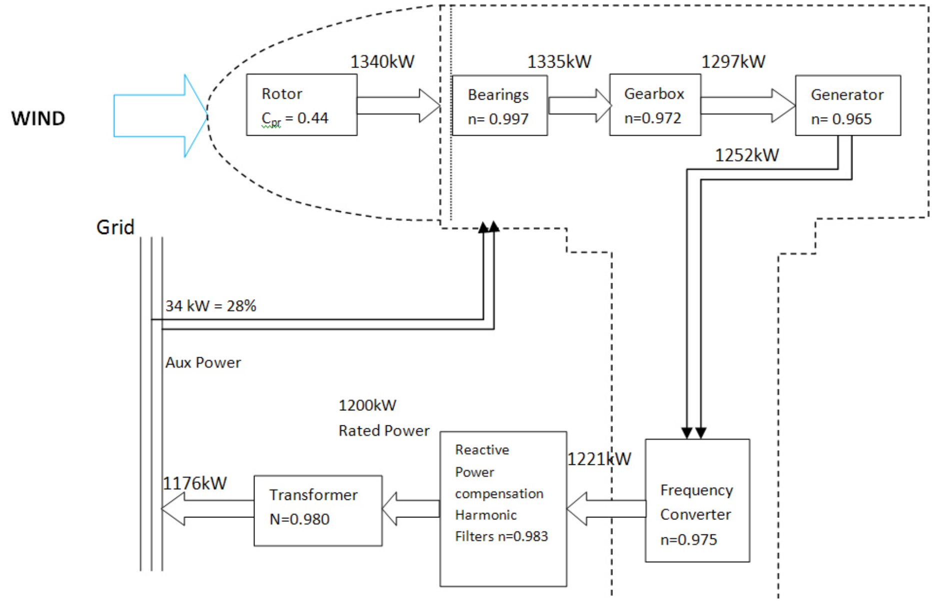

Figure A22: Energy flow through the mechanical electrical energy conversion chain [5].

Key to power optimization is the rotor design and the rotor power coefficient which is achieved at a certain value of the tip-speed ratio. When plotting the rotor power coefficient against wind speed [with a fixed rotor speed] it is shown how the variation in turbine characteristic/designs depends on wind speed [as shown in **Figure A23**]

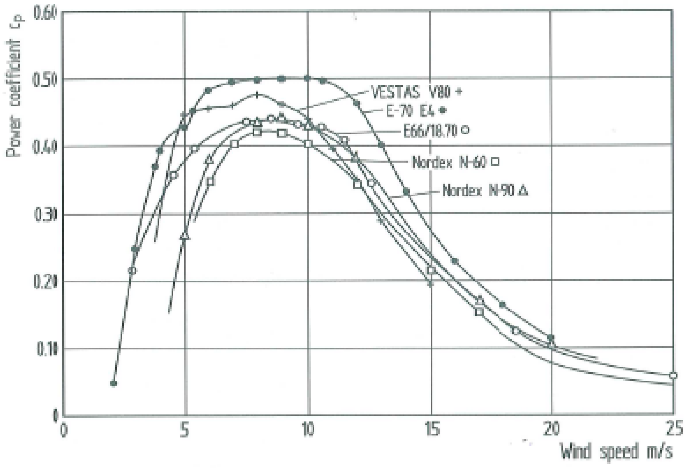

FIgure A23: Sample of power co-efficents for modern wind turbine generators [5].

The graph in **Figure A23** illustrates that the 'peak' can be shifted towards lower or higher wider speeds for different rotor speeds or conversely the frequency distribution of the wind speed at a given site only has its maximum at a certain wind speed. Therefore to optimise energy output the rotor speed must be selected with a broad range of wind speeds for the site. The choice of rated power therefore influences optimum rotor speeds.

Shaft speed is also considered. For a fixed wind speed the power output of the wind turbine varies with the shaft speed, with an optimum output related to shaft speed as shown in **Figure A24** for a 7.5 Kw turbine.

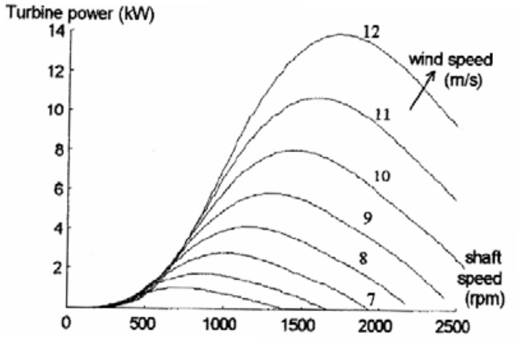

Figure A24: Wind turbine power output vs. shaft speed [19].

Wind Speed versus Power Output

The power curve is the basis of the energy output under the specific wind condition with its calculation being set by the rotor power characteristics and other factors discussed. The shape of the curve is determined by cut in, cut out and rated wind speed.

Cut in wind speed related to when the wind turbine generator starts to generate power, cut out wind speed is the highest speed the turbine will operate will producing power.

Rated wind speed is the wind speed at which rated generator power is reached. The power produced is understood to mean "output" – all losses caused by turbine such as discussed above. **Figure A25** illustrates a typical power output curve/graph of wind speed versus power output.

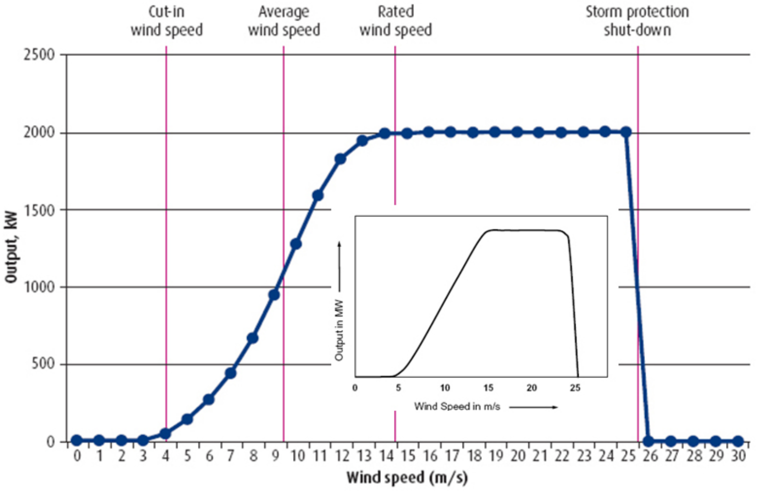

Figure A25: Typical wind turbine power curve [20].

Influences on the power curve relate to wind related to specific site being annual wind speed, frequency distribution of the wind speed and shear wind profiles with elevation. Air density also is key as power curves will be specified by manufactures as mean sea level and therefore must be corrected for site keeping in mid air density carried with altitude and temperature.

Turbulence, rotor diameter and rotor speed must also be considered. The power control [i.e. blade pitch vs. stall controlled] system also has positive and negative feature with respect to energy yield and the power curve for a given turbine design. The turbines technical concept also plays a decisive role.

Sound Power Curve – Wind Speed, Power Output and Sound Power Levels

The power curve [KW] vs. sound power level curve [dBA] for a single 2 MW wind turbine is shown in **Figure A26**. The same power curve and its corresponding sound output curve are shown in **Table A3.**

Points to note from these two figures are below the cut in wind speed of about 3.5 m/s the wind turbine does not generate power accordingly the wind turbine does not generates noise. The turbine power increases rapidly between cut in and rated wind speeds. In this wind speed range the wind turbine sound increases slowly. The rated wind speed of this turbine is 15 m/s [54 km/h]. Between rated wind speed and the cut-out wind speed the turbine generates constant power. The noise from the turbine is constant, or can decrease over this range. The cut out wind speed is 25 m/s [90 km/h] in this example. Once the wind turbine shuts down it again generates little to no sound.

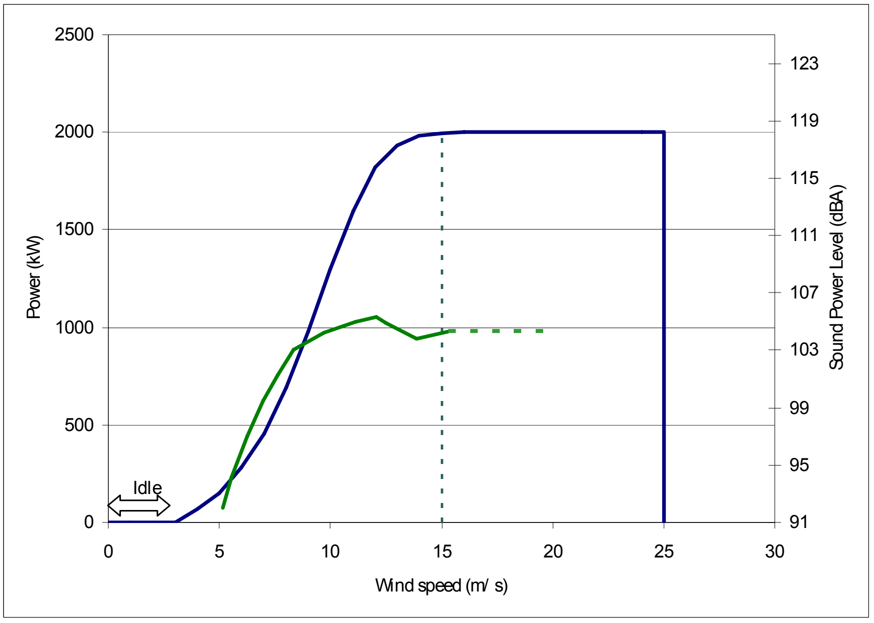

Figure A26: Power [Kw] and Sound Power Level Curves [dBA] for a 2 MW wind turbine [7].

The sound curve and sound power level for different operating wind speeds [L_{wa}] for a Vestas V90 3MW wind turbine**.** Note as the wind speed increases so does the overall sound power rating of the turbine [up to 11 m/s]. The table shows the measurements as per IEC61400-11 ed 2. 2002, for hub heights of 65 m, 80 m, 90 m and 105 m for wind speed range between 4 m/s and 13 m/s.

Guaranteed Sound Power Level at Hub Height: Noise mode 0				
Conditions for Sound Power Level:	Measurement standard IEC 61400-11 ed. 2 2002 Wind shear: 0.16 Max. turbulence at 10 meter height: 16% Inflow angle (vertical): 0 ± 2° Air density: 1.225 kg/m³			
Hub Height	65m	80m	90m	105m
L_{wA} @ 4 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	96.4 5.4	97.0 5.6	97.5 5.7	98.2 5.8
L_{wA} @ 5 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	101.5 6.8	102 7.0	102.4 7.1	103.0 7.3
L_{wA} @ 6 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	105.3 8.1	105.8 8.4	106.1 8.5	106.5 8.7
L_{wA} @ 7 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	107.8 9.4	108.2 9.8	108.3 9.9	108.6 10.2
L_{wA} @ 8 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	109.1 10.8	109.3 11.2	109.4 11.4	109.4 11.7
L_{wA} @ 9 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	109.4 12.1	109.4 12.6	109.2 12.8	109.0 13.1
L_{wA} @ 10 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	108.0 13.5	106.7 14.0	106.5 14.3	106.3 14.6
L_{wA} @ 11 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	106.1 14.8	105.9 15.3	105.9 15.6	105.8 16.0
L_{wA} @ 12 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	105.8 16.2	105.7 16.7	105.7 17.1	105.7 17.5
L_{wA} @ 13 m/s (10 m above ground) [dBA] Wind speed at hh [m/sec]	105.6 17.5	105.7 18.1	105.7 18.5	105.7 18.9

Table A3: Guaranteed sound power level data for 3.0Mw wind turbine [21].

Approximate Calculation of Energy Yield from the Wind

If the wind turbine generator is a modern machine with aerodynamically designed two or three bladed rotor, the rotor power co-efficient are the efficiencies of the mechanical electrical energy conversion will differ only slightly. Therefore a standard power co-efficient can be assumed for the wind turbine [5] as follows:

$$\boldsymbol{v_R} = \sqrt[3]{\frac{\boldsymbol{\pi}}{\frac{\varrho}{2}\mathbf{C_P\ R}}} \qquad \textbf{[Eq A10]}$$

Where:

$\pi = \text{ratio of rated power to rotor} - \text{swept area } [\mathrm{W/m^2}]$

$\varrho = \text{air density } (1.225\ \mathrm{kg/m^3} \text{ at MSL})$

$\mathrm{C_P}\ \mathrm{R} = \text{rorot power coefficient at rated power}$

$(\text{appro. } 0.40 \text{ for two} - \text{bladed rotors and slightly above for three} - \text{bladed rotors})$

Capacity Factor

The output from a wind farm or wind turbine generator is sometimes expressed in terms of a capacity factor. The capacity factor is simply the ratio of the turbine's actual output to the output based on the turbine operating at rated power permanently.

The capacity factor may be used where the wind regime for a site is desired from an economic point of view regardless of metrological conditions, and the term capacity factor is used. Capacity factor is defined as the mean power output [output in one year] and the rated power given as

$$C = P / P_R \qquad \textbf{[Eq A11]}$$

Where:

P = Mean Power [1 year]

P_R = Rated Power [KwH]

Capacity factors can be misunderstood as they are simply a measure of relative energy production. It is not a measure of the *efficiency* of the wind farm and nor a measure of how often the wind farm operates. A capacity factor is dependent on both the site wind speed distribution curve and the wind turbine power curve.

Feasible Power Rating

Table A4 shows possible classification system for wind turbines.

Scale	Rotor Diameter	Power Rating
Micro	Less that 3m	50W to 2kW
Small	3m to 12m	2kW to 40 kW
Medium	13m to 45m	40kW to 999kW
Large [commercial]	>45m	>999KW

Table A4: A possible classification system for wind turbines [[22]].

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Appendix B

Introduction

This Appendix contains further detailed information on the science of aerodynamics and acoustics from wind turbine generators which has partially been discussed in the body of the study.

Aerodynamic Lift [Force]

The rotor of a wind turbine generator acts like a wing and generates both a lift force and a drag force. It is this lift force which turns the rotor around its axis. Lift is defined as the force which is *perpendicular* to the oncoming flow direction. The lift force contrasts the drag force which is the force *parallel* to the flow direction.

The rotor is turned by the lift force as the aerofoil is an aerodynamically designed shape that is design to be capable of generating far more lift force than drag force i.e. in order to obtain maximum efficiency it is necessary for the aerofoil to be aerodynamically shaped so as to have a high lift to drag ratio. This is required in the section of the blade near the tip where the speed relative to the air is much higher than close to the centre of the rotor, as shown in **Figure B1.**

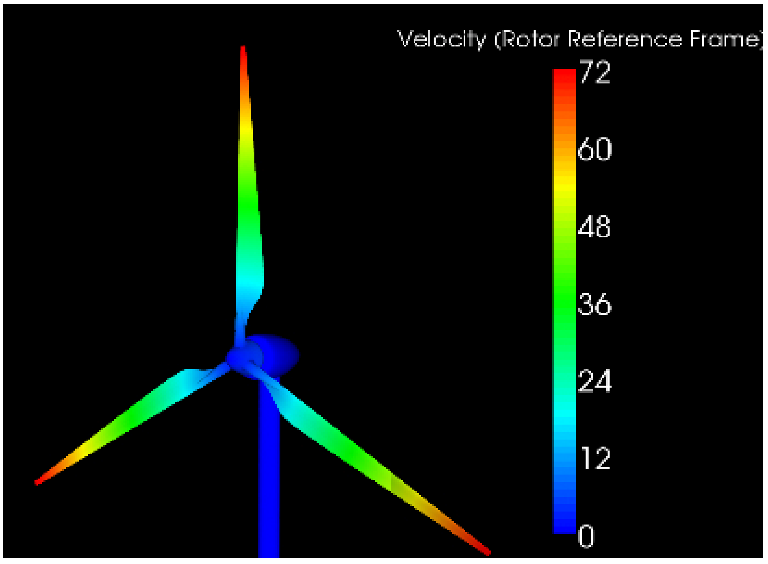

Figure B1: Tip speed velocities on an aerofoil exposed to an air stream [1].

Lift is primarily due to the physical phenomena known as Bernoulli's Law. This physical law states that when the speed of an air flow over a surface is increased the pressure will then drop. **Figure B2** illustrates aerodynamic forces on an aerofoil.

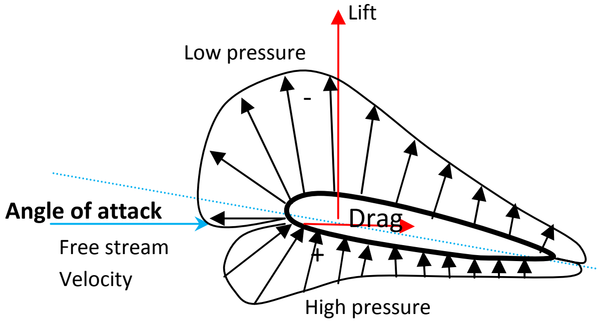

Figure B2: Aerodynamic forces acting on an aerofoil exposed to an air stream [2]. Note the lift of the aerofoil is several times the drag.

Turbulence in the natural wind can create unsteady pressure on the wind turbine blades, leading to the radiation of sound. Aerofoil 'self noise' is the one sound source produced from the interaction of turbulence with blade surface and blade tips. Low frequency type sound may also be produced from rotation of blades or rotation of lifting surfaces.

Torque

An aircraft will fly when air sliding along the upper surface of the wing moves faster than on the lower surface, which means that the pressure will be lowest on the upper surface creating a lift force pulling upwards, allowing the plane to fly.

Lift is perpendicular to the direction of the wind. In relation to a wind turbine rotor, airflow imparts a rotating motion [spin] to the rotor wake. To maintain the angular momentum the spin in the wake must be opposite to the torque of the rotor.

The torque [turning force] in a wind turbine is produced due to the force created as a result of pressure differences on the two side of each blade of the wind turbine. From fluid mechanics it is known that the pressure in fast moving air is less than in stationary or slow moving air. This principle helps to produce force in an aero plane or in a wind turbine. To explain the detail of the force created due to the wind, a cross sectional area of the blade of a wind turbine is shown in **Figure B3**.

Figure B3 shows the air travelling from A to B follows two paths. The shape of the upper surface [path 1] results in higher velocity that the lower surface [path 2]. This will create a low pressure on the path 1 side of the blade. Hence force F, at 90^o to the air flow, will be produced and pushes the blade upwards. This force F multiplied by the radial distance for the hub at which the force is created produces the torque [3].

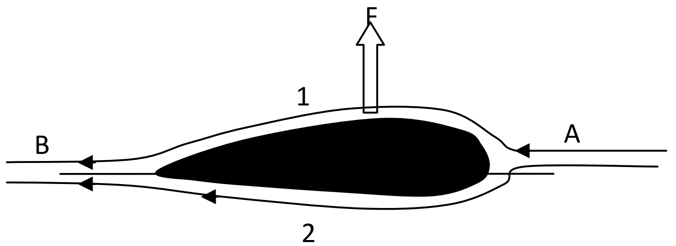

Figure B3: Cross section of a wind turbine rotor blade and air flow paths [3].

If the angle between incoming wind and the blade increases above a given value, instead of the air flow sticking to the surface of the rotor blade along path 1, the air will become irregular and create turbulence and stall.

For a modern horizontal axis wind turbine generator the torque developed by the wind turbine operating at a fixed pitch angle is expressed as:

$$\mathbf{T_T} = \frac{\mathbf{P_T}}{\boldsymbol{\omega}_\mathbf{T}} \qquad \text{[Eq B1]}$$

Where

PT = Power

ω_T – angular velocity of the wind turbine, rad/s

Because the rotor blades are moving the wind will not strike the rotor blades from the same direction the wind is generally coming from. Because the blades are rotating there is also varying wind speeds along the length of the blade tips to the base. The wind will be coming from a much steeper angle [more than from the general wind direction at the site] as you move towards the base of the blade. Therefore, the rotor blade has to be *twisted* so as to achieve an optimal angle of incidence throughout the length of the blade and follow the change in direction of the resultant wind as shown in **Figure B4**.

If the blade is 'hit' by wind at an angle of incidence which is too steep, the rotor blade will stop producing the torque force creating stall [4].

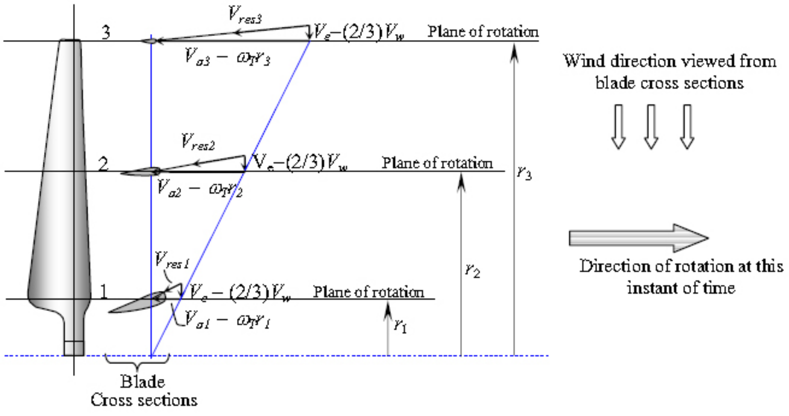

Figure B4: Twisted rotor blade [3]

Where:

Vw = On site wind speed [undisturbed]

Ve= Fraction [max] of undisturbed wind absorbed by the rotor blade for max capture [Ve = [2/3] Vw

Va = Wind crated due to rotation of the wind turbine with radius [Val = ωT r1 [Va at blade radius r1 is Val] Va is perpendicular to Ve and Vw

Vres = resultant wind speed of Va and Ve

r1, r2, r3 = radius at points 1,2 and 3 from the rotor blade.

The cross sectional view of a twisted blade is shown in **Figure B5.**

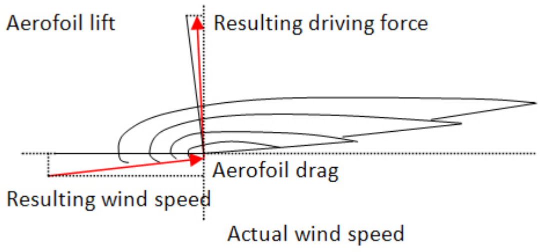

Figure B5: Cross Section of twisted rotor blade [5].

Betz's Elementary Momentum Theory [Disk Actuator Theory]

When the rotor is turning, energy can be extracted. The momentum theory by Betz indicates an *ideal* limit for the extraction of mechanical power from a free stream airflow without considering the design of the energy converter. However the power which can be achieved under real conditions cannot be independent of the characteristics of the energy converter [2]. The first fundamental difference which considerably influences the actual power depends on which aerodynamic forces are utilised for producing mechanical power. The real power co-efficient obtained varies greatly on whether aerodynamic drag or aerodynamic lift is used [6].

Air has mass. Wind is the movement of air which has kinetic energy. To convert kinetic energy of the wind to electrical energy, in a wind conversation system, the wind captures [breaks] the kinetic energy and therefore mechanically drives the rotor of the electric generator. The flow of speed out as it slows down therefore not all of the power can be extracted; this extraction limit was determined by Betz. Betz published writings in which he shows that by applying elementary physical laws, the energy extracted from an air stream passing through a given cross sectional area is restricted to a fixed portion of the energy or power contained within the air stream [7].

Betz theory shows that optimal power extraction can only be realized at a certain ratio between the flow velocity of air in front of the energy converter and flow velocity behind the converter. The kinetic energy of wind is given by:

$$\boldsymbol{E} = \frac{1}{2}\mathbf{m}\upsilon^{2} \quad [\mathbf{Nm}] \qquad \text{[Eq B2]}$$

Where:

E is kinetic energy
υ is velocity
m is air mass

Considering the power of the wind is calculated per unit area at velocity the volume flowing through during certain time unit is

$$\dot{\boldsymbol{V}} = \boldsymbol{\upsilon A} \; [\mathbf{m^3/S}] \qquad \text{[Eq B3]}$$

Where:

A is cross − sectional area
υ is velocity
$\dot{V}$ is volume - per second

The mass flow with the air density *Q* is given by:

$$\dot{m} = \varrho \, \upsilon \, \mathbf{A} \quad [\mathbf{kg/s}] \qquad \text{[Eq B4]}$$

The equation for kinetic energy of the moving air and the mass flow yield the amount of energy through cross sectional are per time unit, this is physically identical to the power, shown as:

$$\boldsymbol{P} = \frac{1}{2} \varrho \upsilon^3 \mathbf{A} \quad [\mathbf{W}] \qquad \text{[Eq B5]}$$

The formula above represents the total wind power entering the wind turbine. For this concept to hold true *v* must be the wind velocity at the rotor which is an undisturbed stream velocity.

The above formula is an idealized one-dimensional analysis where the flow velocity is assumed to be uniform across the rotor and there is no turbulence where flow is inviscid [having zero viscosity]. The volume of air entering the wind turbine should be equal to the volume of air leaving the wind turbine because there is no storage of air in the wind turbine.

As a result volume rate per second *Q*, remains constant which meant the product *Av* remains constant [8]. The change of wind speed pressure and wind speed around the wind turbine is shown in **Figure B6.**

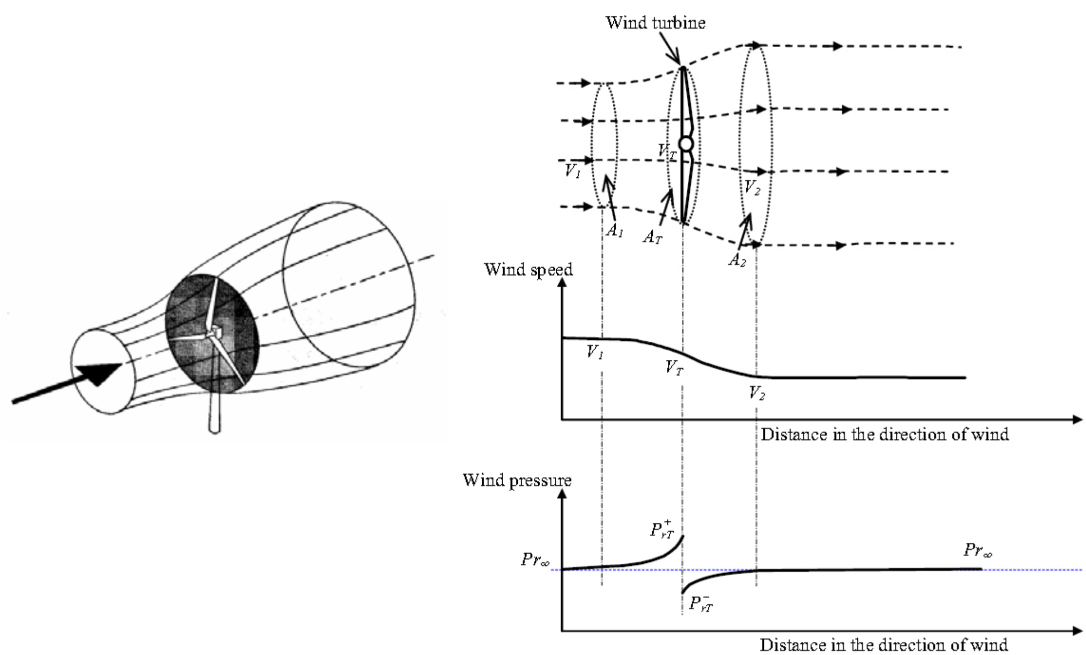

Figure B6: Change of wind speed and wind pressure around the wind turbine [3].

Figure B6 shows the wind at atmospheric pressure [*Pr∞*]. The turbines causes the approaching wind to slow down graudally, which results in a rise in wind pressure. Applyng Bernoullis Equation the wind has highest pressure Pr_∞^+ just before the wind turbine and the wind has lowerst pressure [lower than atmospheric pressure], Pr_∞^- , just after the wind turbine.

As the wind proceeds down stream the pressure rises back to the atmopsheric value causing a further slowing down of the wind speed. The pressures immediately upwind and down wind of the rotor are related to the far upwind and downwind velocities V_1 and V_2 by applying Bernoulli's equation seperately upwind and downwind. Using momentum theory the downwind force on the rotor is equal to the pressure drop across it times the roto blade area [4].

The mechanical power extracted from air flow can be derived from the energy or power difference before and after the converter. The mechnical power output can be expressed as:

$$\boldsymbol{P} = \frac{1}{4}\varrho A\left[v_1^2 - v_2^2\right]\ [v_1 - v_2]\quad [\mathbf{w}] \qquad \text{[Eq B6]}$$

Rotor Blade Geometry

Shape

The geometry of the rotor blade has a considerable effect on the overall sound level produced. Rotor power curves and torque curves are the key features of rotor configuration and design and hence sound output. The magnitude of the power co-efficient and the shape of the curve shows distinct differences, the main parameter dominating the rotor power co-efficient are number of blades, chord length, twist in blade and blade geometry i.e. aerodynamics of aerofoil. Rotor blade tip shape with respect to aerodynamic optimisation can lead to a substantial reduction of the sound emission at higher frequencies and reduce the overall sound level.

The width and length of an aerofoil blade are functions of the desired aerodynamic performance, the maximum desired rotor power, the assumed aerofoil properties and strength considerations. The decisive step from an essentially physical approach to technical rotor dynamics is taken by introducing rotor blade geometry. It is the only means to finding the inter relationship between the actual shape of the rotor and its aerodynamic properties. A method commonly used to this end in wind energy technology is called the blade element or strip theory [9].

Taking the rotor power characteristics, i.e. the variation of the power coefficient as a function of the tip speed ratio, as an example, the approximation of the theoretical models to reality can be illustrated retrospectively. Referred to the power rating of the air stream, the simple momentum theory by Betz provides the ideal constant power co-efficient of 0.593 which is dependent of the tip speed ratio.

Taking into consideration the angular momentum in the rotor wake shows that the power co-efficient is a function of the tip speed ratio. It is only when the tip speed ratios become infinitely high that the power co-efficient approaches Betz ideal value. Introducing the aerodynamic forces acting on the rotor blades, and particular the aerodynamic draft, further reduces the power co-efficient in addition, the power coefficient now exhibits an optimum value at a certain tip speed ratio. **Figure B7** illustrates the approximation of the real rotor power curve by various theoretical approaches with varying blade numbers and tip speed [ratio] [2].

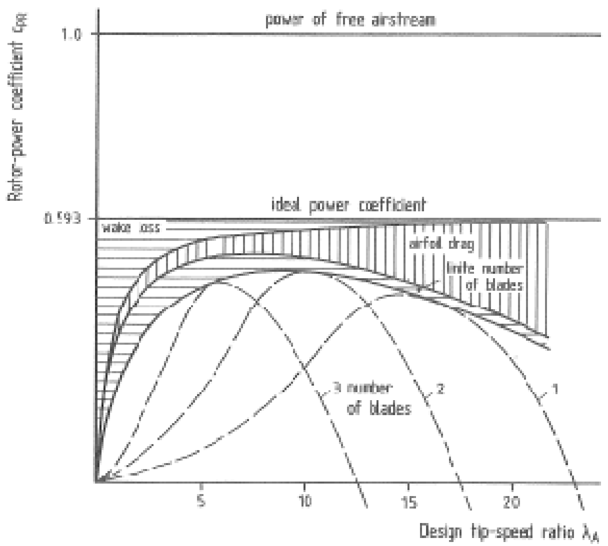

Figure B7: Rotor power characteristics [2].

It is the turbine's power output which may end up being the major influence on the aerodynamic design and sound output, however it will be unavoidable to avoid other key factors such as rotor shape, rotor power control etc. In one study [10] and numerous other studies it is described how the influence of the aerodynamic design parameters on the rotor power co-efficient. Generally the increase in wind speed means an increase in power output, this ultimately leads to an increase in sound levels i.e. as the wind speed increases so does the overall sound power rating of the turbine [up to rated output].

Number of Rotor Blades

In theory the power co-efficient increases with the number of rotor blades. **Figure B8** illustrates the influence of the number of rotor blades on the rotor co-efficient. The reduced increase in power co-efficient with increasing number of blades is illustrated.

While power increases from one to two blades [approx 10%]. The difference between two and three blades is approx 3%. A fourth rotor blade only produces a power increase of approx 1-2% [2].

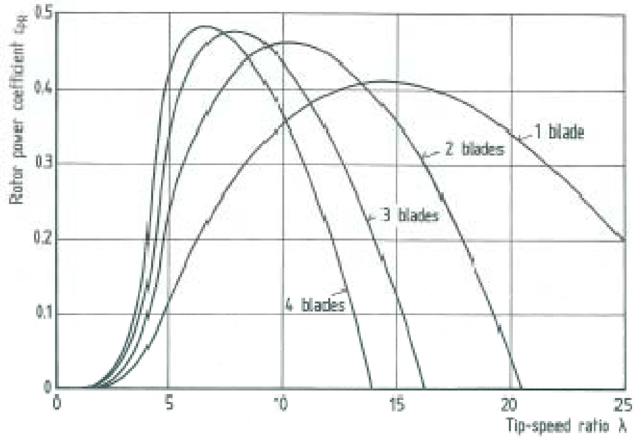

Figure B8: Rotor blades versus power co-efficient [2].

A method of optimising a wind turbine for a particular wind speed condition is to change the rotor size to reflect the site wind speed regime. Generally a wind turbine designed for high wind speed conditions is able to operate with a larger rotor on a lower wind speed site.

Most commercial wind turbine generators are three bladed. A single bladed turbine consists of a single blade off set with a counter weight. The three bladed design has 3% more energy capture than the two bladed design and in turn the two bladed design has 10% more energy capture than a single blade [4]. **Figure B9** illustrates one, two and three bladed concept for a horizontal wind turbine generator.

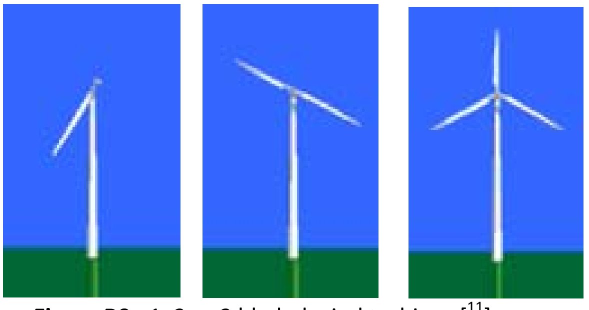
Figure B9: 1, 2 or 3 bladed wind turbines [11].

The single-bladed rotor design is the most structurally efficient as all the installed blade surface area is usually in a single beam. It is normal to shut down [known as park] wind turbines in very high winds in order to protect them structurally. This is because they would experience much higher blade loads and tower loads if they continued to operate. One bladed design allow unique parking strategies with the blade acting as a wind vane or downwind behind the tower which may minimise storm loading impact. However, there are a number of disadvantages with single-blade turbines, such as added mass to provide a counterweight to balance the rotor statically, reduced aerodynamic efficiency due to the higher tip loss of a low aspect ratio single blade and complex dynamics requiring a blade hinge to relieve loads [[12]].

Gardner reports [[13]] that the two bladed rotor design is technically on a par with the established three bladed design. For the benefit of a potentially simpler and more efficient rotor structure with more options for rotor and nacelle erection, either higher cyclic loading must be accepted or a teeter hinge introduced.

The two-bladed rotor is a little less efficient aerodynamically than the three-bladed. Generally speaking there are some small benefits from increasing blade number, relating to minimizing losses that take place at the blade tips. In aggregate, these losses are less for a larger number of narrow blade tips than for fewer wides ones.

Regarding sound emissions the difference between the aerodynamically symmetric three bladed rotor and a single bladed rotor is particularly marked. The high dynamic loads caused by an aerodynamically asymmetrical rotor require additional complexity in the other components of the wind turbine. Moreover, rotors with a high tip speed ratio i.e. single bladed rotors cause a sound emission which is unacceptable at most sites as higher [[2]].

Generally speaking sound pressure levels will increase with the fifth power [5th] of the speed of the blade relative to the surrounding air. Hence modern wind turbines have large rotor diameters [which capture more energy] with preferred low rotational tip speeds.

The rotor blades produce a slight 'swishing' sound [swish-swish-swish] which is usually audible close up at under low wind speeds. The 'swishing' sound is generally broadband in nature and around 1000 Hz range, however it will change if lift forces acting on the blades change rapidly i.e. rapid change in lift due to discontinuous flow conditions. It is these conditions that impulsive or low frequency sound could occur.

Two-Bladed [Teetering] Concept

Two-bladed wind turbine designs have the advantage of saving the cost of one rotor blade and its weight, of course. However, they tend to have difficulty in penetrating the market, partly because they require higher rotational speed to yield the same energy output. This is a disadvantage both in regard to sound emissions. A teetering rotor allows the rotor speed to be accurately controlled by adjusting the pitch of the rotor blade. Two and one bladed machines require a more complex design with a hinged [teetering hub] rotor as shown in **Figure B10** below, i.e. the rotor has to be able to tilt in order to avoid too heavy shocks to the turbine when a rotor blade passes the tower. The rotor is therefore fitted onto a shaft which is perpendicular to the main shaft, and which rotates along with the main shaft. This arrangement may require additional shock absorbers to prevent the rotor blade from hitting the tower [[11]].

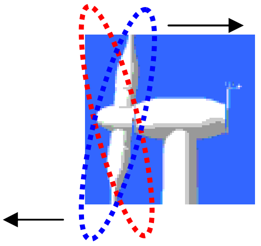

Figure B10: Teetering hub concept [[11]]

Modern wind turbine engineers avoid building large machines with an even number of rotor blades. The most important reason is the stability of the turbine. A rotor with an odd number of rotor blades [and at least three blades] can be considered to be similar to a disc when calculating the dynamic properties of the machine. A rotor with an even number of blades will give stability problems for a machine with a stiff structure. The reason is that at the very moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lowermost blade passes into the wind shade in front of the tower [[11]]..

Optimum Rotor Blade Shape

In general rotor shape is not optimum due to fabrication difficulties, furthermore when an 'optimum' blade is run at a different tip speed ratio than the one for which it is designed, it is no longer 'optimum'. Thus blade shapes must be designed for easy fabrication and overall performance over the range of wind and rotor speeds that they will encounter. In considering non-optimum blades, one generally uses an iterative approach – that is one can assume the blade shape and predict its performance try another shape and repeat the prediction until a suitable blade has been chosen.

The primary aerodynamic factors affecting the blade shape design are detailed including [[14]]:

- Design rated power and rated wind speed;
- Design tip speed ratio;
- Solidity and build-ability;
- Aerofoil;
- Number of blades;
- Rotor power control [stall and variable pitch];
- Rotor orientation.

The shape of the aerodynamic profile is decisive for blade performance. Even minor alterations in the shape of the profile can greatly alter the power curve and sound level.

Therefore a blade designer does not merely sit down and outline the shape when designing a new blade. The shape must be chosen with great care on the basis of past experience.

Blade tip sound is dependent upon blade tip speeds, with tip sound from modern turbines usually being classed as higher frequency sound and broadband in nature. By optimising aerofoil shapes it is possible to reduce sound for varying conditions.

Based on the theory that pressure levels will increase with the fifth power [5^{th}] of the speed of the blade a blade tip speed reduction of approx 25% results in a sound level reduction of 6 dB. Such sound level reductions are significant.

Mechanical power from the wind is influenced by shape of the rotor blade, with the crucial criteria being in relation to applying the Betz momentum theory is the rotor blade radius among other things. Rotor blades of a three or four blades rotor become extremely slender when the design tip speed ratios are large [λ =15]. It is obvious that the construction of such slender blades is associated with problems of strength or stiffness. It is therefore, mandatory for high speed rotors to have only a small number of blades [[2]].

The shape of the aerofoil plays a major role in the efficiency and control of the rotor blades. An important parameter is the airfoil lift to draft ratio defined as:

$$L/D = C_L / C_D \qquad \text{[Eq B7]}$$

Where:

$C_{L=}$ Lift Co-efficient
C_D = Draft Co-efficient

When the lift to drag ratio decreases, the power co-efficient which is achievable also decreases, with the "optimum" point of the power co-efficient shifting to lower design tip speed ratios. Low speed rotors will generally need more blades because when the lift to drag ratio and tip speed ratios are high [L/D = 100] the number of blades appears to have relatively little influenced on the achievable rotor power co-efficient, but when the lift to drag ratio and tip speed ratio are low [L/D = 10] the apparent number of blades is of greater importance [[2]].

As stated above aerofoil design has developed from aircraft with the requirements of wind turbine blades being different to that of an aeroplane and hence the reason why aerofoil for wind turbines have developed their own set of criteria and design parameters. The most common aerofoil in aviation has been complied in aerofoil catalogues [[15]]. The most famous of aerofoil shapes being National Advisory Committee for Aeronautics [NACA] airfoil. The shape of the NACA airfoils is described using a series of digits following the word "NACA." The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties [16]. The characteristic of a NACA aerofoil are shown in **Figure B11.**

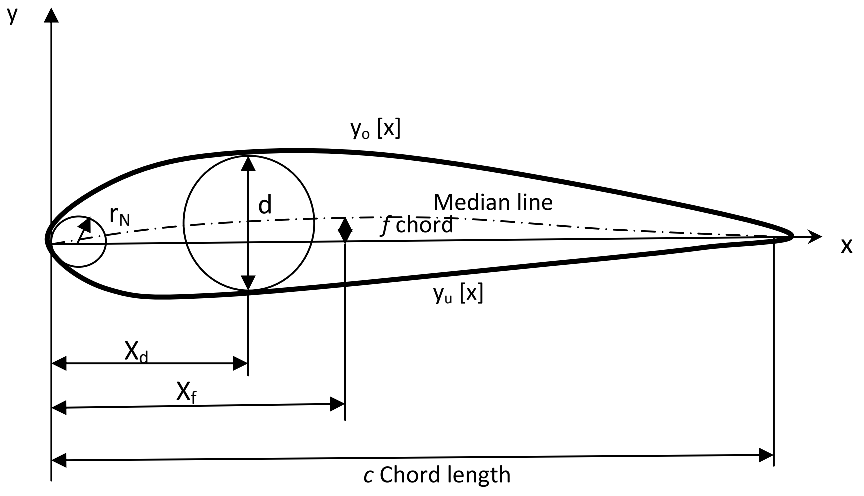

Figure B11: NACA aerofoil [sectional].

Where:

c= chord length

f = maximum camber f or camber ratio [f/c] in percent, as max curvature over the median line

X_f = maximum camber position

d = maximum aerofoil thickness

X_d =position of maximum thickness

r_N = nose radius

The air flow past a NACA0012 aerofoil with an angle of attack of 10 degrees [incompressible Euler] is shown in **Figure B11**, this illustrates the surface mesh and a cut through the grid are in **Figure B12**.

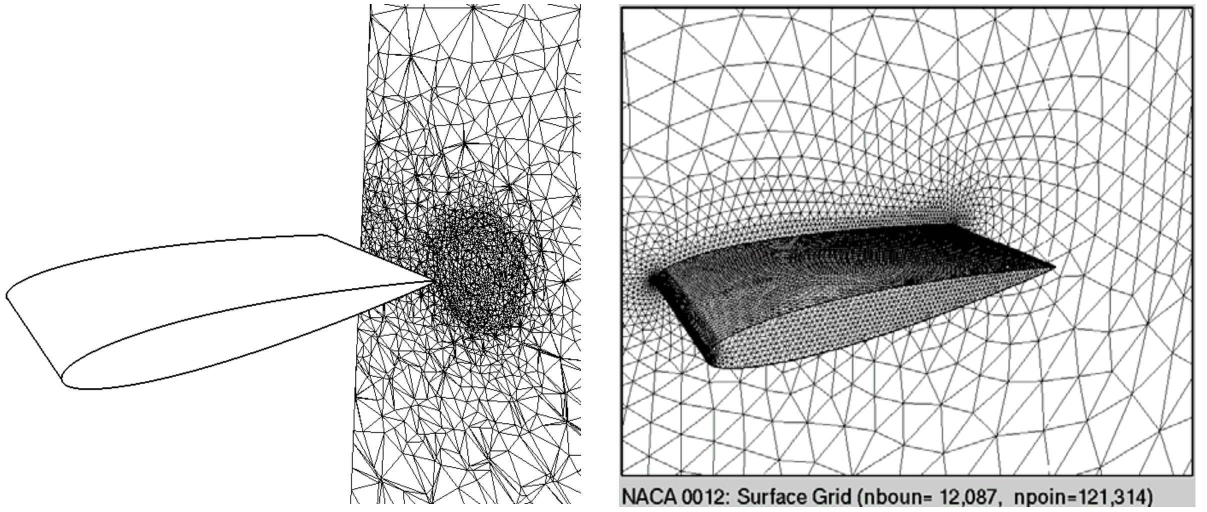

Figure B12: Air flow past a NACA0012 aerofoil [17]

The surface pressure and the vortex on an aerofoil are shown in **Figure B13.**

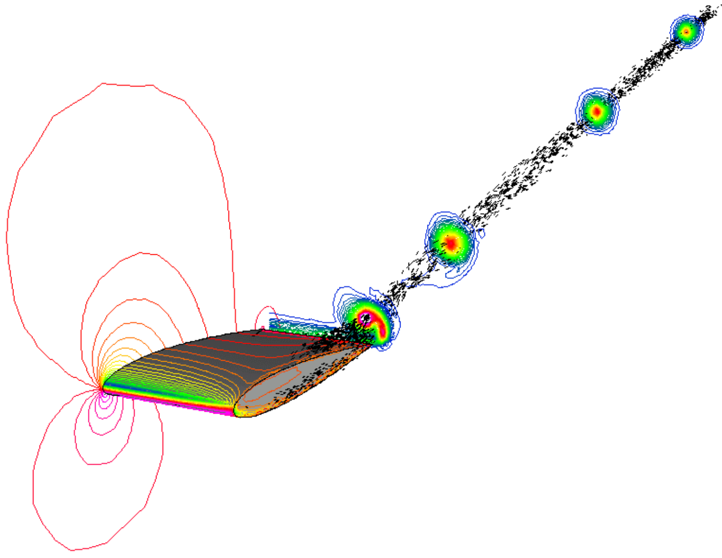

Figure B13: Surface pressures for a NACA0012 aerofoil [17].

In regards to acoustic output, as the angle of attack increases, the outflow will increase leading to the development of a vortex above the blade [as occurs on the wings of large aircraft on landing]. Sound associated with the tip is centred in the 2 to 3 kHz region, depending upon angle of attack and tip speed. Blade tip sound can be reduced through design of the tip shape and through control of the rate of change of pitch angle.

Solutions such as pitch angle change of the blade or boundary layer trips, improved quality control of blade manufacturer [trailing edge whistles] in blades have reduced or removed these sources of sound. Regardless this aerodynamic sound source is usually of high frequency and therefore attenuated and rapidly as distance from the turbine increases.

Blade Tip Aerodynamics

The tip of the aerofoil moves considerably faster than the 'root' of the blade. A lot of design consideration is therefore carried out for performance reasons and including sound emissions. Blade tip sound is associated with the pressure difference between the lower and upper surfaces of the blade around the tip area which leads to an outflow of air from the underside of the blade to the low pressure upper surface.

The outer blade area is of much higher importance for the rotor performance from the aerodynamic point of view. The choice of blade shape and surface quality must be given close attention. Analogously to conditions for airplane wings, the shape of the blade tip arc influences the tip vortices produced thus the induced aerodynamic drag. According to recent investigations, power can be noticeably improved for wind rotors by optimizing the tip shape. Moreover, the shape of the tip arc has some influence on the aerodynamic sound emission of the rotor. Many manufactures are therefore paying increasing intention to the shaping of the blade tip, the edge curve. In some cases the rotor blades were retrofitted with aerodynamically more 'advantageous' tip shapes in the hope of reducing aerodynamic sound emissions [2].

Rotor Blade [Tip] Designs

Profile choice for rotor blades involves a number of compromises including lift and stall characteristics. The majority of modern rotor blades are made of glass fiber reinforced plastics i.e. glass fiber reinforced polyester or epoxy. Wood, wood/epoxy, or wood/fiber-epoxy composites have been used for rotor blades, although not common. Aluminum or steel type alloys have also been used but the issue of weight and metal fatigue arise and therefore would likely only be utilised for small scale turbines.

Due to the wind coming from a much steeper angle [as you move towards the root of the blade, and the centre of the rotor] the rotor blades may also be twisted so as to achieve an optimal angle of attack throughout the length of the blade. However, in the case of stall controlled wind turbines the blade is built so that it will stall gradually from the blade root and outwards at high wind speeds.

In terms of aerodynamic performance the outer blade area is of high importance with blade shape and surfaces requiring close attention in the design stage. The blade tip can influence tip vortices and thus the induced aerodynamic drag. Power can be increased when the tip shape is optimised; **Figure B14** illustrates various rotor blade tips.

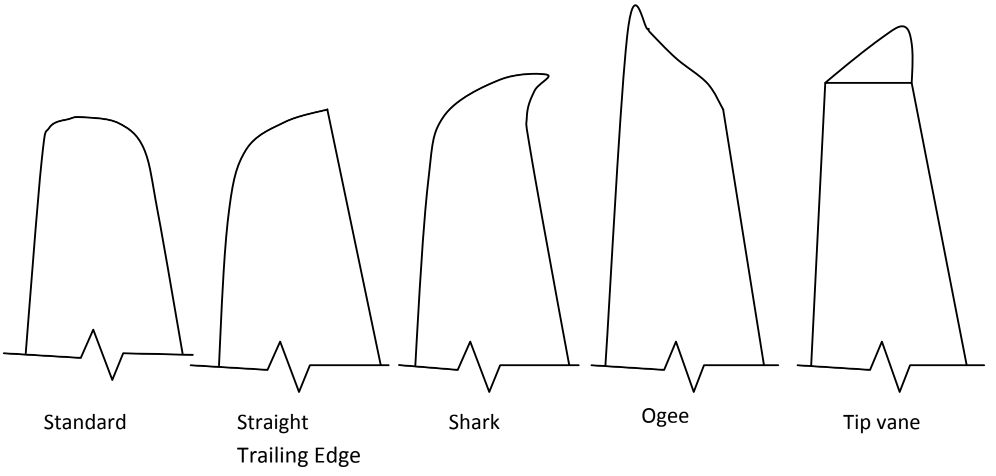

Figure B14: Rotor blade tip designs.

Many manufactures are paying increasing attention to the shaping of the blade tip, the edge curve. In some cases the rotor blades were retrofitted with aerodynamically more adventurous tips hopes in the hope of reducing the aerodynamic sound. The more recent rotor blades all have aerodynamically optimised blades [[2]].

However in practice tip shapes have made only modest changes in overall sound emission levels with more success being found at higher frequency. Current research into the 'Ogee' tip appears to be dominant as opposed to most other types of tips.

Tip Speed Ratio

It is noted that a very important aspect of the rotor design is the consideration of the tip speed ratio and its relationship with the aerodynamics and hence sound emission of the rotor. Naturally sound emission in the outer blade region can be controlled by slower tip speeds and keeping the tip speed ratio within limits, however this does not orchestrate well with current world wide trends of builder larger wind turbines which in turn have larger swept rotor areas to break the wind and produce more energy output.

Simply defined the tip speed ratio is the speed of the blade tip divided by the wind speed or the blade tip speed to the actual wind speed. For optimal extraction the rotor blade must travel at a rotational frequency which is related to the speed of the oncoming wind, however the rotational rotor frequency decreases with an increase in radius of the rotor.

Wind turbines must be designed to operate at their optimal tip speed ratio in order to extract as much energy as possible from the wind. Tip speed depends upon the number of blades and aerofoil design used among other key factors. Generally a high tip speed ratio is desired as it allows for a high rotational speed of the turbines mechanical shaft and hence greater power for the generator; however there are disadvantages to a high tip speed ratio with higher tip speeds comes increased sound levels.

By increasing the tip speed ratio for a three bladed turbine you become closer to the Betz Limit [~59% efficiency]. However efficiency of turbine decreases with increased wind speed because blades are adjusted by changing the pitch angle so that they expose less area to the wind hence such an area decrease reduces stresses by high wind on the blades.

As discussed above, Betz's simple momentum theory is based on the modelling of a two-dimesional flow through the actuator disc. The airflow is slowed down and the flow lines are deflected in only one plane. In reality, however, a rotating converter, a rotor, will additionally impact a rotating motion, a spin, to the rotor wake. To maintain the annuular momentum, the spin in the wake must be opposite to the torque of the rotor. The energy contained in this spin reduces the useful proportion of the total energy content of the aristream at the cost of the extractable mechanical energy so that, in the extended momentum theory, taking into consideration the rotating wake, the power co-efficent of the turbines must be smaller than the value according to Betz. Moreover, the power co-efficient now becomes dependent on the ratio between energy components from the rotating motion and the translatiorial motion of the air stream [2].

Figure B15 illustrates the simple flow model relating to the Betz's momentum theory.

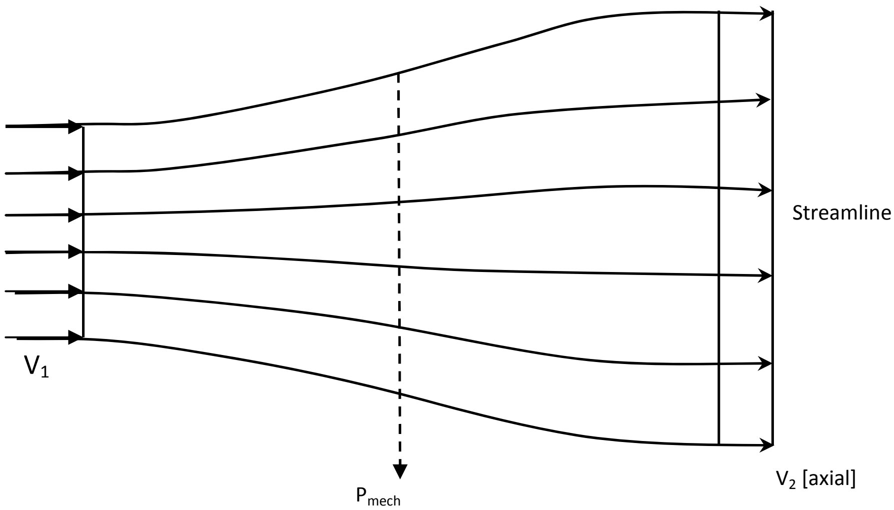

Figure B15: Simple flow model relating to the Betz's momentum theory **[2].**

Figure B16 below illustrates the extended momenturm theory, taking into account rotatating rotor wake.

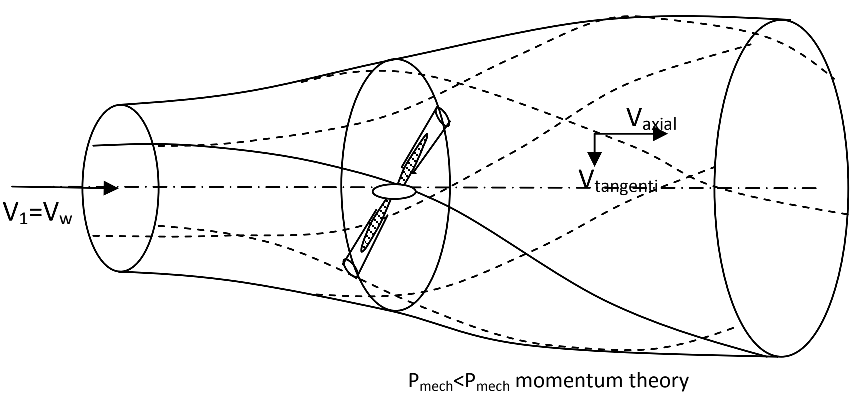

Figure B16: Extended momentum theory, taking into account rotating rotor wake **[2].**

Simply put the rate at which the ends of the blades of the wind turbine turn [tangential speed] in comparsion to how fast the wind is blowing is the tip speed ratio expressed as:

$$\boldsymbol{TSR} = \frac{\mathbf{V_{tn}}}{\mathbf{V_{w}}} = \frac{\boldsymbol{\omega_T} \mathbf{r}}{\mathbf{V_{w}}} \qquad \textbf{[Eq B8]}$$

Where:

V_{tn} − tangential speed of the blades at the tips

ω_T − angular velocity of the wind turbine

r − radius of the wind turbine

V_w − undisturbed wind speed in the site.

A fundamental function of the power co-efficient [power output] is a function of the tip speed ratio, as shown in **Figure B17.**

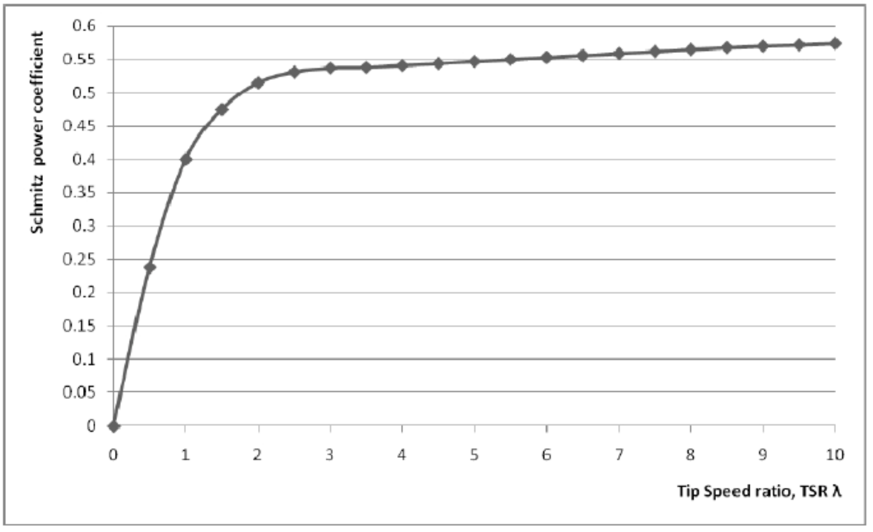

Figure B17: Power co-efficient vs. tip speed ratio [18].

In terms of sound out-put a low tip speed ratio is considered an important criteria, however as stated above the higher the tip speed ratio the better for power extraction. Hau states [2] that in regard to sound that a variable speed or two speed rotor, such operations are 'attractive' to developers particularly at low wind speeds when the ambient background sound has not yet been increased by the wind speed and hence the rotor can be operated at a low speed.

Tower Aerodynamics

Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower. Almost all modern commercial wind turbine generators are horizontal up-wind axis machines. Depending upon the position of the blades horizontal wind turbines are classified into upwind or down wind machines. **Figure B18** illustrates up/downwind turbine configurations.

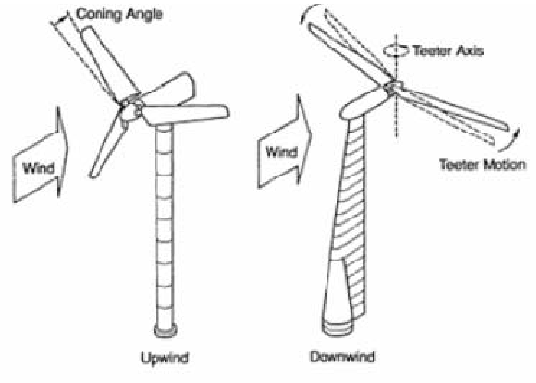

Figure B18: Upwind and downwind wind turbines.

Upwind machines have the rotor facing the wind. The basic advantage of upwind designs is that one avoids the wind shade behind the tower. By far the vast majority of wind turbines have this design. There is also some wind shade in front of the tower, i.e. the wind starts bending away from the tower before it reaches the tower itself, even if the tower is round and smooth. Therefore, each time the rotor passes the tower, the power from the wind turbine drops slightly. The drawback of upwind designs is that the rotor needs to be made rather inflexible, and placed at some distance from the tower. In addition an upwind machine needs a yaw mechanism to keep the rotor facing the wind [11]. Upwind rotors emit broad band sound emissions, including low frequency sound and infrasound.

Sound sources associated with infrasound frequencies are generated by unsteady loading of the wind turbine blade. This sound is associated with 'downwind' turbines, i.e. turbines with blades downwind of the tower or other turbine support structure. The result of such a wind turbine configuration is that the blade passes through the wake caused by the presence of the tower in the airstream, generating high levels of acoustic energy at the blade passing frequency and associated harmonics.

The development of upwind turbines has lead to machines operating at lower rotational speeds. The aerodynamic flow around the tower on the rotor is at a minimum when the rotor is mounted in an upwind position of the tower. The upwind rotor is affected merely by a retardation of the flow in front of the tower, also referred to as "tower dam" or "bow-wave" effects. The tower dam effect was considerable in older machines, however has not been reduced due to slender tower design. Tower dam is still however a potential hazard with respect to the excitation of tower vibration if the rotor speed remains within the range of the natural bending frequency of the tower for any length of time. The aerodynamics of the tower must therefore be considered especially due to the disturbance of potential tower shadow effects for both down and upwind designs [2].

The electric power output of downwind rotors is a clear indicator of the influence of tower shadow interference. In extreme cases, power losses of up to 30 or 40% below the average output were measured. At the usual rotor speeds, the frequency of tower shadow interference falls within the range of some critical natural frequency of the turbine, in particular that of the drive train. The influence of the tower shadow on the sound generated by the wind turbine must be pointed out. This effect turned out to be of such importance that it caused the virtually complete disappearance of downwind rotors among today's wind turbines [2].

A blade radiates sound when the forces on the blade change due to the variation in wind velocity. This change occurs every time the blade passes the tower as the wind is slowed down by the tower. The small pressure pulses are caused when the blades interact with the wind flow at the tower.

These changes have a fundamental frequency of about 1 Hz, analysis of their sound gives frequencies in the infrasound region, but at a very low, inaudible sound pressure level.

Figure B19 illustrates an acoustic photograph showing wind velocity for up wind turbine.

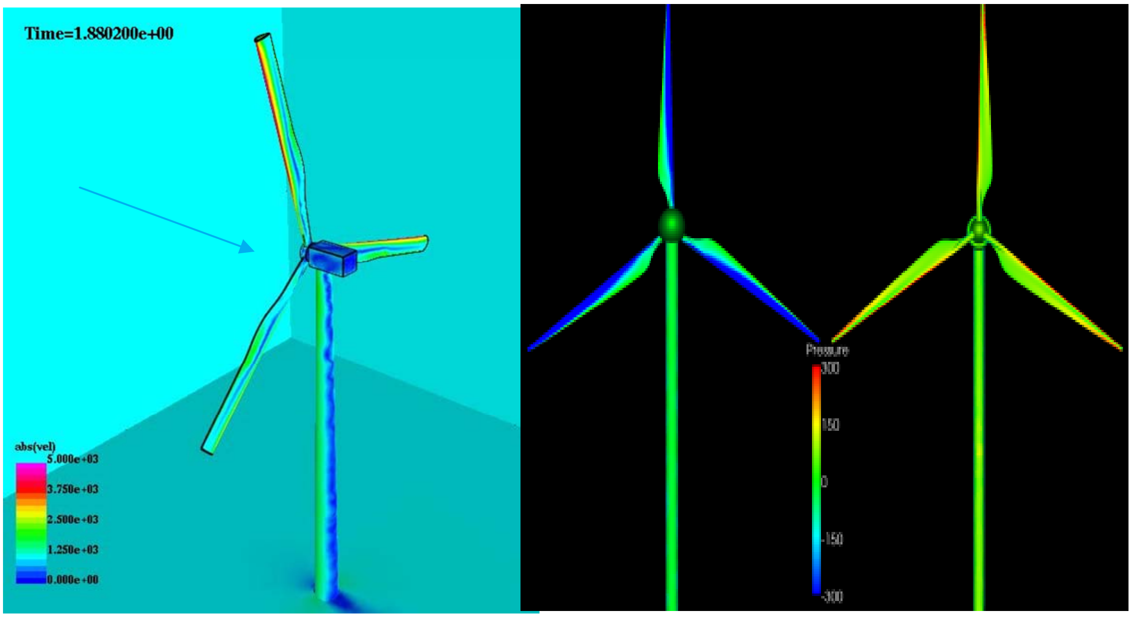

Figure B19 [Left]: Acoustic photograph showing wind velocity for up wind turbine - velocity [19].
[Right]: Acoustic photograph showing wind velocity for up wind turbine – pressure [1].

Downwind Wind Turbine Generators

Downwind machines have the rotor placed on the lee side of the tower. They have the theoretical advantage that they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. For large wind turbines this is a somewhat doubtful advantage, however, since you do need cables to lead the current away from the generator. The basic advantage of the downwind machine is that it may be built somewhat lighter than an upwind machine. The basic drawback is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower. This may give more fatigue loads on the turbine than with an upwind design [[11]].

Sound sources associated with infrasound frequencies are generated by unsteady loading of the wind turbine blade. This sound is associated with 'downwind' turbines, i.e. turbines with blades downwind of the tower or other turbine support structure. The result of such a wind turbine configuration is that the blade passes through the wake caused by the presence of the tower in the airstream, generating high levels of acoustic energy at the blade passing frequency and associated harmonics.

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Figure B20 illustrates sound pulses from a downwind machine and the related tower dam effect as measured close to the machine.

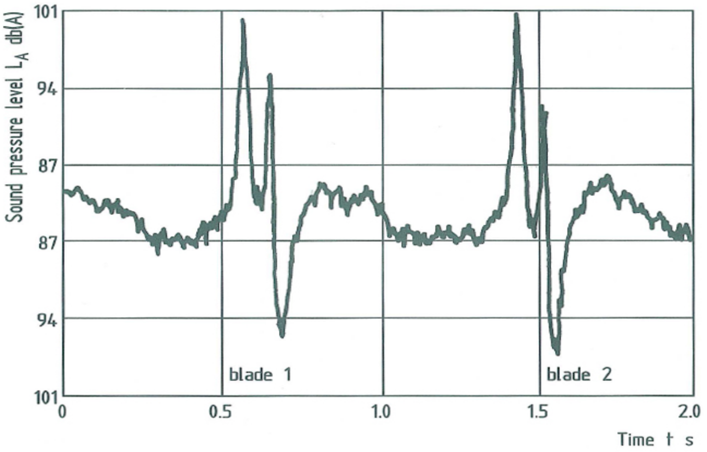

Figure B20: Sound pulses for a downwind machine and the related tower dam effect as measured close to the machine [[2]].

A blade radiates sound when the forces on the blade change due to the variation in wind velocity. This change occurs every time the blade passes the tower as the wind is slowed down by the tower. The small pressure pulses caused when the blades interact with the wind flow at the tower. These changes have a fundamental frequency of about 1 Hz, analysis of their sound gives frequencies in the infrasound region, but at a very low, inaudible sound pressure level.

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