ROTORDYNAMICS IN ALTERNATIVE ENERGY POWER GENERATION

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Ivan Cortes-Zambrano

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Abstract

This thesis analyses and discusses the main alternative energy systems that work with rotordynamics machines to generate power. Hydropower systems, wave and ocean energy, geothermal, gas turbines, wind power, tidal energy and biofuels are the most important systems that use rotating shafts to generate power.

Descriptions of the principles of vibration follow with analysis of rotordynamics. The Jeff rotor, fluid film bearings and magnetic bearings are explained.

The protection of the environment is one of the most important features of renewable energy and biofuel is a crucial area. Fossil fuels are a limited resource and burning them contributes to carbon dioxide levels with catastrophic effects for the atmosphere. This thesis analyses the biofuels process in electricity generation and overviews the topic of biofuels for transport.

The undesirable effects of pollution from burning fossil fuels, an increase in international petroleum prices as well as the risk of using nuclear power have combined effects that illustrate the importance of research in this area.

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1. Introduction

Rotating machines are vital for generating power using alternative energy systems. Increasing demand for clean energy comes not just from the long-term threat to environmental sustainability, but also from new energy generation that will be necessary to fulfil the requirements of the world's technological advances.

The first resources that were used to supply heat, light, and utilizable power were renewable resources (water, wind, sun, biomass). However, the remarkable demand for energy required by industrial and residential areas, transport sectors and others, has been met primarily by fossil fuel energy (in recent times by nuclear technology) with negative consequences in the context of global climate change.

Anthropogenic greenhouse gases in the atmosphere are the main causes of global climate change. During the 20th century, the average global temperature has risen by approximately 0.6 ^{0}C and there have been predictions of an alarming increase of between 1.4^{0}C and 5.8^{0}C over the period 1990-2100. Environmental changes such as climatic modification in some zones as well as rising sea levels by 88cm by 2100 have potentially dramatic effects.

In the case of nuclear power plants, although they do not burn fossil fuels, there are several concerns. Release of radioactive material in the event of malfunction is a latent risk. Chernobyl and recent problems with nuclear power plants in Japan are examples. Furthermore, many plants discard waste heat to natural bodies of water with adverse effects on aquatic life. Moreover, the infrastructure to generate nuclear power allows for the development of nuclear weapons.

In addition, the vulnerability of energy infrastructure was exposed in the petroleum crisis in 1973, when a traumatic oil embargo was imposed by the Organization of the Petroleum Exporting Countries. Countries worldwide experienced directly the implications of fuel shortage on electricity costs.

This thesis has three main objectives: 1) to analyse the most important alternative energy systems that work with rotordynamics machines to generate power, 2) to explain the mathematical principles of rotordynamics and 3) to explain the generation of power using biofuels and their main emissions.

For the first objective, in order to illustrate the analysis, based on a scenario community of 900 homes in New Zealand, three different alternative systems of energy are selected and in each case a mathematical model is developed.

For the second objective, mechanical vibration is reviewed before analytical concepts of rotordynamics are explained.

To meet the third objective, three processes that use biomass to generate electricity are explained. Gas emissions associated with biofuel cycles are also explained.

2. Literature Review

2.1 Rotordynamics

In the new global economy, productivity has become a central issue for competitiveness. In every single area where operations take place, enhanced productivity is crucial in order to be a part of the marketplace. Machines have to remain on line for longer periods of time, with fewer technical problems and high standards of productivity.

Many industries depend on reliable trouble-free processes that involve rotating machinery, for example power generation, land, sea and air transportation; manufacturing, computer disk drivers, heating and air conditioning; aerospace, petrochemical processes, textiles, military systems and various home appliances. Consequently, a vital duty for any engineer involved in this area is diagnosis.

In the mechanics of rotating machinery vibration, it is necessary to consider aspects such as limits on vibration levels, machine durability and reliability. Although modern technology has reached high standards, to make any rotor perfectly mass-balanced is impossible and therefore every spinning rotor has some level of vibration.

Turbo-machinery is a rotating structure that involves energy transfer between a flowing fluid and rotor. When the rotor transfers the energy to the fluid, the machine operates as a pump, fan or compressor. When the flow of energy comes from the fluid to the rotor, the machine works as a turbine. Additional examples of turbo-machinery include gas and steam turbines, turbo generators and turbo expanders, turbochargers, auxiliary power units (APU), and so on.

In order to compete in international markets, gas turbine industries are heading in the direction of producing larger sizes and higher-power equipment to improve performance and thermal efficiencies. This means that different rotary parts will face greater stress. As a result, it is necessary for the rotordynamics area to take part in process development from the prediction phase during experimental tests to the routine operation.

There are various problems relating to rotordynamics at different stages in the life cycle of an industrial gas turbine. In the first phase, analysis of critical speeds is a fundamental point: assessment up to the third or fourth critical speed is essential. In the next phase, problems inherent in rotordynamics such as bearings performance or maximum unbalance can very easily affect the design of tolerances in several mechanical components such as rotors and bearings. Finally, during operational stage, it is vital to monitor parameters of vibration as they can indicate any fault in the equipment.

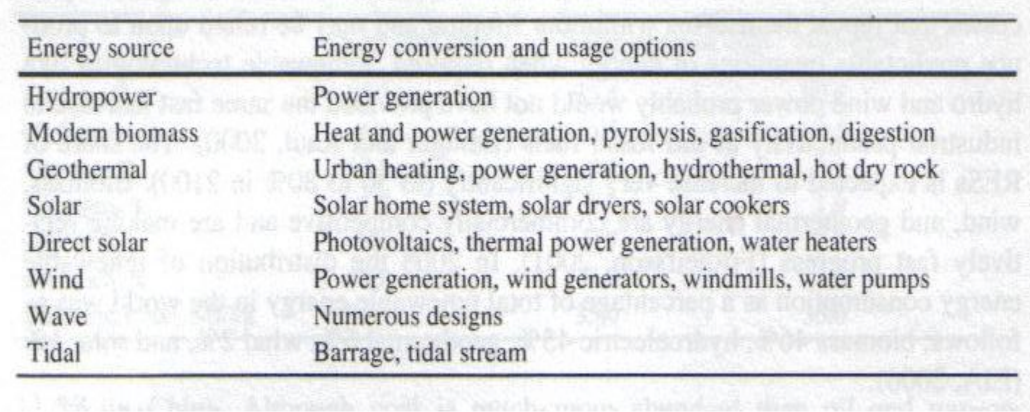
Critical speeds can be defined as the rotating speeds at which vibration characteristics as a result of rotor unbalance are at a maximum. Large amplitudes of synchronous vibration frequently signify a rotor unbalance problem since one of the main features of rotor unbalance is always synchronous whirling. Critical speeds can be linked with the eigenvalues of a rotor model.

The rotordynamics of turbomachinery cover the structural analysis of rotors (shafts and disks) as well as the design of fluid film bearings and seals which are fundamental parts that finally govern the dynamic performance given the mandatory functional conditions.

2.2 Power Generation: Natural Resources and Biofuels

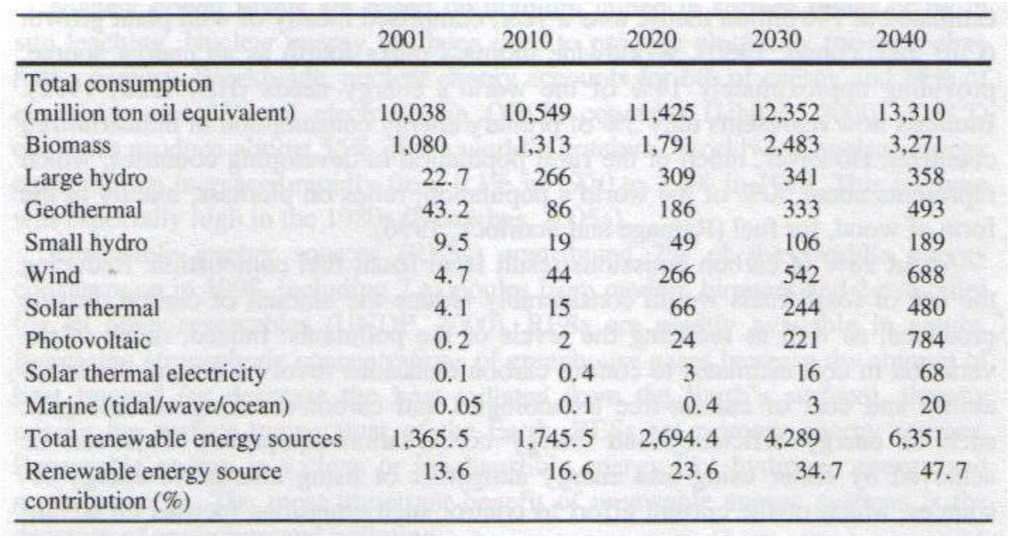
In physics, energy is defined as the capacity for doing work. Attached to this definition is a universal principle known as Conservation of Energy, that is: "Energy may change from one form to another, but the total amount in any closed system remains constant." (Tiwari & Ghosal 2007). This theorem is fundamental in explaining various energy phenomena.

Natural resources (regenerative or virtually inexhaustible) such as wind, geothermal, tidy, rain, and so on, can generate energy. The energy obtained from these resources is known as renewable energy. Table 2-1 shows the main renewable energy sources. Table 2-2 illustrates the scenario to be expected by 2040. This thesis will explore renewable energy produced by rotordynamics machinery.



Energy source	Energy conversion and usage options
Hydropower	Power generation
Modern biomass	Heat and power generation, pyrolysis, gasification, digestion
Geothermal	Urban heating, power generation, hydrothermal, hot dry rock
Solar	Solar home system, solar dryers, solar cookers
Direct solar	Photovoltaics, thermal power generation, water heaters
Wind	Power generation, wind generators, windmills, water pumps
Wave	Numerous designs
Tidal	Barrage, tidal stream

Table 2-1 Main renewable energy sources and their usage forms (Demirbas 2008 p8).



	2001	2010	2020	2030	2040
Total consumption (million ton oil equivalent)	10,038	10,549	11,425	12,352	13,310
Biomass	1,080	1,313	1,791	2,483	3,271
Large hydro	22.7	266	309	341	358
Geothermal	43.2	86	186	333	493
Small hydro	9.5	19	49	106	189
Wind	4.7	44	266	542	688
Solar thermal	4.1	15	66	244	480
Photovoltaic	0.2	2	24	221	784
Solar thermal electricity	0.1	0.4	3	16	68
Marine (tidal/wave/ocean)	0.05	0.1	0.4	3	20
Total renewable energy sources	1,365.5	1,745.5	2,694.4	4,289	6,351
Renewable energy source contribution (%)	13.6	16.6	23.6	34.7	47.7

Table 2-2 Global renewable energy scenario by 2040
(Demirbas 2008 p8).

Hydropower is a system that uses the potential energy of water flowing from a higher position to a lower position under the earth's gravitational forces. Rivers flowing from upstream areas in the direction of the ocean convert part of their power into kinetic energy with flow speed. This kind of energy conversion generates different types of hydropower: Impoundment Hydropower that employs a barrier to store water; Run-of–River hydropower that uses the natural flow of the river and Pumped Storage. When the demand for electricity is low, water is pumped up from a low reservoir to a high location where the resource is kept; however, when there is an increase in electricity demand, water goes in the opposite direction and electricity is generated by the water flowing from a higher location to a lower reservoir.

Prospecting works for **geothermal** resources are started with geographical inspection to locate rocks which have been chemically modified by a hot geothermal saline solution. Hot springs and mud are studied with great care as thermal expressions. Chemical studies and gas leakage through fissures permit assessment of the composition and potential of fluids. However, the most effective technique to locate geothermal resources is the combination of resistivity studies and electrical methods. When the aquifer is found, exploration and production wells can be drilled using methods such as hard rocks and high temperatures. The pressure of aquifers increases, reaching 10 MPa, so dense wet and soft earth is required to avoid a blowing if a gas column is discharged. (Kishore 2008)

There are different ways to control and use **wave power**. One option is to absorb energy using huge floating devices such as one designed in the United Kingdom by Salter, known as the “Nodding Duck”, or the so-called Wave Swing, which was developed in Holland. These devices allow the use of wave motion to pump liquids like water, or any other hydraulic liquid, through a turbine to generate electricity.

In modern times, **gas turbine** technology has had an important and extraordinary increase in popularity in the industry of power generation. In the 1960s, gas turbines were used predominantly by the aviation industry. During the next 20 years, they became an interesting resource as standby and peak power units due to their ease of start-up. In recent years, they have become one of the principal generators of power, reaching 90% of the new capacity in the United States for the coming years.

The air in movement is wind and the wind contains kinetic energy. The **wind turbine**, which is attached to a tall tower and has two or more blades mechanically fixed to an electric generator, catches kinetic energy. This kinetic energy is converted to mechanical energy or electric energy to be used for various tasks. (Nelson 2009)

Fossil fuels are replaced by biofuels. A great amount of production depends on fossil fuels, which means that burning fossil fuels is an important factor to the greenhouse gas emission related to biofuels. Natural gas is basic to make N fertilizers; fossil fuels based on mineral oil frequently power machines for agriculture and transport. Industries transforming biomass into fuels are mixed in their application of fuel. The process of biomass is associated with the emission of CH_4 due to anaerobic conversion and CH_4 is a tremendously flammable gas and asphyxiant (displaced oxygen) in an enclosed space. The capture and practical use of CH_4 in **electrical generation** by burning it as a fuel in a steam boiler or gas turbine should help.

Many facilities do not use any fossil fuels. In Brazil for instance, the factories that transform sugar into ethanol use harvest residues of sugar cane to power a machine. In countries like Sweden, biofuel production tends to use wood chips from forest residues. However in other countries like France and Germany, factories producing bioethanol usually operate with fossil fuels.

There may also exist non-CO_2 carbonaceous emissions connected to fossil fuel utilization. For example, during the transport and utilization of natural gas, there may be an escape of CH_4 (methane) and emission of hydrocarbons and/or carbon monoxide (CO) if the combustion process is not optimized. The tendency on a basis molecule-for-molecule analysis is that non-CO_2 carbonaceous gases has a greater greenhouse effect than CO_2. However, in life cycle evaluation, this effect is regularly ignored, although in solid industrial economies such underestimation will be small.

Despite the research that has been conducted in this area (the main biofuels from harmless vegetable oil crops and bioethanol from starch and sugar crops), there have been insignificant improvements, if any, over present fossil fuels.

Emission of biogenic carbonaceous greenhouse gases may be reduced by incrementing a carbon reserve during the period of feedstock development. The emission of greenhouse gases resulting from changes in ecosystem carbon stocks associated with land use resulting from expansion of feedstock production may be decreased or even inverted by the growing of feed stocks on soils with low carbon stocks. Furthermore, reduction of greenhouse gas emissions could be achieved by improving efficiencies in the transformation of feedstock to biofuel.

Currently, there has been an important reduction in fossil fuel use in the production of biofuels and additional reduction is expected. Ethanol has the first place due to efficiency.

In terms of feedstock, fossil fuels are replaced by agricultural residues, mainly in high yielding crops. In Thailand, for instance, coal is a fuel of relevance in transforming sugar cane into ethanol. Coal can be substituted for residues of sugar cane or the processing of oil palm fruits.

Concerning ethanol, with some restrictions related to maintenance soil C stocks, production of ethanol from sugar cane presents the additional option of **generating electricity** from the bagasse (a sugar cane residue).

In the case of sugar cane production, emission of pollutants can be reduced when the burning of sugar cane is replaced by mechanical means of harvesting.

Climate change and non-greenhouse gas emissions are two important factors in the life cycle of biofuels. Their study requires a consideration of the entire process of biofuels due to several impacts on the environment at every stage. In the agricultural area, significant impact may be expected from fossil fuel-powered machines as well as emissions from nitrogen fertilizers such as N_2O and nitrate and other substances such as pesticides. In particular, the Mississippi and the Atchafalaya rivers would augment the annual standard fluctuation of dissolved inorganic fixed nitrogen by 10-34% as a result of the US production of 15 billion gallons of ethanol. In countries like Brazil, the ethanol produced from sugar cane crops is a contributing factor to the fast change in the biochemical N cycle as nearly 30% of N fertilizer is deposited in the tissue of sugar cane. (Hordeski 2007)

The selection of cultivated plants to be used as biodiesel feedstock is also an important issue. This is because the production of isoprene – a contributor to oxidizing smog - changes from plant to plant. Energy consumption and emissions are linked to biomass production to be used in biofuels. As a result, the production of dry mill fuel ethanol is responsible for considerable emission of ethanol, acetaldehyde, acetic acid and ethylacetete. (Kemp 2006).

It is important to consider that life cycle impacts are generally affected by uncertainty. Evaluate life cycles imply uncertainty in input data (parameter uncertainty), in normative selections (scenario uncertainty) and math relationships (model uncertainty). In this study the model uncertainty is very much alike in all kinds of fuels.

In order to limit parameter uncertainty, it is important to use inventories of good quality emissions and data like the inventory of JLCA-LCA from Japan and the Ecoinvent database as well-related research. This view makes uncertainty rather limited, especially in developed countries. On the contrary, in some developing countries, uncertainty may be large due to major uncertainty surrounding fuels, energy efficiency and environmental technology. This is because uncertainty of C and N in cropping and feedstock is significant. In general, uncertainty of C stocks in ecosystems is considerable.

In the case of normative selections, they are an important base of uncertainty. In this case, we have to consider the length of time that the land will be used for the production of biofuels. This is important to determine the net greenhouse gas emissions because of changes in land use (Rejinders & Huijbregts 2009). Allocation for multi-output production is to be considered. There are three types of allocation, the first one is based on price, the second is based on physical categories including energy and weight, while the third allocation refers to substitution processes.

2.3 Research Methodology

Alternative energy in power generation is an important area for research in the 21st century and rotordynamics machinery is pivotal to this area. Turbines are responsible for large-scale power generation supplied to a primary grid. This thesis will explain the main power generation systems that use rotating shafts to produce electricity.

Chapter three analyses the fundamental principles of vibration and rotordynamics. Topics such as the torsional systems, Jeffcott rotor (rigid bearing support and flexible bearing support), the effect of support flexibility on critical speeds, fluid film bearings and magnetic bearings are explained.

Chapter four considers the main rotating systems technology that generates electricity with alternative energy. Hydropower, tidal energy, gas turbines, wave and thermal energy, wind turbines and geothermal systems are analysed.

Chapter five discusses the use of biofuels in power generation and explains the transformation process of biomass to produce electricity. Biofuel emissions such as N_2O, biogenic CO_2 emissions and other carbonaceous emissions are also explained. In addition, this chapter overviews biofuels and transport, with four cases being selected to illustrate gas analyser measures of emissions.

In chapter six, to illustrate the theory explained in chapters three, four and five, three systems - the Pelton turbine, wind turbine and gas turbine - are selected. Based on a scenario community of 900 homes, a mathematical model is developed to illustrate power generation in each case.

In summary, to meet the objectives, this thesis starts by explaining the mathematical principles of rotordynamics and progresses through several topics of alternative energy and biofuel to develop a mathematical model that illustrates turbines in power generation. Chapter seven presents the final discussion and conclusion.

This chapter has reviewed the general literature relating to the major topics in this thesis, namely Rotordynamics and Alternative Energy in Power Generation. The following chapters will look at the main concepts of Vibration and Rotordynamics and the mains systems that generate power using natural resources, review the topic of biofuels and electricity production, and present a practical example.

3. Rotordynamics System Vibration

3.1 Introduction

The inevitable growth in user requirements (larger size and high-speed machines) has increased dependency on maintenance based on complete consideration of vibratory motion. The rotating and reciprocating elements of a mechanism produce vibrations and noise, and the analysis of this crucial information is of vital importance in assessing the performance and general condition of the machine.

The mechanics of rotating machinery vibration is a crucial topic to consider aspects such as limits for vibration levels, machine durability, and reliability. These are obligatorily connected to the vibration characteristics implicit in this kind of design.

Fundamental topics in Mechanical Engineering such as torsional vibrations in rotating machines, whirling of rotating shafts, the effect of flexible bearings, fluid film bearings, magnetic bearings, rotor design, turbomachinery, rotor imbalance, and gyroscopic effects can be methodically understood only on the principles of Rotor Dynamic studies.

3.2 Mechanical System Analysis

The vibration analysis in this chapter is based on two books: *Engineering Vibration* (3^{rd} ed.) by Daniel J Inman and *Schaum's outline Mechanical Vibrations* by S. Graham Kelly.

3.2.1 Mechanical Vibration Components

There are several components in a mechanical system: inertia elements, stiffness elements and damping elements. When the system has movement, the inertia element presents kinetic energy. The kinetic energy for a solid body subject to planar movement is:

$$EC = \frac{1}{2} m\overline{v^2} + \frac{1}{2}\bar{I}\omega^2 \tag{3-1}$$

$\bar{v}$ is the velocity of the body's mass centre.

ω is the body's mass angular velocity about an axis perpendicular to the plane of motion.

m is the body's mass.

$\bar{I}$ is its mass moment of inertia about an axis parallel to the axis of rotation through the mass centre.

In a linear spring, the linear stiffness factor has a force displacement analogy:

$$\mathbf{F = k}\boldsymbol{x} \tag{3-2}$$

F is applied force and *x* component's change in length.

K is stiffness (dimensions of force per length).

In some cases, a mechanical system comprises *dashpot,* a mechanical element that provides viscous damping. The relation between force-velocity in linear viscous damping can be written in the form:

$$\mathbf{F = cv} \tag{3-3}$$

C is damping coefficient (dimensions mass per time).

3.2.2 Equivalent Systems Analysis

In figure 3-1, the simple mass-spring-dashpot represents 1-degree-of-freedom systems with viscous damping. If X is the generalized coordinate, the kinetic energy of a linear system is:

$$EC = \frac{1}{2} m_{eq}\dot{x}^2 \tag{3-4}$$

EC: Kinetic Energy.

X: Generalized coordinate.

And the potential energy is:

$$PE = \frac{1}{2} k_{eq} x^2 \tag{3-5}$$

The work done by a mechanism with viscous damping force in any linear system between two undetermined positions X_1 and X_2 can be represented as:

$$W = -\int_{x_1}^{x_2} c_{eq} \dot{x} dx \tag{3-6}$$

W is work done by the viscous damping force in a linear system between two undetermined positions X_1 and $X_{2.}$

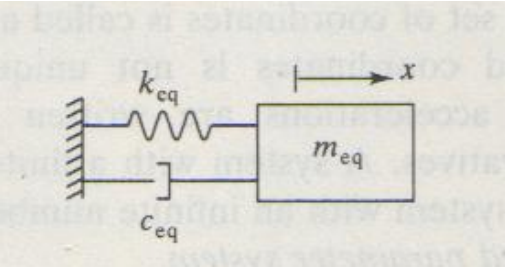


Figure 3-1 The simple mass-spring-dashpot (Kelly 1996, p 2)

3.2.3 Torsional Systems

If a linear system uses an angular coordinate as a generalized coordinate, the equivalent torsional system shown in figure 3-2 can represent the system. The angular velocity of the system is proportional to the moment applied to a linear torsional viscous damper while the moment applied to a linear torsional spring is proportional to the angular rotation of the system. In order to determine the equivalent system coefficients for a torsional system, in the original system it is necessary to calculate the kinetic energy, potential energy, and work done by viscous damping forces in terms of the generalized coordinate that has been selected:

$$EC = \frac{1}{2} I_{eq} \dot{\theta}^2 \tag{3-7}$$

$$PE = \frac{1}{2} k_{teq}\, \theta^2 \tag{3-8}$$

$$W = -\int_{\theta_1}^{\theta_2} c_{teq} \dot{\theta} d\theta \tag{3-9}$$

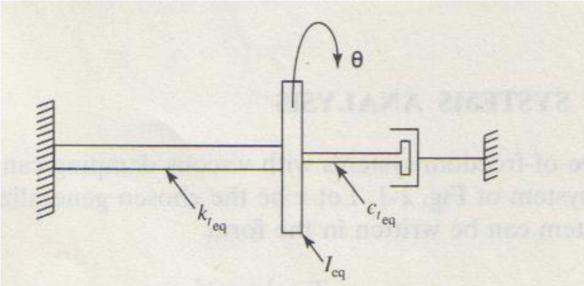


Figure 3-2 Torsional System (Kelly 1996, p 2)

3.2.4 Single-Degree of Freedom System

Newton's law of motion

In any engineering system, a particle with mass and elasticity is capable of changing position as a result of an applied force. The second law of Newton is the fundamental principle that governs movement and for a one-degree-of-freedom (DOF) system, the scalar equation can be written as:

$$\mathbf{\Sigma F = ma} \tag{3-10}$$

F is sum of forces acting upon body

m is mass of body

a is acceleration of the body

For the mechanism in figure 3-3, the equation of motion based in the second law of Newton is:

$$m\ddot{x} + c\dot{x} + kx = f(t) \tag{3-11}$$

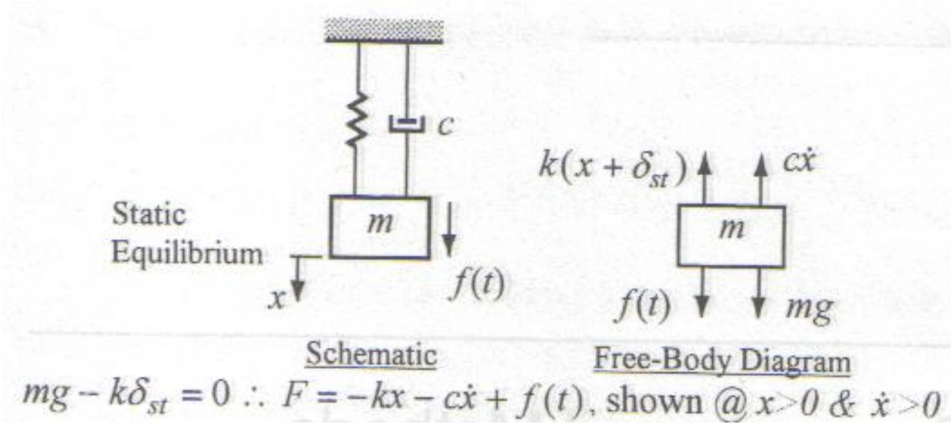


Figure 3-3 Single Degree of Freedom (Adams 2001, p 2)

Analysis of the free body diagram shows that the forces acting upon the rigid body are the externally applied time dependent force, f(t), the spring and damper motion-depending connections forces, -kx and $-c\dot{x}$. For the spring, the minus sign represents the force resisting displacement (X) in both directions from the equilibrium position and for the damper, it illustrates the force resisting velocity ($\dot{x}$). Finally, the resultant force between the static deflection that the weight causes in the spring and the weight (mg) is zero.

3.2.5 Unforced System

When the system is considered to be unforced, f(t) =0 and inertia, stiffness and damping properties can be expressed by the next equation of motion (second-order homogeneous ordinary differential equation):

$$m\ddot{x} + c\dot{x} + kx = 0 \qquad (3\text{-}12)$$

In order to solve this equation, it is necessary to specify the two initial conditions, X(0) and $\dot{x}$(0). In addition, it is necessary to assume C and K positives. For this equation, three kinds of solutions can be found:

(a) *underdamped*, (b) *critically damped*, and (c) *overdamped*

By replacing the known solution form $\left(Ce^{\lambda t}\right)$ in the second order differential equation, the extracted two roots (eigenvalues) $\lambda_{1,2}$ can be found as follows:

$$m\lambda^2 + c\lambda + k = 0$$

(3-13)

$$\lambda_{1,2} = -\frac{c}{2m} \pm \sqrt{\left(\left(\frac{c}{2m}\right)^2 - \left(\frac{k}{m}\right)\right)}$$

From the last equation, three types of root can be analysed:

1. Underdamped, $\left(\frac{c}{2m}\right)^2 < \left(\frac{k}{m}\right)$, complex conjugate roots,

$$\lambda_{1,2} = \alpha \pm i_{wd}$$

2. Critically damped, $\left(\frac{c}{2m}\right)^2 = \left(\frac{k}{m}\right)$ equal real roots

$$\lambda_{1,2} = \alpha$$

3. Overdamped, $\left(\frac{c}{2m}\right)^2 > \left(\frac{k}{m}\right)$ real roots

$$\lambda_{1,2} = \alpha \pm \beta$$

(from rotating machinery vibration, Adams)

Figure 3-4 illustrates X(t) time signals for these three solution categories:

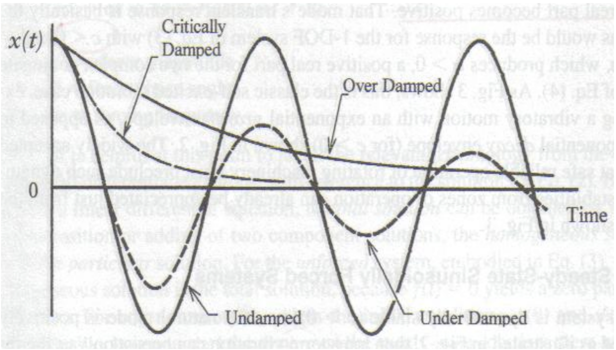


Figure 3-4 Motion types for the unforced one-degree-of freedom systems
(Adams 2001, p 3)

In several mechanical systems, the so-called under-damped roots models hold the most important vibration features; specifically, this is the case for rotor dynamics systems.

The motion of the unforced under-damped system can be represented in any one of the four modes below:

$$x(t) = Xe^{at} \begin{Bmatrix} \sin\left(\omega_d t + \phi_s{}^{+}\right) or \sin\left(\omega_d t + \phi_s{}^{-}\right) \\ OR \\ \cos\left(\omega_d t + \phi_s{}^{+}\right) or \cos\left(\omega_d t + \phi_s{}^{-}\right) \end{Bmatrix} \tag{3-14}$$

X single-peak amplitude of exponential decay envelope at t=0

$\omega_d = \sqrt{\left(\omega_n{}^2 - \alpha^2\right)}$ Damped natural frequency

phase angle, $\phi_s^- = -\phi_s^+ = \phi_c^+ + 90^0$ and $\phi_c^- = -\phi_c^+$ yield same signal

$\alpha = -\dfrac{c}{2m}$, real part of the eigenvalue for an under-damped system

$\omega_n = \sqrt{\left(\dfrac{k}{m}\right)}$, undamped natural frequency

$$i = \sqrt{-1}$$

(from rotating machinery vibration, Adams)

3.2.6 Steady-State Sinusoidally Forced System

In rotating machinery, the remaining mass unbalance distribution in the rotor is the long-term forcing mechanism that is continuously present and it can never be totally eliminated. Equivalent forces fixed in the rotor can describe rotor mass unbalance systems. The projected element of the mentioned rotating unbalance force varies sinusoid in time at the rotor spin frequency when it is analysed from a fixed radial direction.

The unbalance driven vibration of a rotor and the steady state response of the 1-DOF system illustrated by the differential equation of motion, show significant similarity. If $f(t) = F_0 \sin(\omega t + \theta)$

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin(\omega t + \theta) \tag{3-15}$$

F_0 = force magnitude

Θ = force phase angle

ω = forcing frequency

In general, the next four steady-state solution structure can express the solution for this equation:

$$x(t) = \begin{cases} \sin\left(\omega t + \phi_S^{+}\right) \; or \; \sin\left(\omega t - \phi_S^{-}\right) \\ \cos\left(\omega t + \phi_C^{+}\right) \; or \; \cos\left(\omega t - \phi_C^{-}\right) \end{cases} \tag{3-16}$$

The steady-state single-peak vibration amplitude (x) and its phase angle relative to the force (let Θ = 0) have a particular sinusoidal solution changing force Magnitude (F_0), frequency (ω), mass (m), spring stiffness (k), and damper coefficient (c) quantity. The standard normalised form in figure 3-5 shows this solution.

When $r = \frac{\omega}{\omega_n} = 1$ the maximum amount of base motion is transferred to displacement of the mass and resonance occurs.

The transmissibility ratio is bigger than 1 for values $r < \sqrt{2}$. It signifies that the motion of the mass is an amplification of the motion of the base. Also, it is important to note that for different values of r, the intensity of amplification depends on the damping ratio ζ; particularly, the smaller ζ generates larger transmissibility ratios.

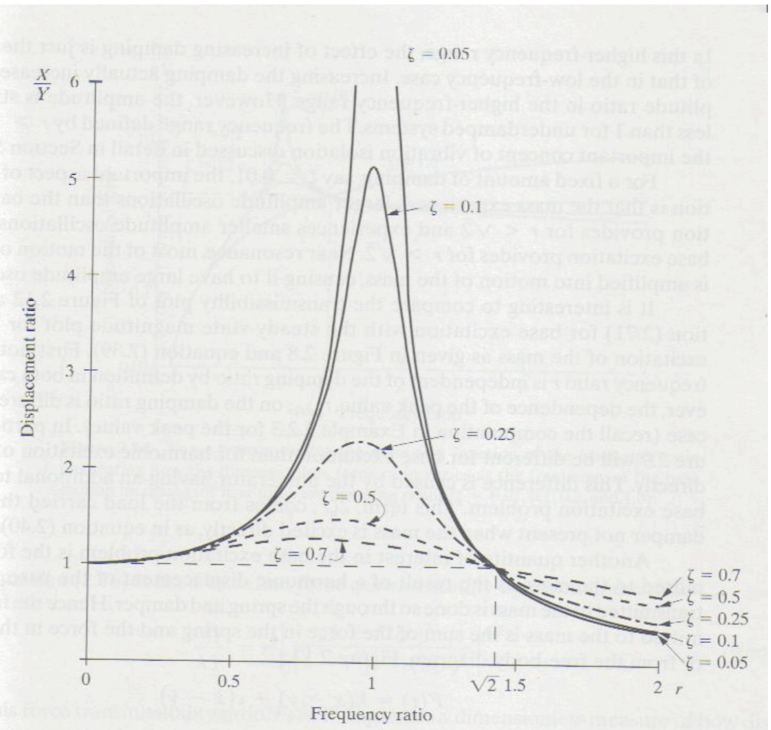


Figure 3-5: Displacement transmissibility as a function of the frequency ratio (Inman 2008, p 133)

The transmissibility ratio is less than 1 when $r > \sqrt{2}$; the amplitude of the motion of the mass is smaller than the amplitude of the base motion.

The result of increasing damping in this range of high frequency has the opposite effect compared to that in the low frequency because it increases the amplitude ratio.

3.2.7 Multi-Degree-of-Freedom Models

Two Degrees of Freedom

Figure 3-6 shows a general 2-DOF model. Analyzing the free body diagram and applying F=ma for each mass, the two equations of motion can be written:

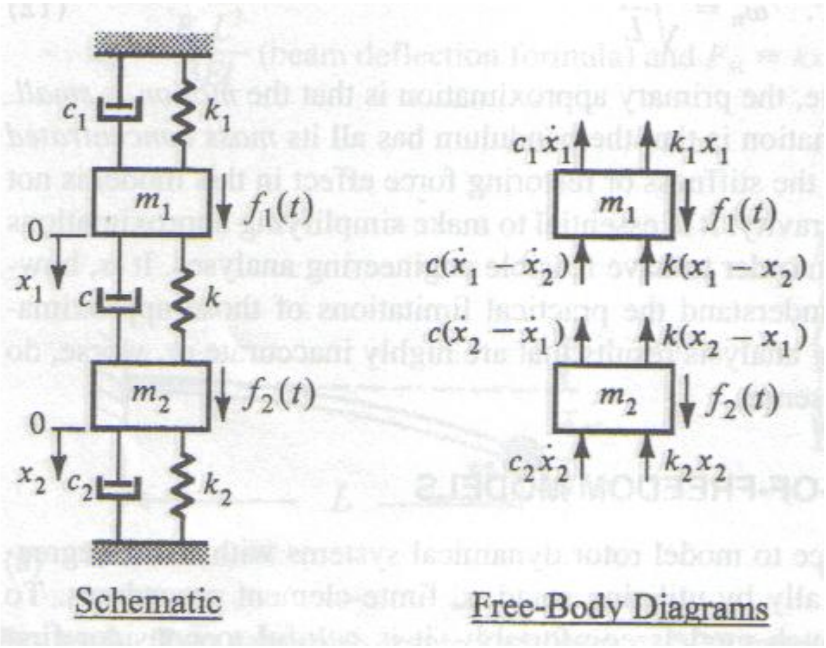


Figure 3-6: Two degrees of freedom model (Adams 2001, p 10)

$$m_1\ddot{x}_1 + (c + c_1)\dot{x}_1 + (k + k_1)x_1 - c\dot{x}_2 - kx_2 = f_1 t$$

(3-17)

$$m_2\ddot{x}_2 + (c + c_2)\dot{x}_2 + (k + k_1)x_2 - c\dot{x}_1 - kx_1 = f_2 t$$

When there are two or more DOFs, it is useful to use the matrix form to write the equation of motion:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c + c_1 & -c \\ -c & c + c_2 \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k + k_1 & -k \\ -k & k + k_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} f_1(t) \\ f_2(t) \end{Bmatrix}$$

(3-18)

In general, the motion equations can be written in a condensed matrix form when there is a multi-DOF system with a discretionary number of DOFs:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f(t)\}$$

(3-19)

[M] ≡ Mass matrix
[C] ≡ Damping matrix
[K] ≡ Stiffness matrix

The planar double compound pendulum (figure 3-7) is also a second 2-DOF example and a useful model for introducing the Lagrange equations. The Lagrange method directly applies Newton's second law, F=ma, but it does not use the free body diagram. The Lagrange equation, in its fundamental form for generalized coordinates q_i, is:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i \tag{3-20}$$

$$i = 1,2,3\ldots\ldots\ldots\ldots n_{DOF}$$

In this equation, $\mathbf{q_i}$ and $\dot{q}_i$ are the generalized coordinates and velocities. Respectively, **T** is the Kinetic Energy, **V** is the potential energy, and $\mathbf{Q_i}$ are generalized forces.

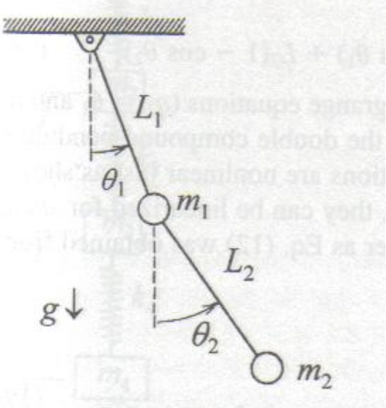


Figure 3-7: A planar double compound pendulum with concentrated masses. (Adams 2001, p 11)

Summarizing the two equations of motion for the 2-DOF double component pendulum:

Kinetic Energy:

$$T = \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 \qquad (3\text{-}21)$$

Here, m_1 and m_2 have v_1 and v_2 speeds respectively $\Longrightarrow$

$$v_1^2 = L_1^2 \dot{\theta}_1^2$$

$$v_2^2 = L_1^2 \dot{\theta}_1^2 + L_2^2 \dot{\theta}_2^2 + 2L_1 L_2 \dot{\theta}_1 \dot{\theta}_2 (\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2)$$

Potential Energy:

$$V = m_1 g L_1 \left(1 - \cos\theta_1\right) + m_2 g \left[L_1 \left(1 - \cos\theta_1\right) + L_2 \left(1 - \cos\theta_2\right)\right] \qquad (3\text{-}22)$$

Now, replacing T and V terms into the Lagrange equations (q_1= Θ_1 and q_2= Θ_2), it is possible to obtain the two equations of motion for the pendulum; however, those two equations are not linear. If we consider small motions (Θ_1<< 1 and Θ_2<< 1), they can be linearized to obtain the following:

$$\begin{bmatrix} (m_1 + m_2)L_1^2 & m_2 L_1 L_2 \\ m_2 L_1 L_2 & m_2 L_2^2 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} (m_1 + m_2) g L_1 & 0 \\ 0 & m_2 g L_2 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad (3\text{-}23)$$

More than Two Degrees of Freedom

A system has n degrees of freedom when it is necessary to select n independent coordinates in order to identify the position of the masses of the system. In general and compared with two degrees of freedom, similar analysis can be made to find the solution for n degrees of freedom.

3.3 Rotor Dynamics Analysis

The Rotor Dynamics analysis in this chapter is based on three books: *Rotating Machinery Vibration* by Maurice Adams, *Handbook of Rotordynamics* by Fedric F. Ehrich, and *RotorDynamics* by J.S. Rao.

3.3.1 The Jeffcott Rotor

The Jeffcott rotor consists of a central disk mounted on a massless flexible uniform shaft supported by two bearings. This simplex model shows many of the important features of more intricate systems in relation to response to unbalance. In addition, this model is an interesting tool that assists in analyzing the (lowest) critical speed in shafts.

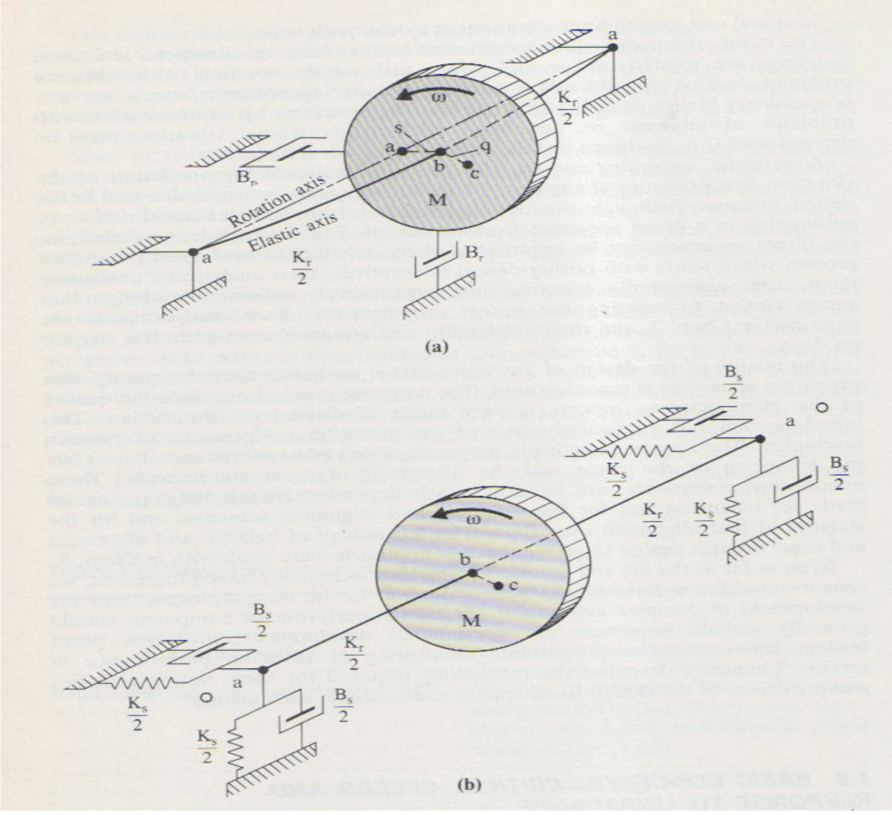


Figure 3-8 a) Jeffcott rotor on rigid bearing supports; b) Jeffcott rotor on flexible bearing supports. (Ehrich 1992, p 1.4)

There are two conditions to be considered in this model (figure 3-8):

a) Rigid bearing support, and
b) Flexible bearing support

3.3.1.1 The Jeffcott Rotor on Rigid Bearing Support

In this situation, the only damping B_r existing for the model is provided by the fluid medium around the rotor. As shown in Figure 3-8a, there are two types of unbalance: unbalance due to mass eccentricity **q** and unbalance due to shaft bolt **s.**

Case 1: Mass Eccentricity. In this case, the rotor disk centre of mass **c** is out of the elastic axis of the bar by a radial distance **q.** At idle position, point **b** exactly corresponds with the axis of rotation **a-a** (shaft bow=0). When the rotational speed of the mechanism increases, the centrifugal force of the eccentric mass **M** causes the elastic centre of rotor **b** to move externally and whirl around the axis of rotation at distance **r_b**. The response to unbalance based on the steady-state solution of the differential equation is determined as:

$$w_{b1} = \frac{r_b}{q} = \frac{\tau^2}{\left[\left(1-\tau^2\right)^2 + \left(2\zeta\tau\right)^2\right]^{\frac{1}{2}}} \tag{3-26}$$

$$\lambda_B = \arctan\frac{-2\zeta\tau}{1-\tau^2} \tag{3-27}$$

It is important to considered that the whirl amplification factor W_{b1} and the phase angle λ_b (the angle linking the displacement vector and the unbalance vector) are functions of the speed ratio τ

$$\tau = \frac{\omega}{v} \tag{3-28}$$

$$Where$$

$$v = \left(\frac{k_r}{M}\right)^{\frac{1}{2}}$$

ω: Rotational speed and v: undamped critical speed

K_r: Rotor stiffness M: rotor mass

$$\zeta = \frac{B_r}{2Mv} \tag{3-29}$$

ζ = Damping ratio B_r = System damping

2Mv= Critical Damping

Critical damping: Maximum value of damping over which the reaction of the system to an impulsive force does not present any oscillation.

Case 2: Shaft Bow. In this case, it is assumed that the rotor has perfect balance, the centre of mass **c** exactly corresponds with the elastic centre **b** (mass eccentricity q=0); however, the elastic bar or shaft shows a permanent bow due to thermal distortion or physical deformation. Thus, at the idle position, there is radial distance **s** (the bow in the uniform shaft) between the elastic centre **b** and the rotation axes a-a, as shown in figure 3-10a. When the speed augment, under the influence of centrifugal force, point **b** changes its initial position to a new position **b**$'$ with a whirl radius $\mathbf{r_b}$, the amplification factor W_{b2} based on the steady-state explanation of the differential equations can be written:

$$w_{b2} = \frac{r_b}{s} = \frac{1}{\left[\left(1-\tau^2\right)^2 + \left(2\xi\tau\right)^2\right]^{\frac{1}{2}}} \qquad (3\text{-}30)$$

The equation for the phase angle λ_b was given in case 1.

The whirl amplification factor W_{b2} is function of the speed ratio τ and the damping ratio ξ.

3.3.1.2 The Jeffcott Rotor on Flexible Bearing Support

The stator and the rotor are considered as flexible parts in this specific system and the only damping in this model is related with the bearing support.

In figure 3-8b, it is important to consider the specific case where the rotor is supposed to be infinitely rigid $(k_r = \alpha)$. Here, the mathematical model is the same as the pattern of figure 3-8a (the flexible rotor on rigid bearing supports). The undamped critical speed μ can be expressed as:

$$\mu = \left(\frac{k_s}{M}\right)^{\frac{1}{2}} \qquad (3\text{-}31)$$

K$_s$ is the Stiffness of the support and **M** is the mass of the rotor.

The division between rotational speed **ω** and the undamped critical speed **μ** generate a new speed ratio **σ**

$$\sigma = \frac{\omega}{\mu} \qquad (3\text{-}32)$$

The support damping **B$_s$** divided by the critical damped **2M μ** is equal to the new damping ratio **η**

$$\eta = \frac{B_s}{2M\mu} \qquad (3\text{-}33)$$

Figure 3-9 a and b and subsequent equations (applying to the flexible rotor on rigid bearing support) can represent the response to unbalance of the rigid rotor on flexible supports; however, before it is necessary to substitute **σ** for τ and **η** for ξ.

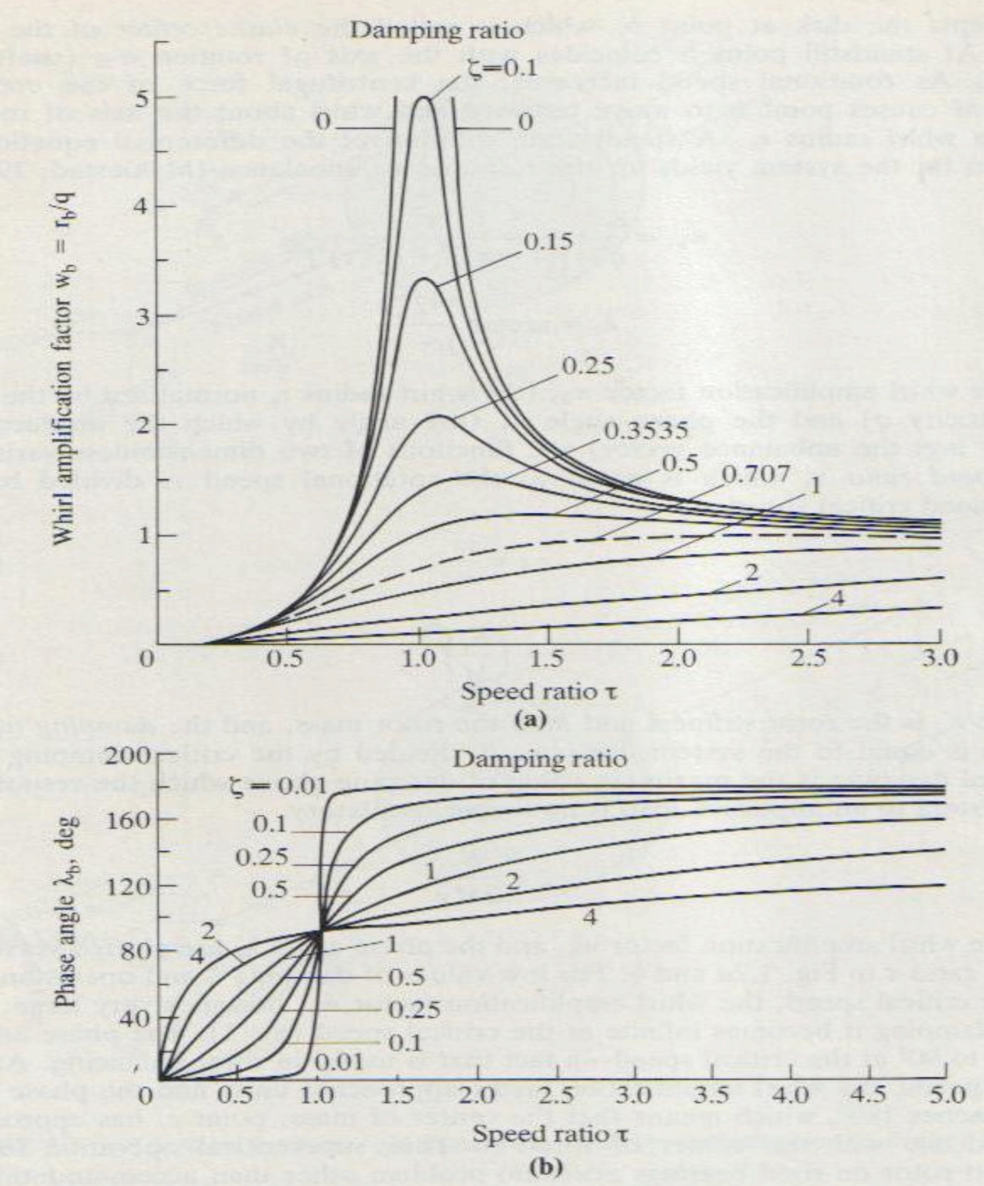


Figure 3-9 a) Response to imbalance (mass eccentricity q) versus rotational speed- Jeffcott rotor on rigid bearing supports b) Phase angle versus rotational speed- Jeffcott rotor on rigid bearing supports. (Ehrich 1992, p 1.6)

For the mechanism of figure 3-8b (flexible rotor and flexible supports), a steady - state solution of the differential equation of motion generate the response to unbalance.

$$\omega_a = \frac{r_a}{q} = \frac{\sigma^2}{\left[c_1^2 + (c_3 c_2)^2\right]^{\frac{1}{2}}} \qquad (3\text{-}34)$$

$$\lambda_a = \arctan\left(\frac{-c_3 c_2}{c_1}\right) \qquad (3\text{-}35)$$

$$\omega_b = \frac{r_b}{q} = \omega_a\left[(1+k)^2 + (c_3 k)^2\right]^{\frac{1}{2}} \qquad (3\text{-}36)$$

$$\begin{aligned} &\lambda_b = \arctan\frac{-c_3}{(1+k)c_1 + c_3^2 k c_2} \\ &Where \rightarrow c_1 = 1-(1+k)\sigma^2 \\ &c_2 = 1-\sigma^2 k \\ &c_3 = 2\sigma\eta \end{aligned} \qquad (3\text{-}37)$$

The phase angle λ_a is the relative angle between the displacement vector r_a and the unbalance vector q.

The phase angle λ_b is the relative angle between the displacement vector r_b and the unbalance vector q.

The equations systems are functions of three dimensionless variables: The speed ratio **σ,** the damping ratio **η,** and the stiffness ratio **k.**

The stiffness ratio is equivalent to the support stiffness $\mathbf{K_s}$ divided by the rotor stiffness $\mathbf{k_r}$

$$k = \frac{k_s}{k_r} \tag{3.38}$$

In addition, **k** may also be considered as a flexibility ratio. The static deflection **δ_r** in the rotor divided by the static deflection **δ_s** in the stator (deflected by the rotor's weight):

$$k = \frac{\delta_r}{\delta_s} \tag{3.39a}$$

$$\delta_r = \frac{w}{k_r} \tag{3.39b}$$

$$\delta_s = \frac{w}{k_s} \tag{3.39c}$$

W = rotor weight

Effect of Support Flexibility on Critical Speeds

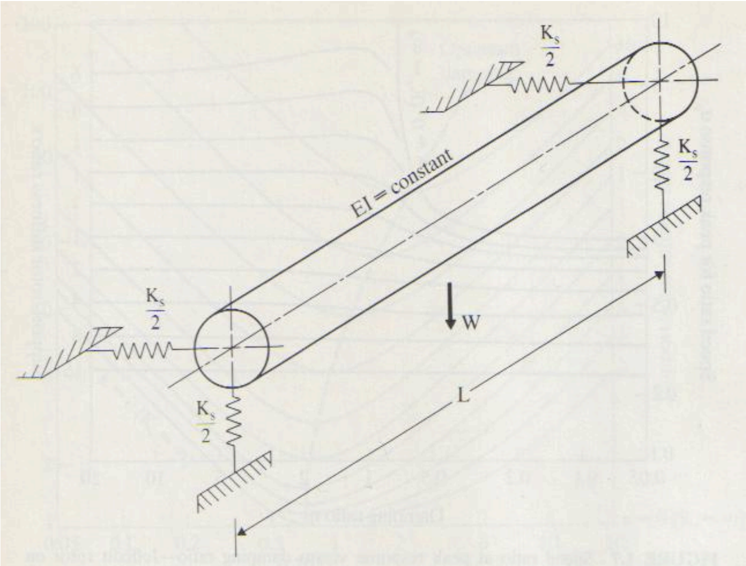


Figure 3-10 Rotor of uniform cross-section on flexible bearing support
(Ehrich 1992, p 1.18)

The effect of distributed mass can be represented by a simple model of a uniform bar of circular cross-section. The bar is supported by bearings on each side as figure 3-10 illustrates. The critical speed with bearing flexibility to the first critical speed ω / ω_1 on rigid bearings: (K_s=α) is plotted against the dimensionless function $\left[\delta_s \Big/ \left(g \big/ \omega_1^2 \right) \right]$

where δ_s represents the flexibility of the bearings supports (equation 3-39c) and $\left(\dfrac{g}{\omega_1^2} \right)$ corresponds to the flexibility of the rotor.

(figure 3-11)

The next equation represents the first critical speed ω_1 on rigid bearings:

$$\omega_1 = \pi^2 \left(\frac{gEI}{WL^3} \right)^{\frac{1}{2}} \tag{3-40}$$

Where g = acceleration due to gravity

E = modulus of elasticity

I = moment of inertia of cross section

W = total weight of span

L = span length

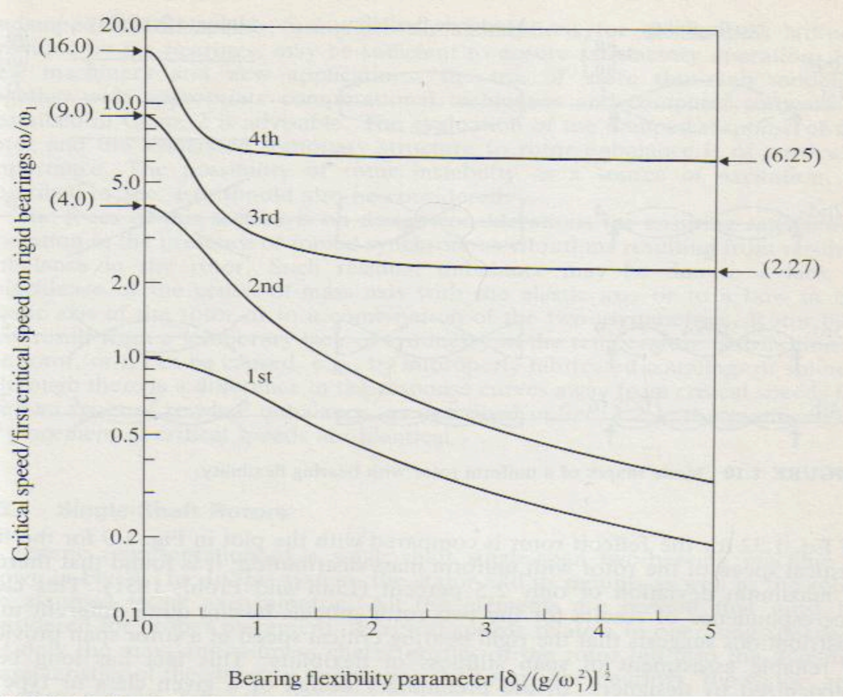


Figure 3-11 Critical speeds of a uniform rotor with bearing flexibility

(Ehrich 1992, p 1.19)

Here, it is important to note that the first and second critical speed ratios present a continuing reduction with increasing bearing flexibility for each value of the rigid bearing first critical speed ω_1. At the same instance, the relate mode shape steadily change and become the first and second rigid-body mode shapes for great values of bearing flexibility as illustrated in figure 3-12. The rigid-body critical speed for the first critical speed as well as for the second critical speed moves towards zero when the bearing flexibility approaches infinity.

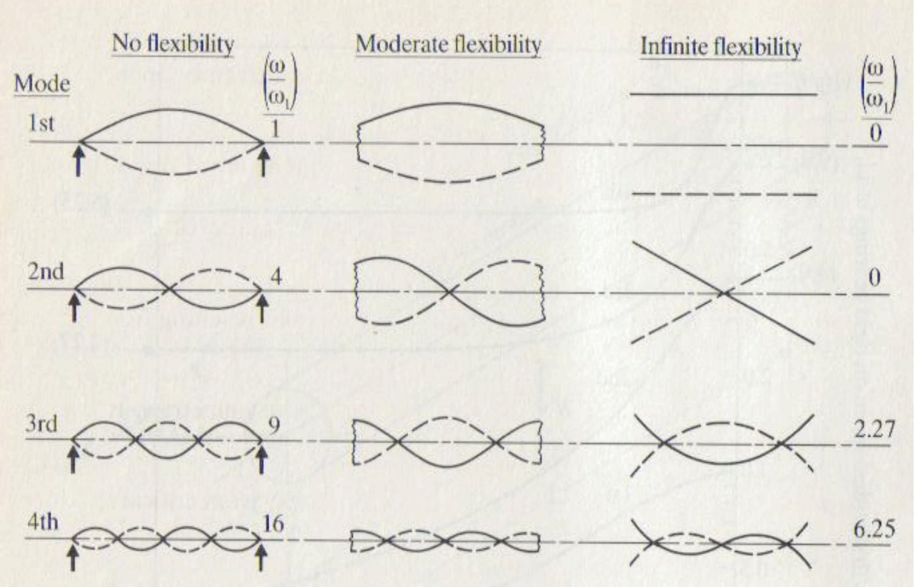


Figure 3-12 Mode shapes of a uniform rotor with bearing flexibility
(Ehrich 1992, p 1.10)

In the case of the third and fourth critical speeds, when the bearing flexibility augmenting the ratio of these speeds shows a fast regression, then they stabilize and asymptotically come close to values 2.27 and 6.25. In order to indicate the statement that there is no restriction in any support point, these two modes in many occasions are referred to as the first and second “free-free” modes of the system.

3.3.3 Comparison with the Jeffcott Rotor

The expression of the static deflection **δ_r** of the rotor on rigid bearings can be utilised to state the rigid bearing critical speed **V.**

$$V = \left(\frac{g}{\delta_r}\right)^{\frac{1}{2}} \qquad (3\text{-}41)$$

Resolving for **δ_r ,** the critical speed ratio is:

$$\frac{w}{v} = \frac{1}{\left(1+\frac{\delta_s}{\delta_r}\right)^{\frac{1}{2}}} = \frac{1}{\left(1+\frac{\delta_s v^2}{g}\right)^{\frac{1}{2}}} \qquad (3\text{-}42)$$

If the first critical speed of the rotor with uniform mass distribution plots in figure 3-11 is compared with equation 3-42 for the Jeffcott rotor, it is possible to verify that the maximum deviation is only 2.5 percent. This small difference indicates that the rigid bearing critical speed of a rotor span offers a consistent evaluation of span stiffness or flexibility for the two rotor models having relatively different mass distribution.

3.3.4 Fluid Film Bearings

Fluid film bearings frequently used in heavy rotating mechanism are mechanical elements that are crucial in the dynamic performance of rotors. The rotor load is supported by the thin film separating the dynamic surfaces; this film acts like a spring and provides damping caused by the squeeze film effect. The critical speeds and out of balance reaction of a rotor are considerably altered by the stiffness and damping characteristics of the oil film.

3.3.4.1 Liquid lubricated Fluid- Film Journal Bearings

The three coupled fluid momentum partial differential equations (the ‘Navier-Stokes’ equations) plus the single conservation -of- mass partial differential equations (the ‘continuity equation’) in general are the basis point for the mathematical representation of fluid mechanics problems. Applying Newton’s second law, $\sum \vec{F} = \frac{d(m\vec{v})}{dt}$ to a differential control volume of a continuum flow field, the three scalar Navier-Stokes equations can be obtained.

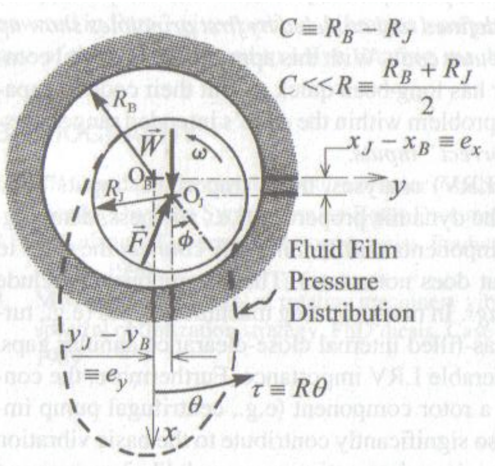


Figure 3-13 Generic journal bearing configuration and nomenclature
(Adams 2001, p 150)

In general terms, it is necessary to keep in mind that the classic Reynolds lubrication equations (RLE) are valid to an incompressible laminar (no turbulence) strictly viscous (no fluid inertia) thin fluid film between two closely spaced surfaces in relative motion. Figure 3-13 illustrates a basic journal bearing. All the nonlinearities (convective inertia terms) are eliminated from Navier-Stokes equations because of the neglect of fluid inertia. In addition, it is important to consider these assumptions:

Firstly, disregard the surface curvature and the gradients of fluid shear stress components in the local plane of the thin fluid film since they are extremely small compared with the gradients across the thin fluid film. Furthermore, ignore the fluid velocity and the change in local pressure normal to the local plane of the film. The Navier-Stoke equation for the direction normal to the film is removed after all the aforementioned statements are applied.

The remaining two Navier-Stokes equations are separated from the existing connection. Integrating these two differential equations and employing the surface velocity boundary conditions generate solutions for the two-in plane velocity distributions in the film. These velocity results with the conservation of mass condition generate the Reynolds equation.

For rotor dynamics conditions, the sliding velocity term results in the bearing stiffness coefficients and the squeeze film velocity term yield the bearing damping coefficients.

$$\frac{\partial}{\partial\tau}\left(\frac{h^3}{\mu}\left(\frac{\partial p}{\partial\tau}\right)\right)+\frac{\partial}{\partial z}\left(\frac{h^3}{\mu}\left(\frac{\partial p}{\partial z}\right)\right)=6\omega R\frac{dh}{d\tau}+12\frac{dh}{dt} \qquad (3\text{-}43)$$

(1) → Sliding Velocity term

(2) → Squeeze-film term

$$p=p(\tau,z),h=h(\tau,z),0\le\tau\le 2\pi R,-\frac{L}{2}\le Z\le\frac{L}{2};\mu=vis\cos ity$$

$p=p(\tau,z)$→Film pressure distribution→' unknown' term

$h=h(\tau,z)$→Film thickness distribution

L= Hydrodynamic-Active axial length of the journal bearing

3.3.4.2 Steady State Characteristics of Plain Cylindrical Hydrodynamic Bearings

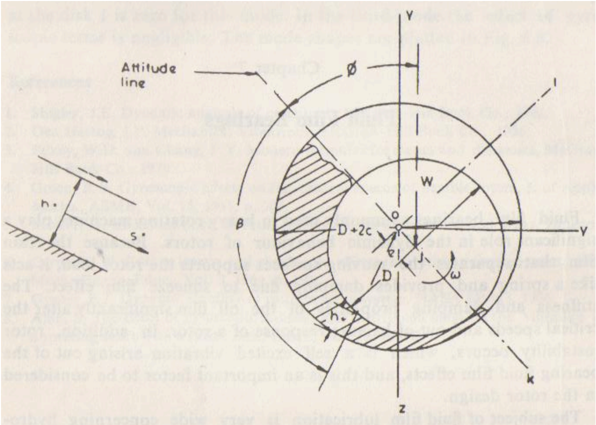


Figure 3-14 A plain Cylindrical Hydrodynamic Bearing

(Rao 1991, p 92)

D: Journal Diameter=2R; C: Radial clearance; e: Eccentricity; W: Radial load; h^*: Film thickness; Φ: Attitude angle; s^*: Coordinate=Rβ; U: Peripheral Velocity; ω: Speed (rad/sec); N: Speed (rev/sec);

Sommerfeld number=(μDLN / W) $(R/C)^2$; μ: Coefficient of viscosity

ε: Eccentric ratio e/C.

The Reynolds derived governing equation for the bearing in figure 3-14 is:

$$\frac{\partial}{\partial s^*}\left[\frac{\rho h^{*3}}{\mu}\frac{\partial p^*}{\partial s^*}\right]+\frac{\partial}{\partial x^*}\left[\frac{\rho h^{*3}}{\mu}\frac{\partial p^*}{\partial x^*}\right]=6U\frac{\partial\left(\rho h^*\right)}{\partial s*} \qquad \text{(3-44)}$$

In case the bearing operates under incompressible conditions, ρ (the density of the fluid) is eliminated in the above equation.

μ: Viscosity of the lubricant in centipoises units,

$1\text{cp}=1.0054\text{x}10^{-3}$ N sec/ m^2

x^* = axial coordinate

p^* = pressure developed in the film

Some dimensionless parameters are considered:

$$h=\frac{h^*}{C}$$

$$X=\frac{x^*}{L} \qquad \text{(3-45)}$$

$$p=\frac{p^*}{\mu N}\left\{\frac{C}{R}\right\}^2$$

Where L is the length of the bearing.

If $\partial s^{*} = R\partial\beta$, the Reynolds equation changes to:

$$\frac{\partial}{\partial\beta}\left[h^{3}\frac{\partial p}{\partial\beta}\right]+\left\{\frac{R}{L}\right\}^{2}\frac{\partial}{\partial X}\left[\frac{\partial p}{\partial X}\right]=12\pi\left[\frac{\partial h}{\partial\beta}\right] \tag{3-46}$$

Working specifically with plain cylindrical bearing, the film thickness is:

$$h = 1 + \varepsilon\cos\beta \tag{3-47}$$

Є is the eccentricity ratio

$$\varepsilon = \frac{e}{C} \tag{3-48}$$

Now the Reynolds equation can be written:

$$\frac{\partial}{\partial\beta}\left[(1+\varepsilon\cos\beta)^{3}\frac{\partial p}{\partial\beta}\right]+\left\{\frac{R}{L}\right\}^{2}\frac{\partial}{\partial X}\left[(1+\varepsilon\cos\beta)^{3}\frac{\partial p}{\partial X}\right]=-12\pi\varepsilon\sin\beta \tag{3-49}$$

If L/D >>> 1 (infinitely long bearing)

$$\frac{\partial p}{\partial X}\approx 0 \tag{3-50}$$

If L/D <<< 1 (infinitely short bearing)

$$\frac{\partial p}{\partial\beta}\approx 0 \tag{3-51}$$

Magnetic bearings

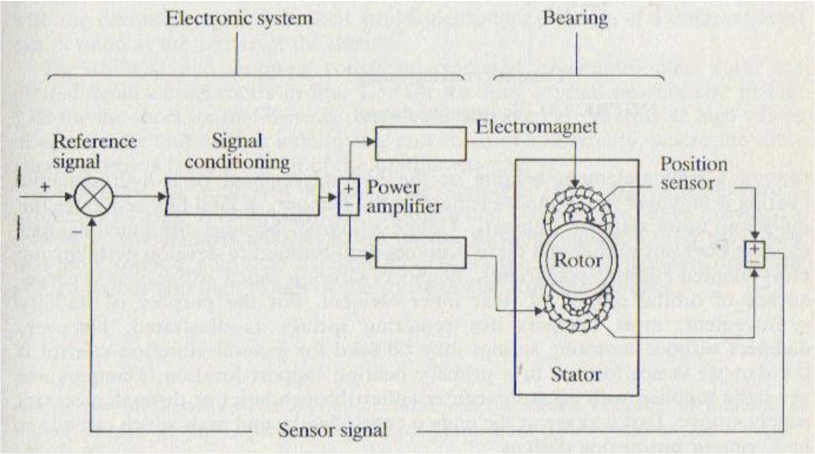


Figure 3-15 Magnetic bearing control loop schematic
(Ehrich 1992 p 1.53)

There are several characteristics that influence the load capacity of magnetic bearings such as geometry of electromagnets, power electronics, assembly and geometry of the electromagnets, and of the control laws – a diagram with main components is presented in figures 3-15 and 3-16.

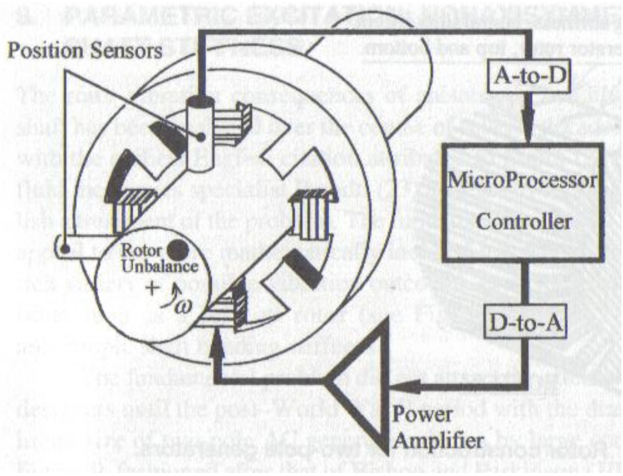


Figure 3-16 Active mechanic bearing carrying a rotor load
(Adams 2001, p 328)

Currents or permanent magnets generate magnetic fields, and magnetic fields generate magnetic forces.

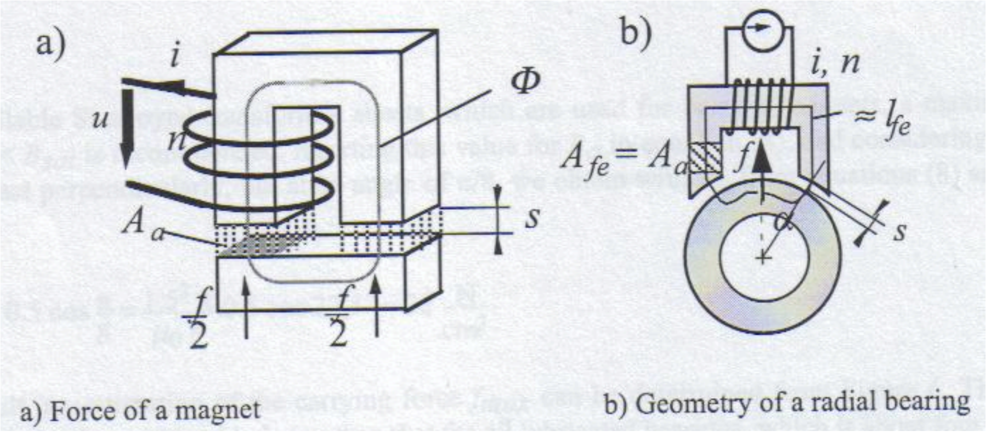
In magnetic bearings technology, the magnetic flux circulates in a magnetic loop due to electromagnets or permanent magnets. The magnetic flux **Φ** can be represented by magnetic fields lines and the density of these lines denotes the flux density **B.** Now, the flux density **B** and the magnetic field **H** (magnetic induction) are connected by:

$$\vec{B} = \mu_0 \mu_r (H) \vec{H}$$

μ_0 = 4π 10^7 V_s / Am remains for the magnetic field constant of the vacuum.

μ_r = Relative permeability depending on the medium the magnetic fiels acts. μ_r = 1 in a vacuum and approximately the same in air. When ferromagnetic material ($\mu_r >> 1$) is used, the core of the material concentrates the magnetic loop.

Figure 3-17 illustrates a single two pole magnetic bearing (part of a complete bearing ring of figure 3-16) showing the direction of the magnetic flux **Φ.**



a) Force of a magnet

b) Geometry of a radial bearing

Figure 3-17 Single two pole magnetic bearings
(Schweitzer 2002, p 2)

In order to derive the force in an Active Magnetic Bearing) AMB, it is necessary to consider some assumptions:

In the magnetic loop, the iron part l_{fe} is disregarded; the iron core and the air gap present a homogeneous flux Φ; the cross sectional areas are identical ($A_{fe} = A_a$); a long the magnetic loop, the induction $B=B_a$ is the same. The current **i** is proportional to the induction **B** until the saturation induction B_{sat} is achieved. Force **f** apply can be found by taking into consideration energy $\mathbf{W_a}$ accumulates in the air gap between magnet and rotor:

$$W_a = \frac{1}{2} B_a H_a A_a = \frac{1}{2} B_a H_a A_a 2s \qquad \text{3-52}$$

Thus

$$f = \frac{dWa}{ds} = B_a H_a A_a = \frac{B_a^2 A_a}{\mu_o} \qquad \text{3-53}$$

This chapter has presented a review of the mathematical models of Vibrations and Rotordynamics, which serves as a basis for further study of Rotordynamics and Power Generation.

The next chapter will address rotating systems in electricity generation technology.

4. Rotating Systems in Electricity Generation Technologies

4.1 Introduction

The generation of power involves processing electricity from other types of energy. In turbines and compressors, turbo machinery transfers energy between a rotor and a fluid. When the flow is perpendicular to the axis of rotation, the machines are called radial or centrifugal, but, if the flow is parallel to the same axe, they are designated as an axial.

In the 21st century, renewable energy is an area of great importance. By 2040, power production from renewable sources will constitute more than 80% of global electricity generation. Natural resources such as falling water, wind, gravitational forces (tides) and geothermal energy are converted to marketable energy by renewable energy technology.

Clearly, there is no other area that brings more optimism and greater expectation than to find the technology that allows us to meet the challenges of climate change and secure the supply of energy.

4.2 Hydropower

Hydropower, also called hydroelectric power, is the oldest renewable energy resource in which water from rivers and streams can be captured and turned into hydropower. More than 40 per cent of the electricity used in developing countries and approximately one quarter of the world’s total electricity supply is provided for large-scale hydropower systems.

Turbines are used in most facilities to transform hydro energy to electricity by turning an electric generator attached to its rotating shaft.

These days, hydropower installations are very efficient and the production ranges are from just a couple of kWe up to 10.000 MWe.

Figure 4-1 Hydropower Turbine
(Cink.(n.d.). *Turbines photogallery*. Retrieve from http://www.cink-hydro-energy.com/galerie/turbiny/galerie/pelton/pel_kolo.jpg)

Hydropower has been used for hundred of years in the milling of grains, textile industries and other light industries. It has been in use since the 18th century, during the days of the industrial revolution in Europe and in the US. At that time, many plants were located along riverbeds for producing power and transporting goods.

Near the beginning of production times, water wheels were mostly used for generation of mechanical power (Reynolds, 1983). Nevertheless in China, India and in the less developed nations, small systems of hydropower are still working and they are an important part of the production chain (Boyle2004).

What kinds of hydropower turbines can we find?

Impulse and reaction are the two principal types of hydropower turbines. Selection depends upon the height of the water stored, which is known as the head, plus the water in the site. Depth, efficiency and cost are other factors to be borne in mind.

In the impulse turbine, the rotating system of blades (runner) is moved by the velocity of the water. The down side of the turbine does not operate with any kind of suction and the water flows leave the lowest part of the rotor after hitting each bucket in the system.

A Pelton wheel uses several jets in order to eject water into an aerated area hitting the buckets of the runner. The rotating system has to be located above the highest tailwater in order to operate under atmospheric pressure conditions.

The Turgo Wheel is a kind of Pelton wheel. This cast wheel has a shape similar to a fan blade with closed external edges. The water is applied on one of the sides across the blades and it goes out through the other side.

Cross flow

This type of turbine is shaped like a drum and operates with a rectangular, elongated nozzle directed against curved vanes on a runner in the form of a cylinder. This permits the water to flow from the outer side of the blades into its interior, and then from the inside to the outside again. There is a guide which directs the jet to some part of the runner. Cross flow turbines can handle much more water than the Pelton wheel with a minor head.

Francis

The Francis turbine has a rotating system of blades with buckets or vanes, regularly nine or more, that are fixed. Above the runner and around it, water is injected so that later the water falls through producing the runner spinning action. In addition to the runner just described, the turbine has other important parts known as the scroll case, draft tube and wicket gates.

Kinetic

Kinetic power turbines are also known as free-flow turbines because they use natural kinetic energy that is part of the flowing water to produce electricity instead of potential energy from the head. These systems operate in artificial channels and rivers and also in the ocean. Large civil works are not required for Kinetic applications, although they can make use of bridges or channels.

According to the United Nations Development programme (UNDP), there are three kinds of small hydropower projects:

Micro: projects in the range 1-100kW

Mini: projects in the range 100 kW to 1MW

Small: no universal consensus, however the range is 1 MW to 30 MW.

In 1996, the European Small Hydro Association estimates small hydro capacity at 47,000 MW around the world with a further 180,000 MW remaining to be exploited. The small hydro capacity of the European continent is approximately 9000 MW and there are places for 18,000 MW more. There is capacity of up to 70,000 MW for sites to be exploited in China. Madagascar claims it has a theoretical small hydro potential of 20,000 GWh each year. Clearly, in various countries around the world, this area represents a solid and interesting prospect for development.

Hydropower works with water and thus does not pollute the air. In addition, it relies on the water cycle, and is therefore a renewable power source. Moreover, electricity on demand can be supplied using several types of engineering technology. In many cases, hydropower reservoirs can be used for recreational purposes like swimming, fishing and boating (Johansson, Kelly, Reddy & Williams 1993).

In contrast, hydropower systems can be impacted by the climate and, if the availability of water is not sufficient, the capacity of the plant can be affected. What is more, hydropower plants may have a negative influence on aquatic life if it interferes with fish migration.

4.3 Wave and Ocean Thermal Energy

According to Dutch researchers, the world has 20,000km of coastline, making it possible to use wave power.

In the 1970s, there was an interesting advance in this area with the development of the Wells Turbine. The design of this technology allows a kind of wind turbine to rotate at all times in the same direction, independent of the wind direction. The 'oscillating water column' system is based on this principle and when the wave goes up and subsequently falls, an oscillating wind current is created in an air compression chamber. This process allows the bidirectional turbine to operate without any complicated and costly check valves.

Norway has built a channel that gradually narrows and when the water flows along it, the water level increases and reaches a tank located above sea level. Power is produced as the wave falls back to the sea through hydroelectric generators.

As waves are the result of wind blowing across large bodies of water, wave energy resources are greater when winds are strong.

Wave power varies according to the square of the wave height and linearly with respect to the wave period. Wave energy is the most concentrated form of energy that can be renewed.

Figure 4-2 Wave energy conversion devices (Green living Answers.(n.d.). *Wave farms, hydropower and the pelamis wave energy converter*. Retrieve from http://www.greenlivinganswers.com/archives/156)

Energy from waves is variable in time, and this occurs also with wind energy. Available wave energy can be predicted somewhere between 24 and 48 hours in advance by using satellites to remotely sense the surface winds and wave heights across the ocean area.

Wave power is still in the phase of development and therefore is not commercially viable at the moment.

Ocean Thermal Energy

Ocean Thermal Energy Technology is known as OTEC. It takes energy from differential temperatures between the warm waters on the surface and the cool layers deep in the ocean. In order to use this resource, a 20ºC difference is required at the depth of one kilometre.

This technology employs solar energy principles, making use of the ocean as a large solar collector. Similar to the way that steams are used in power plants, OTEC uses a fluid-like ammonia to operate a turbine. However, because this technology is ten times less efficient than standard power stations, in order to produce the energy required, the system needs to pump enormous quantities of water.

OTEC is an alternative resource for island towns where fuel has to be imported. In addition, the technology can also provide desalinated water.

Unfortunately, the main problem with producing commercial energy with this resource is the cost of the technology, and its operation is restricted to demonstration plants in the Pacific.

OTEC systems comprise the following features:

(a) Closed cycle: Using fluids with a low boiling point, like ammonia, to rotate turbines.

(b) The mini TEC experiment developed in 1979 by the Natural Energy Laboratory achieved the first production at sea of electrical power from the closed cycle OTEC.

(c) Open cycle: Electricity is made from warm surface waters. When this water is placed in a container at low pressure, it starts to boil and the expanding steam powers a low-pressure turbine which is connected to the generator. The steam without salt as it remains in the container at low pressure is the freshest water.

Figure 4-3 Ocean–based renewable energy plant – Kona coast of Hawaii
Wapedia.(n.d.).*Wiki: Ocean thermal energy conversion* (1/3). Retrieve from
http://images.gizmag.com/gallery_lrg/otec-hawaii.jpg

(d) In order to transform warm seawater into low-pressure steam, a vertical-spout evaporator was designed by the National Renewable Energy laboratory. Efficiencies of energy conversion of 97% were achieved and then an OTEC experimental plant in Hawaii generated around 50,000 watts of electricity.

(e) Hybrid: This is a combination of closed/open cycles. In this case, the seawater penetrates a vacuum chamber where it is evaporated to form a steam in a way similar to the open cycle system.

4.4 Geothermal Energy

The earth was formed approximately 4600 million years ago by hot substances. It then cooled and the surface became a hard layer. Inside, however, it continued to contain material at a very high temperature. At the centre, the temperature is about 7000ºC, so the huge temperature difference between the surface and the interior generates a gradual heat flows out. The earth also has radioactive isotopes such as thorium 232, uranium 238 and potassium 40 which create heat during their disintegration. The flow of heat produced by the earth each year is 10^{21} J, which is small when compared with 5.4×10^{24} J from the sun's energy over the earth. In the end and in a gradual process, the heat is transported through the earth by hot substances.

Figure 4-4 Turbine generator at geothermal power plant

(Alternative Energy News 2009, *Geothermal Energy: Intelligent Use Of The Earth's Heat.* Retrieve from http://www.alternative-energy-fuels.com/geothermal/geothermal-energy-intelligent-use-of-the-earth%E2%80%99s-heat)

The variation in temperature from one side to the other side of the convecting layer is minimal because the convective heat transfer process is very effective. However, near the external layer, at a distance of approximately 100 km, materials are too hard to convect, which means that heat has to be carried by another process called conduction. The lithospheric plates - fragments that appear when the solid external boundary layer breaks down - move through the surface a few centimetres every year being controlled by the convective motions underneath.

Technologies for utilization of geothermal resources

Technologies that benefit from geothermal heat are divided into two groups: the use of geothermal fluids directly and the use of heat exchangers for removing heat. The direct technique can in turn be divided into dry steam plants, single flash plants and double flash plants.

Dry steam plants operate where there is an availability of 180-185ºC and 0.8-0.9 MPa. Modern plants can achieve 6.5 kg steam/kWh. Non-condensable gases, including carbon dioxide and hydrogen sulphide, affect the plant efficiency.

In relation to the single flash system, the fluid that comes up to the surface is a wet steam because the water is flashed inside the well or it may be that hot water is found at a high pressure. Frequently, it is a better practice to avoid the flashing inside the well as this could result in the formation of scale deposits that finally plug the well. Conventional steam turbines can also be used, but they are less efficient because of their lower steam and pressures.

Double flash systems (figure 4-5), on the other hand, are the best choice in cases where geothermal fluids have low levels of contamination. Thus, problems with oxide or non-condensable gas are minor. The steam is then combined with the exhaust coming from the turbine operating at a high pressure to move a second turbine, increasing the power efficiency by 20% or 25% for just 15% in costs of plant.

Indirect procedures that use geothermal heat employ a binary cycle plant or ORC (Organic Rankine Cycle) (figure 4-6) system which uses a secondary fluid with a boiling point less than water, for example pentane or butane, which is employed to power the turbine. (Kishore 2008)

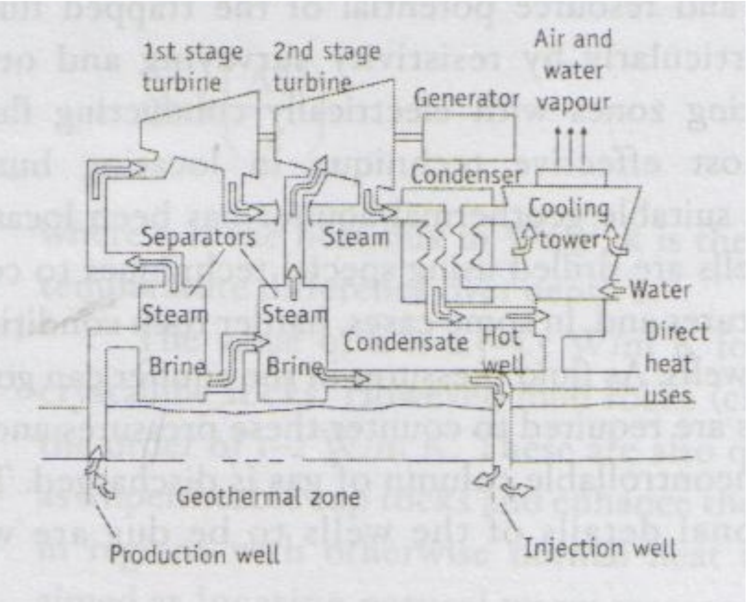


Figure 4-5 Double-Flash steam power plant
(Kishore 2008 p 602)

These plants have been used in solar ponds and in systems of the OTEC (Ocean Thermal Energy Conversions) as their advantages are working with low temperatures as well as providing protection from pollution. However, their capital costs and power consumption are high as they use large injection pumps and secondary fluid operation, etc.

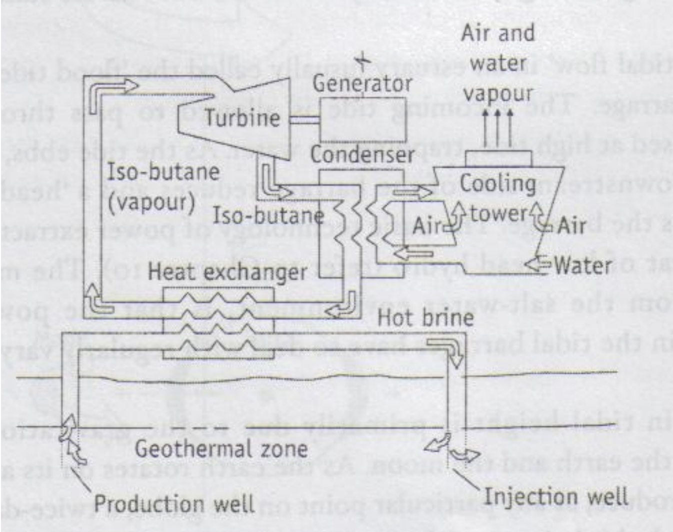


Figure 4-6 Binary cycle power plant (Kishore 2008 p 603)

4.5 Gas Turbines

A number of factors have contributed to the development of this technology. In Europe and the USA, gas is now available due to the deregulation of its supply and the growing expansion of its networks. Furthermore, coal fired plant operations are now expensive due to strict emissions-control regulations, making pollution-free natural gas more viable. In addition, from an economic standpoint, deregulation of the power sector has attracted innovative generating companies looking for quick revenue from theirs investment. The infrastructure of gas-turbine-based power stations can be developed very quickly as they are based on standardized units, and the capital cost of gas turbines has had a gradual decrease, making a viable investment.

Conversely, the most influential aspect in the establishment of gas turbines has been the development of a plant which operates in a combination of cycles. With this design, a single power station works with a mixture of gas and steam turbines. This leads to a unit of power generation that is reasonable from a cost standpoint, operating with high capacity, great efficiency and low emissions. These plants operate with a net conversion efficiency of about 50% and potential efficiencies of 55%. Thus, combined cycle plants provide power generation companies with a product that provides the most in terms of economic and environmental benefits, which is the best that technology can offer at this time.

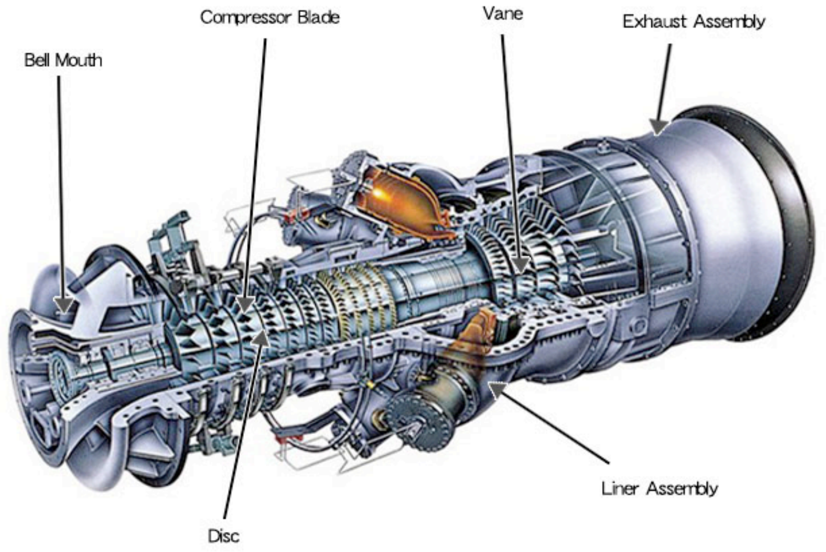


Figure 4-7 Gas Turbine (Japan Air Tec Co. *Gas Turbines*. (n.d.). Retrieve from http://www.j-airtec.co.jp/e_gas.html)

However, this unexpected popularity was a source of concern for power generating companies. For example, in the United Kingdom in the 1990s, the market refocused on gas-fired plants operating with combined cycles. At the end of that decade, new regulations in the market led to a substantial decline in electricity prices and there was concern that the economic impact would prevent combined cycle plants from generating power at a reasonable profit.

Economic factors then become the main inconvenience for gas turbine power generation. Gas turbine technology is not expensive; however, the combustible, generally natural gas is not cheap. Electricity and gas prices are consequently neuralgic points where it is necessary to evaluate the financial side of gas-based generation.

Gas turbines can use diverse kinds of fuel such as coal-bed methane. However, the modern trend is to burn natural gas and biogas.

There are some disadvantages associated with biogas and biomass. When compared with coal or liquid petroleum or petroleum-derived fuels, the energy density is low. Furthermore, chemistry processes for transforming biomass, such as bioconversion, increase working costs.

NATURAL GAS

The change from coal and oil plants to natural gas-operated plants is a widespread trend. Natural gas production increased by 4.1% in the 1996 to 1999 period. In China, for instance, the increase was 10.9% in 1999 while in the Asia Pacific region the increase was 6.5% and in Africa 9.1% according to the World Energy Council statistics.

In 2001, the United States was the biggest consumer according to the United States Energy Information Administration, followed by Russia, Germany, the United Kingdom and Canada. In contrast, Russia and the United States were the countries with the biggest annual production, together around 44%, followed by Canada, UK and Algeria.

It is expected that natural gas usage will increase in Europe in the coming decades. Consumption passed from 332 million tones of oil-equivalent in the year 2000 and is predicted to pass 471 by 2020, representing a rise of 42%. The United Kingdom, Germany, Italy, France and the Netherlands are the main consumer countries in Europe. However, the United Kingdom and the Netherlands alone generate significant quantities of gas. The other countries need to import the fuel to supply the internal consumption.

The use of natural gas results in lower environmental pollution in comparison with coal or oil. This includes lower levels of emissions from sulphur dioxide, nitrogen oxides (NOx), hydrocarbon particulates and carbon dioxide. Consequently, regulations can be met by using gas for power plants instead of using coal or oil.

The gas industry is willing to work on the promotion of gas as a clean fuel, but there is strong criticism to this move. The future of sustainable energy must make use of renewable sources of energy and the problem is that gas is not renewable at all. That is, the supply of gas in the world is limited.

The United States and Western Europe are very concerned about their gas reserves. At the current production rates shown, gas reserves in the United States will be exhausted within nine years. Elsewhere, estimated reserves are still substantial. For example, in Western Europe, countries such as the Netherlands and Norway have extensive gas reserves and Western Europe imports large quantities of gas from Russia and Algeria. However, this could be dangerous from the perspective of energy security.

There are some disadvantages associated with biomass. When compared with coal or liquid petroleum or petroleum-derived fuels, the energy density is low. Furthermore, chemistry processes for transforming biomass, such as bioconversion, increase working costs.

4.6 Wind Power

Wind is the change in the position of the air due to differences of pressure in the atmosphere. This differential pressure creates a force causing masses of air to move from a high-pressure region to another region where the pressure is lower. However, why is wind said to be a kind of solar energy? The answer is that heating from the sun over the earth's surface causes differences in atmospheric pressure.

Every year, approximately 1.7 million TWh of energy in the form of wind is generated over the earth's landmasses. This quantity does not refer to the entire planet, for which the energy is much greater. However, just a small fraction of energy from wind can be a useful type of energy.

The Size of Turbines

The first wind turbines dating back to the 1970s and early 1980s had a capacity of 30-60 kW. During the 1980s, their capacity progressively increased and projects were developed for a capacity of more than 1MW. However, by the 1980s, the standard wind turbine had a capacity ranging from 300 to 500 kW.

At the turn of the century, manufacturing companies started to introduce various types of multi-megawatt machines. In 2004, 2MW units were very common. However, in recent times, larger turbines with a 5MW capacity have been developed and these have blades of up to 60m in length.

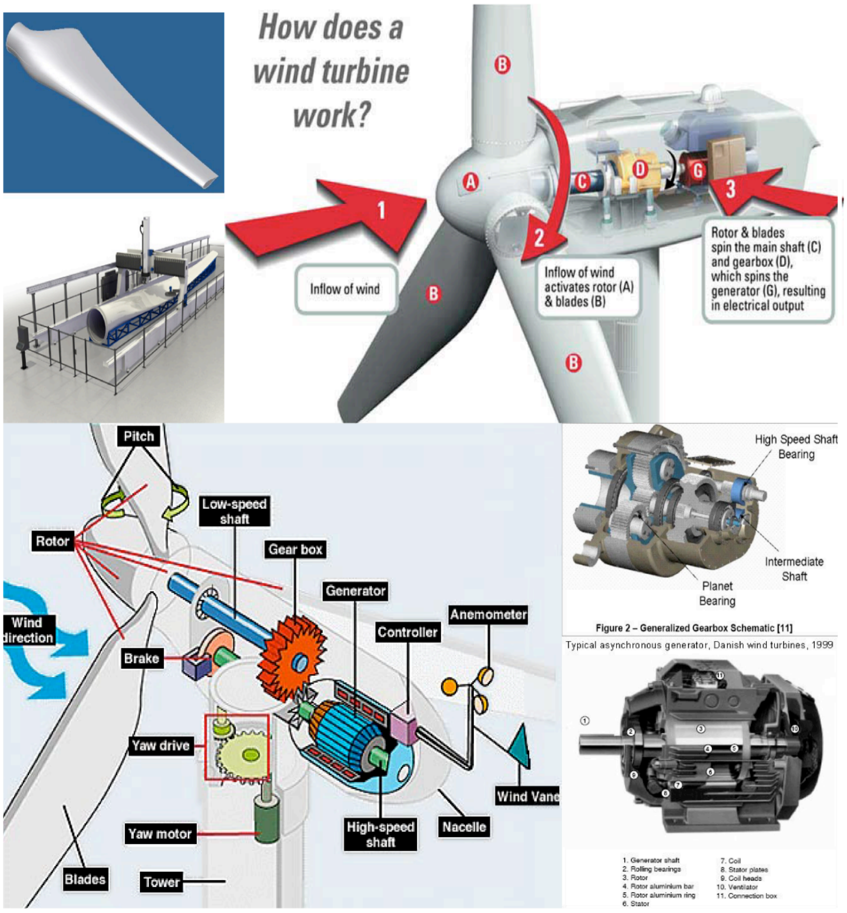


Figure 4-8 Wind Turbines Maes, B. (2009).*Part 1: Green Technology~ Wind Turbinesand CNC.* Retrieve from http://bertmaes.wordpress.com/2009/07/02/part-1-green-technology-wind-turbines-and-cnc/

Are they horizontally or vertically operated?

Standard wind turbines are equipped with a vertical rotor connected to a horizontal shaft. The rotor turns vertically and blades must therefore be elevated above ground. They also have a gearbox and a generator high above ground as they are directly connected to the shaft. This system is therefore costly in terms of installation and maintenance. In addition, horizontal axis wind turbines require a yawing mechanism so that the rotor and the nacelle are able to rotate when the wind changes direction.

Vertical axis wind turbines present an interesting alternative. These types of machines have a ground-level bearing that supports all of their weight. The gearbox and generator can also be place on the ground so maintenance costs are lower than those associated with horizontal axis wind turbines. Furthermore, vertical axis wind turbines work regardless of wind direction, making the yawing mechanism unnecessary.

In the past 30 years, a number of different vertical axis turbines have been tested. The Darrieus wind turbine, a machine designed by French engineer G.J.M. Darrieus in 1931, was the most thoroughly investigated design. This machine, resembling an eggbeater, consists of a pair of thin, curved blades with an aerofoil cross-section attached to a vertical axis. (Nelson 2009)

Several kinds of vertical axis wind turbine have been designed, including an H-shaped rotor. However, the vertical design has not yet been commercially successful.

Turbulence

This is a phenomenon caused by the flow of wind over uneven ground and interference by trees and bushes. The turbulent air puts additional pressure on the blades of wind turbines and increases metal fatigue. In order to minimize fatigue, wind turbines will normally be placed on towers, tall enough for the blades to clear wind turbulence.

When dealing with sea applications, turbulence is usually less of a problem due to the smooth surface of the ocean. However, turbine blades need to be high enough to avoid being disturbed by waves in rough sea and consequently increased wind turbulence. For both onshore and offshore turbines, it is necessary to determine the most favourable height before installation.

Although wind power is an interesting option for alternative energy generation, it has some disadvantages. Discontinuous power supply and performance at less than full capacity, both consequences of the dependence on wind speed, are examples. In addition, wind turbines require the high cost of installation and connection to transmission lines.

4.7 Tidal Energy

In order to generate electricity, tidal power uses natural energy that the mass of water in movement contains. This recurrent rising and falling of the ocean is known as tides - the result of a combination of forces produced by gravitational attraction between the sun, the moon and the earth's rotation (Boyle 2004).

Water bodies and their movement have significant quantities of energy present. This natural feature allows the mass of water to be used as a source of electricity in different ways:

(a) Tidal energy: This technology uses the hydraulic principle of the head (height difference) between low and high tides. The fall uses the potential energy of the water like any hydropower development.

(b) Wave energy: The kinetic energy of waves is used to actuate a power turbine underwater, thus generating electricity.

(c) Thermal energy: Like geothermal power generation, oceans provide thermal energy to obtain electricity.

The operation of tidal energy could be summarized as follows: when the tide hits the coast, it is stored in dams (also known as barrages). The equipment also includes gates and turbines. Gates are opened when the difference between the levels of the water in different parts of the dam are adequate so that the water can pass through the turbines, actuating the generator to produce energy.

When the demand for energy is low, turbines also act as pumps to provide extra water inside the basin behind the dam. When conditions change and demand on the plant is very high, the water is released and the tidal station works as a “pumped storage” hydroelectric service.

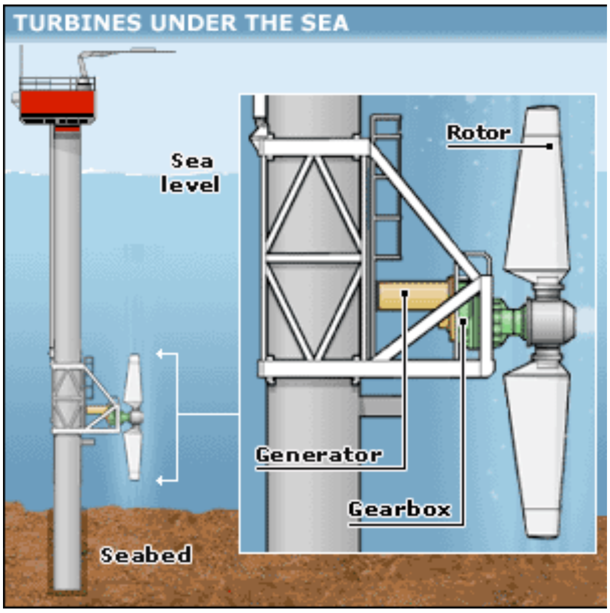


Figure 4-9 Tidal Turbine (Shaw 2008). *Tidal Power for the Severn - the Next Stage*. Retrieve from http://trymtales.blogspot.com/2008/01/tidal-power-for-severn-next-stage.html

Tidal developments require very specific places; in fact, the topography is crucial because it must have facilities to allow civil construction. It is important to note that this technology requires a difference of at least 4 metres in the elevation of the high and low tides in order to work effectively.

Tidal energy is a clean operation that requires no fossil fuels, although there is a high silt formation at the coastline and disturbance of marine life close to the basin on the seaside, which raises concern for ecologists.

The case of India: This country has the option to generate tidal energy as it is surrounded by the sea. In this respect, it has important locations like the Gulf of Cambay, the Gulf of Kutcvh, the Ganges Delta, Sunderbans, and West Bengal. In the end, the Gulf of Cambay produces near 90% of the total tidal energy generation estimate in 8,000 MW.

Other countries:

France seems to be the only country that is succeeding in trapping tidal energy and it has the biggest plant in the world. In 1966, the country constructed the La Rance tidal power station of Electricity de France (EdF) in Mont Saint Michel, which has a capacity of 240 MW. This station has 24 bulb-type turbines with a capacity of 10 MW each.

In the United Kingdom across the Bristol Channel, the Severn Barrage and the River Severn offer facilities for generating tidal power. In fact, a project is planned to construct a colossal power station with an average annual generation of 17 Gwh by mounting a total of 214 turbines of 40 MW each and installed capacity of 8,560 MW.

As stated above, tidal energy uses the gravitational force of both the sun and the moon. It is possible to find tides with different degrees of strengths on coastlines and at sea, although in this case tides are better known as currents. The term flood tide means the tide coming in or rising, while the ebb tide is the tide that goes out. Tidal energy is an old method of using energy as proven by the mill devices from before 1100AD found on the coasts of France, Spain and the United Kingdom.

In summary, the main characteristics of tidal power are:

1. Renewable;
2. Non-contaminating and no fuel requirement;

3. Operates only when tide comes in and goes out;
4. Tidal barrages are costly to construct and affect big areas.

A proper place for a tidal barrage is hard to locate, so underwater turbines prove to be a better option than barrages in terms of costs and impact on the environment.

This chapter has considered a number of options for using renewable energy, such as hydropower, wind power, gas turbines, wave and ocean thermal energy, geothermal and tidal energy. With a clear understanding of alternative energy power generation, the next chapter will address biofuels and electricity production.

5. Rotating Equipment and Biofuels

5.1 Introduction

The end-use functional requirements of a mechanism are the main focus of the engineer. In the case of systems that involve rotating elements in their design, such as power generation, power conditioning, and power absorption equipments, it is of vital importance that the designer can predict environmental acceptability (along with durability, reliability, performance, and general user satisfaction).

One example of environmental acceptability is a design that works with biofuels instead of fossil fuels. As a large amount of production works with fossil fuels, which contribute to greenhouse gas emission, it is important to consider designs that are more environmentally acceptable.

Biomass can be used by power plants to generate electricity. In this process, burning biomass after gasification or direct burning are common practices. Wood, animal waste, harvest residues, landfill gas and vegetable oil are the main products used to generate power.

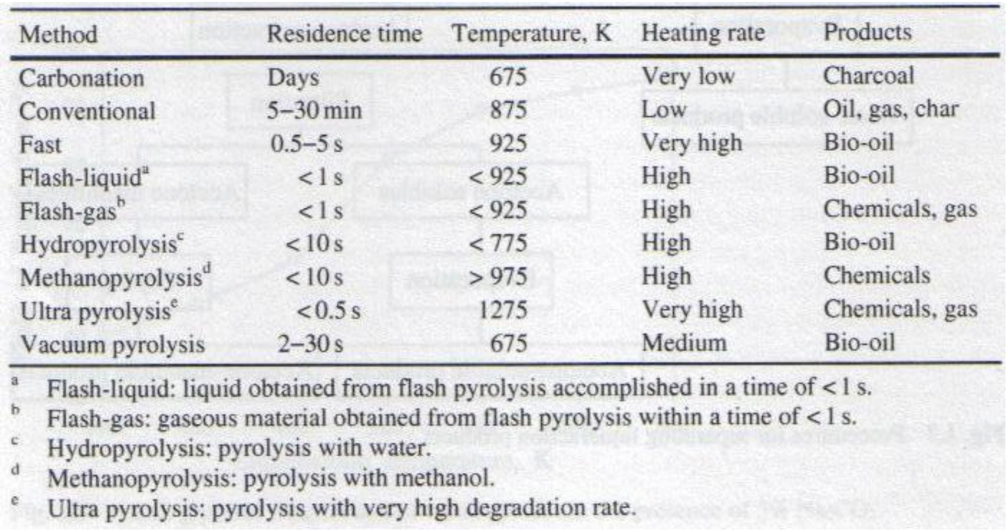
A major factor that this topic will address with respect to climate change is greenhouse gas emission. This factor can be positive or negative, thus it is important to ascertain the main determinants for the net greenhouse gas emissions.

5.2 Generation of Electricity using Biomass

Electricity can be generated from biomass through several processes, including gasification, pyrolysis, co-firing and direct combustion. Biomass is a reliable biofuel that can be found in all wood forms (i.e. trees and crop residues) as well as animal and municipal waste.

In an oxygen-limited environment, Biomass can be converted to gas at a temperature of 1300^0C. The resulting gas principally made up of hydrogen, carbon monoxide, methane, carbon dioxide, and nitrogen can be used in a boiler or turbine to generate heat, steam or electricity. The simple–cycle gas turbine and the combined-cycle gas turbine (Figure 5-1) are examples that illustrate the use of gasified biomass (biomass integrated gasification combined cycle BIGCC).

Pyrolysis describes the process where biomass is heated within a completely oxygen-free environment at temperatures of $300\text{-}500^0$C. These conditions produce gas, charcoal and bio-oil. Table 5-1 shows variants for pyrolysis methods. To generate heat and electricity as well as other static operations (boilers, furnaces), fuel oil can be replaced by bio-oil (Fig 5-2). Clearly then, bio-fuel represents a useful option for use in rotordynamics machinery to produce electricity.



Method	Residence time	Temperature, K	Heating rate	Products
Carbonation	Days	675	Very low	Charcoal
Conventional	5–30 min	875	Low	Oil, gas, char
Fast	0.5–5 s	925	Very high	Bio-oil
Flash-liquid[a]	< 1 s	< 925	High	Bio-oil
Flash-gas[b]	< 1 s	< 925	High	Chemicals, gas
Hydropyrolysis[c]	< 10 s	< 775	High	Bio-oil
Methanopyrolysis[d]	< 10 s	> 975	High	Chemicals
Ultra pyrolysis[e]	< 0.5 s	1275	Very high	Chemicals, gas
Vacuum pyrolysis	2–30 s	675	Medium	Bio-oil

[a] Flash-liquid: liquid obtained from flash pyrolysis accomplished in a time of < 1 s.

[b] Flash-gas: gaseous material obtained from flash pyrolysis within a time of < 1 s.

[c] Hydropyrolysis: pyrolysis with water.

[d] Methanopyrolysis: pyrolysis with methanol.

[e] Ultra pyrolysis: pyrolysis with very high degradation rate.

Table 5-1 Pyrolysis methods and their variants (Demirbas 2008 p 16).

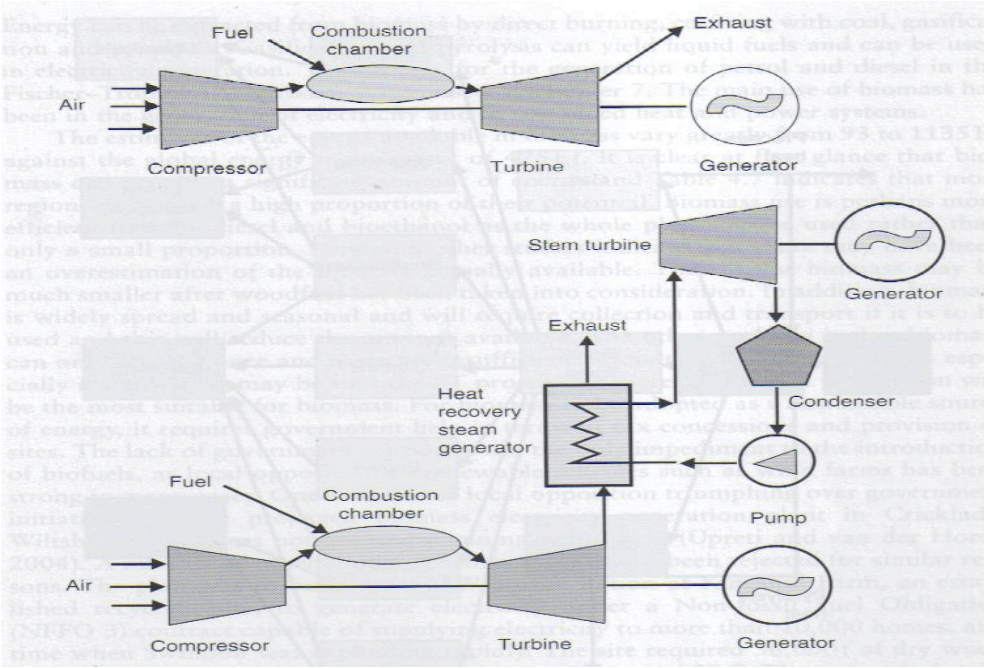


Figure 5-1 Simple cycle gas turbine (top) and the combined cycle gas Turbine, which can be used with gasified. (Scragg 2009 p 77).

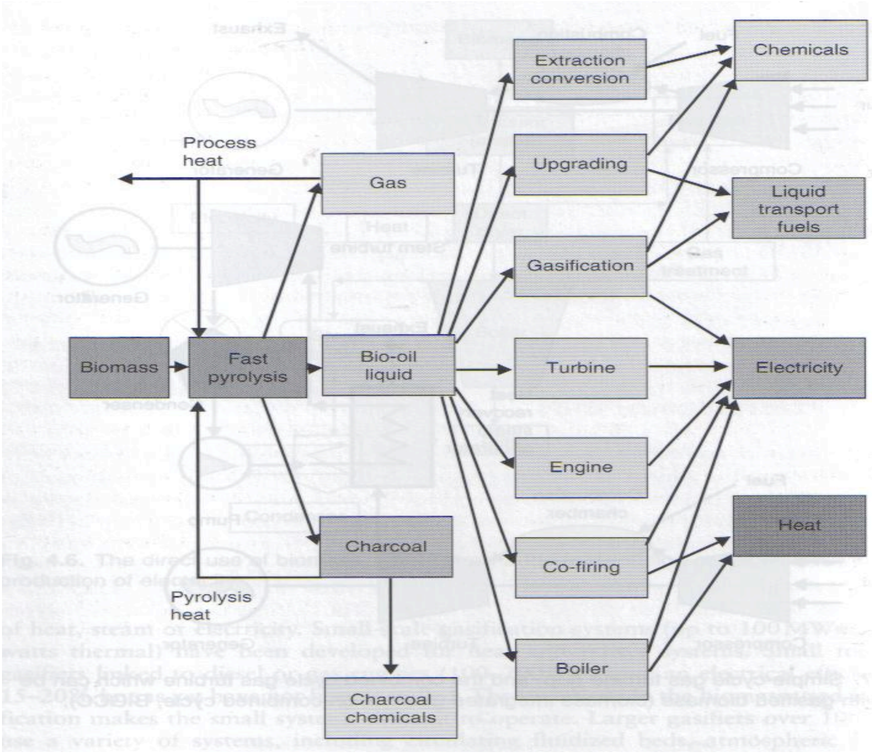


Figure 5-2 Application for bio-oil obtained by the pyrolysis of biomass (Scragg 2009 p 78)

The use of combined heat and power (CHP) from biomass presents favourable circumstances for electricity generation and reduced costs.

Figure 5-3 shows a case where a system uses biomass to produce electricity. In this process, the electricity is generated as a result of heat (steam) generation, which is different from the gas turbine and reciprocating engine where heat is a derivative of the power generation.

This kind of system is generally utilised in industrial processes and can be powered by biomass or biogas (methane from digestion of biomass) with positive results, not just because it encourages the expansion of a biomass market, but also because the features of renewable fuel may qualify for additional incentives. (Scragg 2009)

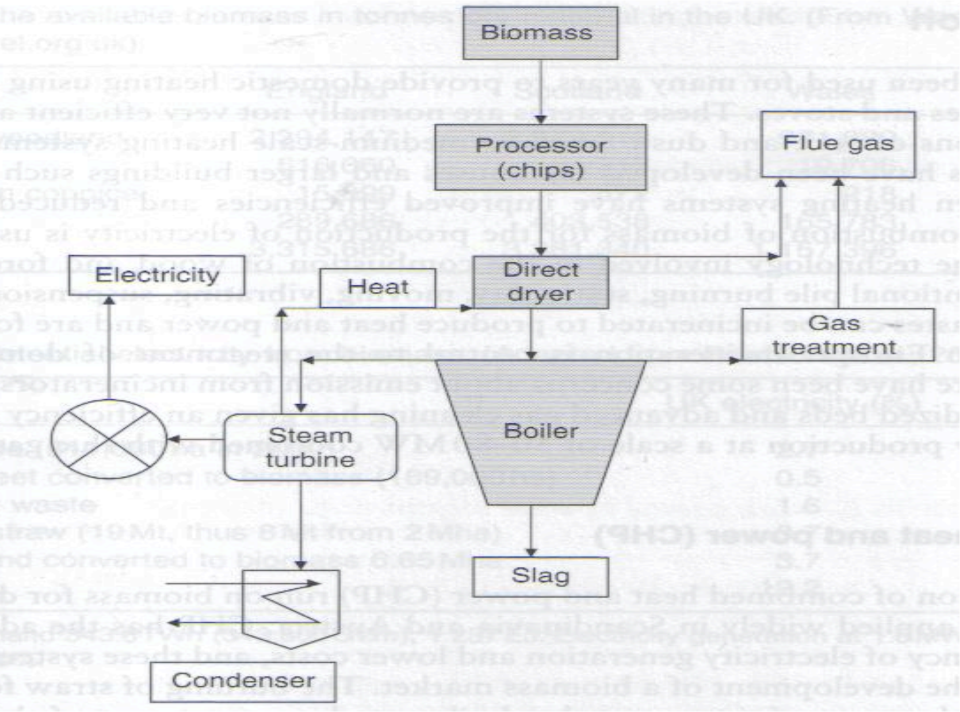


Figure 5-3 The direct use of biomass, wood, straw and short rotation coppice (SRC) for the production of electricity. (Scragg 2009 p 76)

5.3 N_2O Emissions

These emissions can originate during the biofuel life cycle. Production of N fertilizers usually occur with N_2O. NOx emissions, resulting from the fossil fuel combustion process, can be deposited as N compounds in soils, and they can be partly transformed into N_2O by microorganisms. Also, N inputs in plants that are used to produce biofuel crops will be transformed into N_2O, while others report that direct N_2O emissions originating in agricultural fields in association with biofuel cropping could be around 1.25% of fixed nitrogen. Furthermore, they disagree that the fixed nitrogen lost from agricultural fields may also be converted into N_2O by microorganisms. (Reijnders & Huijbregts 2009)

Conditions associated with a particular area as well as the presence of soil moisture may have an important influence on N_2O emissions. The general tendency is that higher temperatures and higher levels of soil organic carbon generate higher emissions of N_2O. Therefore, temperature and precipitation are important determinants for the emissions of N_2O. As such emissions vary with changes in climate, the N_2O emissions derived from biofuel cropping can differ from what they are at the present time.

5.4 Biogenic CO_2 Emissions

The process for producing biofuels can be associated with an adjustment in the effort to capture and store excess carbon dioxide (CO_2) from the atmosphere. In the first place, some changes can occur in the carbon contents of ecosystems, maybe losses or maybe increases in the percentage of the C that in the end causes variations in the concentration of CO_2 in the atmosphere. In some situations, the association between the augment in biofuel production and changes in C sequestration is direct. For example, there is a substantial influence on C sequestration when degraded soil or woodland is cleared in order to plant oil palms serving the biodiesel industry. In other cases, changes in soil use produce more restricted direct effects on stocks of C; in particular when cultivated areas of rubber or coconut are replaced by oil palms that give a higher income.

Increasing biofuel production may also generate *indirect* effects on ground use. One interesting example is inelasticity of food demand.

When the land is used by biofuel production, food production needs to be moved to another place. Presently in Brazil, in order to produce soybeans, there is considerable transformation of areas covered with grass (suitable for feeding livestock) to arable land. This situation tends to lower carbon in the ecosystem, but that is not all. People who rear animals and use pastureland may find different options and unfortunately deforestation is one of them.

Carbon sequestration changes are connected to biofuel life cycles. In relation to production of electricity for biomass, and the production of synthesis gas resulting from biomass, it is possible to capture CO_2 and then store it in soils (in the form of aquifers or gas fields that are no longer in use). With respect to production of electricity, life cycle emissions of greenhouse gases connected to electricity production can be diminished by 75%-84% though other emissions like atrophying and acidifying substances can be increased.

In the production of biofuel, there are usually changes in carbon sequestration in ecosystems. Large emission of greenhouse gases is the result of clearing forests for the cultivation of biofuel crops. For example, calculations of C stocks above the ground in rainforests are somewhere between 130-270 Mg C ha^{-1}. In contrast, others such as Germer and Sauerborn have mentioned that using degraded soil to grow oil plants may result in a considerable increase of aboveground soil organic carbon, approximately 135 Mg C ha^{-1}, in the future. (Kemp 2006)

In life cycle evaluation, it is reasonably easy to include direct changes in land use associated with biofuel production; however, to incorporate indirect changes is more difficult. In fact, Fritsche suggested that for indirect effects, the risk caused by clearing natural flora or any change in the soil use that affects C sequestration and CO_2 emissions has to be considered as a “risk adder ”.

In the end, climate changes modify the levels of soil organic carbon. A rise in the average temperature by $1^{o}C$ could be linked with deprivation of soil organic carbon in cultivable land of about 0.04 Mgha $^{-1}$ year $^{-1}$ according to researchers such Vleeshouwers and verhagen.

5.5 Other Carbonaceous Biogenic Emissions

Clearing forests for biofuel cropping results in huge emission of non-CO_2 carbonaceous greenhouse gases such as CO and hydrocarbons. In reality, such gases may contribute only 10%-20% to the emission of CO_2. Moreover, the transformation of organic waste from biofuel production in open ponds or in dumps linked to anaerobic conversion usually causes large emission of methane.

5.6 Non – Greenhouse Gas Emissions

Compared with fossil fuels, employing biofuels alters the emission of non-greenhouse gases. For example, replacing fossil diesel with biodiesel results in a reduction of sulphur dioxide emissions while nitrogen oxide (NO_x) emissions increase, whereas the effects on respiratory tract do not vary a lot. In order to decrease emission of NO_x caused by switching to biodiesel, it is necessary to adjust the injection pump. The impact is said to be complicated when replacing fossil diesel with biodiesel on particulate matter emissions from cars as biodiesel substitution affects the diesel soot nanostructure, increasing oxidative reactivity and cytotoxity but decreasing mutagenesis. It appears that when fossil fuels are progressively replaced by biodiesel, the number of emission particles is reduced, which would seem to indicate a lower health risk. However, the average size of the particles is also reduced (Kegl 2008; Keskin et al. 2008; Lapuerta et al. 2008), which may increase health risks. Thus, it is necessary to conduct further research in order to determine the effect of such changes on human health.

In the case of fossil gasoline compared with an ethanol-gasoline blend, emission of CO and surrounding O_3 concentrations might be reduced by using an ethanol-gasoline blend. However, this mixture increases the emission of acetaldehyde, which may be carcinogenic in humans, and in addition it increases the concentration of peroxylacetate nitrate (PAN) in the atmosphere, an eye irritant which is said to be mutagenic. Therefore, in practice, it is not easy for ethanol (ETBE) to replace fossil hydrocarbons; however, the overall impact requires advanced research.

A major part of non-greenhouse gas emissions is associated with the cropping period. Fertilizers (nutrients) and pesticides play an important role in this stage. During the process, nutrients can be released into the wider environment, with phosphorus (P) and nitrogen (N) dissolving in water. Infecting the water with nutrients from land where corn is cultivated to produce ethanol (in the Midwest of the USA) is one of the biggest factors in the hypoxic area of the Gulf of Mexico, hypoxic referring to a deficiency of oxygen in living environments attributed to high levels of nutrients. (The hypoxic zone also covers the East China Sea and many other seas around the European continent). Higher concentration of nutrients can result in eutrophication, which is directly associated with reduced biodiversity and harmful alga blooms.

In the case of Jatropa's crop, although it is well-known that this plant produces a nut with insecticidal properties, in order to reduce pest negative consequences, it is necessary to use additional pesticides. In general, the use of pesticides, which may be responsible for ecotoxicity and have toxic effects in humans, is very common when cropping. In addition, non-greenhouse emissions may be impacted by the harvesting process (manual or mechanical). Burning harvest waste of sugar cane to produce bioethanol is an interesting example because it has an impact on people living in these zones, affecting the respiratory tract of children and the elderly. (Reijnders & Huijbregts 2009)

One of the most remarkable pieces of research relating to biofuels was conducted by Zah, who compared a range of plant-based biofuels with conventional fossil fuels. Here, Zah worked on the relationship between life cycle emissions and factors like oxidizing smog, eutrophication and ecotoxicity. With respect to ecotoxicity, Zah found that in several situations, emissions produced by fossil fuels were higher than the emissions produced by crop-based biofuels. However, in some cases with biodiesel from Malaysian palm oil and Brazilian soybean oil, ecotoxicity emissions were higher (at least five times) than diesel life cycle emissions or fossil petrol. In terms of eutrophication, apart from some wood-and grass-based products, biofuels from plants were more harmful than fossil transport fuels along their life cycles. With respect to emission of hydrocarbons that can result in photochemical smog, biofuels were better than fossil fuels. However, soybean-based biodiesel, biodiesel from oil palms in Malaysia, and sugar-cane based bioethanol in Brazil were much worse as their compounds may produce oxidizing smog.

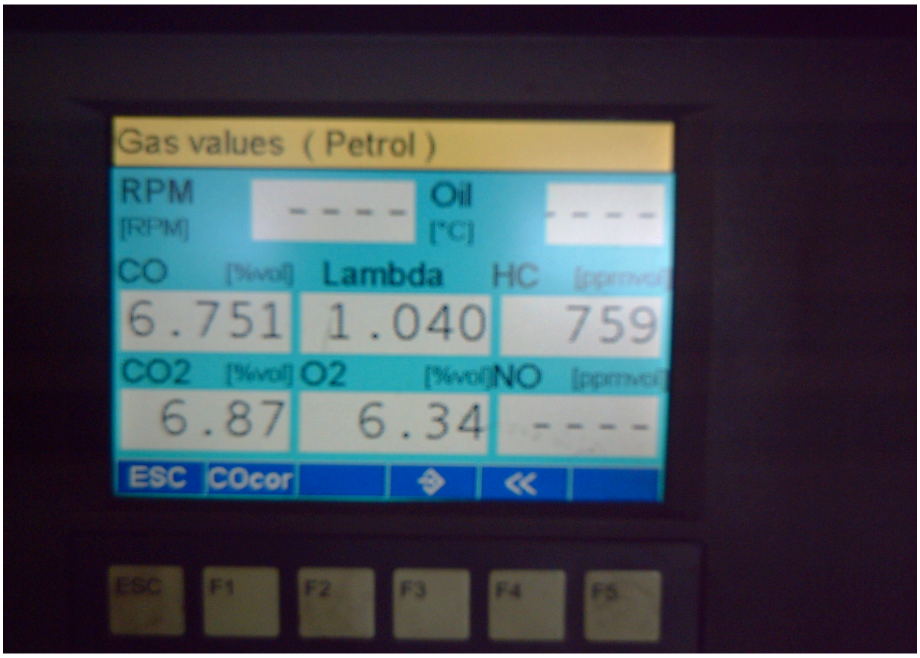
Furthermore, Zah considered emissions linked with methane production from many wastes and compared the results with natural gas. Emission of eutrophying material from wastes was superior and oxidizing smog related to methane was to some extent superior to the analysis made for natural gas. The results of study by these researchers are more favourable to biofuels processed from wastes than for biofuels made from food crops. Conversely, it is important to consider that this conclusion is based on life cycles and at one point waste can be dismissed. When waste becomes part of secondary resources, differences in plant-based biofuels with biofuels made from residue will be less significant. (Reijnders & Huijbregts 2009)

5.7 Transportation and Biofuels

The power in a gasoline engine is generated by the controlled combustion of the air–fuel combination in the combustion chamber. In an ideal combustion process, the exact amount of oxygen would react with the existing fuel. However, there is no perfect combustion process in the gasoline engine and incomplete combustion causes production of carbon monoxide and hydrocarbon in the exhaust.

The Exhaust gases

Tests for emission levels and diagnostic practice can be made by testing the quality of the exhaust. There are usually five exhaust gases to be monitored: carbon monoxide, hydrocarbon, nitrogen oxide, carbon oxide and oxygen (figure 5-4). NO_x levels can only be determined with the vehicle under load. The efficiency of the engine's combustion system can be tested by using the gas analyser (Figure 5-5). Here, in order to test exhaust emissions, the tester probe (Figure 5-6) is inserted into the exhaust pipe (Figure 5-6).



Gas values (Petrol)

RPM [RPM] ----
Oil [°C] ----
CO [%vol] 6.751
Lambda 1.040
HC [ppmvol] 759
CO2 [%vol] 6.87
O2 [%vol] 6.34
NO [ppmvol] ----

Figure 5-4 Gas analyser screen showing the main gases to be monitored

Figure 5-5 Gas Analyser

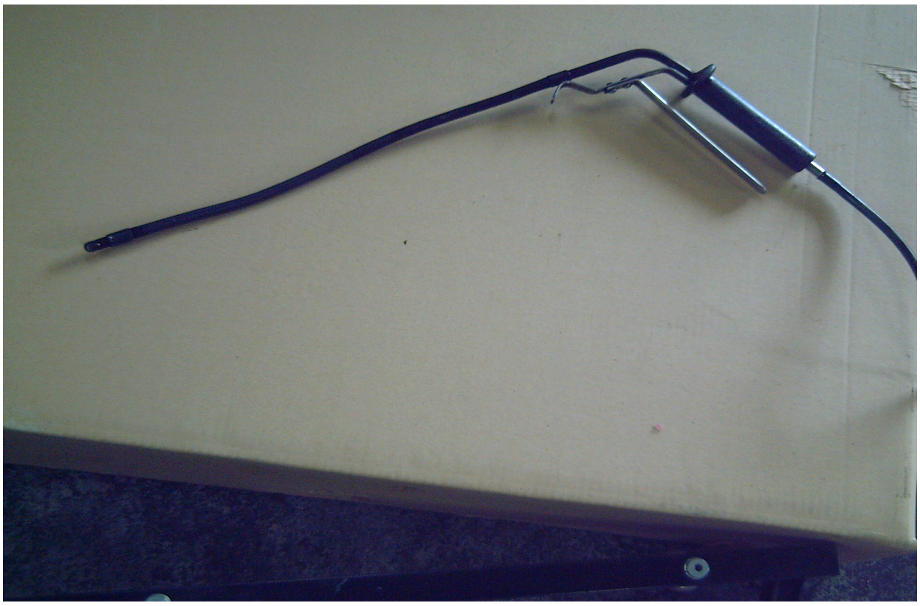


Figure 5-6 The tester probe

Figure 5-7 Tester Probe inside exhaust pipe

Tests for HC and CO can be done at idle and higher speeds, although some manufactures give specific test speeds. Tables 5-2 to 5-5 show the results of emission tests carried out on four vehicles. Each table reflects the tests performed at idle and above idle.

VOLKSWAGON POLO 1998					
RPM	CO (% Vol)	HC (ppm)	CO_2 (% Vol)	O_2 (% Vol)	λ
750	0.02	10	15.3	0.03	1.000
2560	0.03	11	15.4	0.03	1.000

Table 5-2 Emission Test for Volkswagon Polo 1998

MITSUBISHI RVR 1997					
RPM	CO (% Vol)	HC (ppm)	CO_2 (% Vol)	O_2 (% Vol)	λ
750	0.02	42	15.3	0.06	1.000
2500	0.17	45	15.2	0.14	0.999

Table 5-3 Emission Test for Mitsubishi RVR 1997

MAZDA 323 1995					
RPM	CO (% Vol)	HC (ppm)	CO_2 (% Vol)	O_2 (% Vol)	λ
1020	0.14	111	13.3	2.55	1.122
2640	0.73	81	14.5	0.50	0.998

Table 5-4 Emission Test for Mazda 323 1995

FORD LTD 1995					
RPM	CO (% Vol)	HC (ppm)	CO_2 (% Vol)	O_2 (% Vol)	λ
670	2.32	249	13.4	0.23	0.935
2610	4.06	116	12.5	0.04	0.886

Table 5-5 Emission Test for Ford LTD 1995

The analysis of this kind of emission and its impact on human health is a separate topic that is not part of this thesis.

Biofuels

Transport biofuels derived from plants are known as “climate neutral” or “carbon neutral” as these terms refer to the biogeochemical C cycle in which plants participate. The $C0_2$ in the atmosphere is absorbed by plants and transformed into biomass. Later, when the process of burning biomass takes place, the $C0_2$ is released into the atmosphere again. With respect to C neutrality, it has been said that sequestration is equal to $C0_2$ emissions and $C0_2$ is greenhouse gas. In visible light that is considered high-energy solar radiation, greenhouse gas is transparent, however, these gases absorb the infrared radiation affecting atmospheric temperatures. This is the reason it is said that carbon neutrality is equal to climate neutrality, but it is necessary to consider further the relationship existing between biofuels and climate. This relationship refers to the direct effect of plants on the climate and the emission of non-$C0_2$ greenhouse gases as N_2O and CH_4.

When comparing cropping biofuels with natural vegetation, plants that are used to produce biofuels may influence local conditions like roughness of the surface, evapo/transpiration, precipitation and albedo The term albedo refers to the reflection of sun radiation by the surface of the earth (this includes vegetation), which is in the long run a determinant of net radiation. The effects of vegetation change according to the climate in each region, so in cold areas, the replacement of forest by annual biofuel crops will have a cooling effect due to albedo, whereas in tropical areas, the replacement will have a warming effect, because there is a reduction in evaporation and cloud coverage. (Reijnders & Huijbregts 2009)

With reference to biofuels, this chapter has explained the process of using biomass in power generation and described some biofuel emissions. In addition, it has overviewed biofuels for power generation in transport.

The next chapter will analyse three power generation systems and the way in which rotordynamics machines work to generate power.

6. Analysis Experimental

6.1 Introduction

In this chapter, three examples were selected in order to develop a mathematical model that illustrates the way in which rotordynamics equipment works with alternative energy based on physical principles.

In each case, assumptions with respect to flow rate, diameters and mass flow were made to calculate the power generated by the turbines. The general analysis was based on a scenario community of 900 homes in New Zealand.

Due to the existence of phenomena that cannot be modelled, it is not possible to create completely precise models of physical systems. However, mathematical models are useful tools in that they assist in the prediction of system behaviour.

6.2 Pelton Turbine

Case 1

Elevation (H)= 200 m; Flow (Q)= 1 m^3/s; Diameter of penstock (D_P)= 0.6 m; Generator frequency (G_f)=60 Hz; Length of penstock (L)= 2000m; Material= Steel Commercial; Bucket angle (θ)= 165^o;Temperature Water (T^o)= 10^oC; Loss coefficient entrance penstock (C_p)= 0.5; Loss coefficient of the nozzle (C_n)= 0.5; Bucket friction coefficient (K_B)= 0.99; Efficiency of turbine (η_T)= 50% of water velocity.

Nozzle diameter (d)=?; Velocity in the nozzle (V_J)=?; Turbine Diameter (D_T)=?; Torque from turbine shaft (T)=?; Electrical power generated (P_G)=?

The procedure starts by analysing the Energy Equation between the reservoir and the Jet:

$$\mathrm{H} = \left(0.5 + \frac{\mathrm{fL}}{\mathrm{D}}\right)\frac{\mathrm{V}_{\mathrm{p}}^{2}}{2\mathrm{g}} + (0.04)\frac{V_j^{2}}{2g} + \frac{V_j^{2}}{2g}$$

$$200 = \left[\left(0.5 + \frac{(f(2000))}{0.6}\right)\frac{V_p^{2}}{2\times 9.8}\right] + \left[(0.04)\frac{V_j^{2}}{2\times 9.8} + \frac{V_j^{2}}{2\times 9.8}\right]$$

$$Q = V_p A_p \Rightarrow \frac{Q}{\frac{\Pi D_p}{4}} = V_p = \frac{1}{\frac{\Pi\left(0.6^{2}\right)}{4}}$$

V_p = 3.5 m/s

Thus Reynolds number:

$$R_e = \frac{V_p D_P}{\vartheta} = \frac{3.5\times 0.6}{1.30\times 10^{-6}} = 1.6\times 10^{6}$$

The value of the absolute roughness K_R for Commercial Steel:

$$0.030 \text{ X } 10^{-3} \Rightarrow \frac{K}{D_P} = \frac{0.030\times 10^{-3}}{0.6} = 0.00005$$

From Moody diagram, resistance coefficient (**f**)= 0.012

$$200-\left[0.5+\left(\frac{0.012\times 2000}{0.6}\right)\left(\frac{3.5^2}{2\times 9.8}\right)\right]=\left[\frac{V_j^2}{2\times 9.8}(0.04+1)\right]$$

$$174.5=0.053V^2{}_j \Rightarrow V_j=57.37\,{}^{m}\!/\!_{s}$$

$Q_p = Q_j \rightarrow 1\ m^3/s = V_j\ A_j$

$V_j = 57.37$ m/s ; $A_j=\frac{1}{57.37}\Rightarrow A_j=0.017m^2$

$$A_J=\frac{\Pi d^2}{4}\Rightarrow\sqrt{\frac{0.017\times 4}{\Pi}}=d=0.12m$$

Runner velocity (u) [peripheral velocity]= 50% of V_J

$$u=(0.50\times 57.37)\Rightarrow u=28.68m/s$$

The size of the wheel is 14 to 16 times the diameter of the nozzle→

$$16\times 0.14=D_T=2.24m$$

The angular velocity:

$$\omega=\frac{2u}{D_T}=\frac{2\times 28.68}{1.92}\Rightarrow\omega=29.87\,{}^{rad}\!/\!_{s}$$

Or

$$N=\frac{60\omega}{2\Pi}=\frac{60\times 29.87}{2\Pi}\Rightarrow N=285.23rpm$$

The generator and turbine have to turn at an invariable *synchronous speed* in order to produce the necessary constant-frequency alternating current. The number of poles on the generator (an even number) is the base to calculate this speed:

$N = \frac{120f_r}{n_p}$ Where N is the *synchronous speed* in rpm, f_r is the frequency in hertz and n_p is the number of generator poles.

$$\frac{120f_r}{N} = n_p = \frac{120\times 60}{285.23} \Rightarrow n_p = 25.24$$

The nearest even integer = 26

Recalculating the peripheral velocity of the runner:

$$N = \frac{120\times 60}{26} = 276.92rpm$$

$$N = 276.92rpm \times \frac{1m}{60s} \times \frac{2\Pi}{1rev} = 29\, {}^{rad}\!/_{s}$$

To maintain the original peripheral velocity:

$$\omega = \frac{2u}{D_T} \Rightarrow \frac{2\times 28.68}{29} = D_T = 1.97m$$

Power from the turbine:

$$P_T = \rho Q(V_J - u)(1 - k_B \cos 165)u \rightarrow \rho_{w(10^0 C)} = 1000\, {}^{kg}\!/_{m^3}$$

$$P_T = (1000\times 1)(57.37 - 28.68)(1 - (0.99\cos 165))\times 28.68$$

$$P_T = 1.60\times 10^6 \text{ W } ({}^{Nm}\!/_{s}) = 1.60 \text{ MW}$$

Power= Torque X Angular velocity

$$\frac{1.6\times10^{6}}{29.87}=T=53.5\ KN.m$$

Case 2

Elevation (H)= 100 m; Penstock features: length (L): 4 km; resistance coefficient (f)= 0.015; diameter (D_P):0.80 m; Temperature Water = 10° C;

Diameter of jet (D_J)=90mm;Turbine efficiency: 90%; Velocity of water leaving the vane=95%V_J; Deflection of the jet by vane (θ)=165°

Power developed by turbine (P)=?; Resultant force on the vane=?

$$V_pA_p=V_jA_J$$

$$\frac{\pi d^2}{4}=A_j=\frac{\pi\times0.09^2}{4}\Rightarrow A_j=6.3\times10^{-3}m^2$$

$$\frac{\pi d^2}{4}=A_p=\frac{\pi\times0.8^2}{4}\Rightarrow A_P=502.7\times10^{-3}m^2$$

$$\frac{V_J\times6.3\times10^3}{502.7\times10^3}=V_p=12.5\times10^{-3}V_J$$

Applying the energy equation between the reservoir and the jet:

$$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1=\frac{p_J}{\gamma}+\frac{V_J^2}{2g}+z_J+h_L$$

p_1=0; Δz=1000 m; $\frac{V_1^2}{2g}$=0 ; p_J=0; $\gamma = 9800\frac{N}{m^3}$

$$\frac{fL}{D_p}\frac{V_P}{2g} = h_L = \frac{0.015\times 4000}{0.8}\times\frac{\left(12.5\times 10^{-3}V_J\right)^2}{2g}$$

$$h_L = 11.71\times 10^{-3}\,\frac{V_j^2}{2g}$$

$$100 = \frac{V_J^2}{2g} + 11.71\times 10^{-3}\,\frac{V_J^2}{2g}$$

$$100 = \frac{V_J^2}{2g}\left(1 + 0.011\right)$$

$$\sqrt{\left(\frac{100\times 2\times 9.8}{1.011}\right)} = V_j = 44.03\frac{m}{s}$$

$$V_P = 12.5\times 10^{-3}V_J \Rightarrow V_p = 550.3\times 10^{-3}\,\frac{m}{s}$$

Power developed by the turbine:

$$P = Q\gamma \frac{V_J^2}{2g} = \frac{0.27 \times 9{,}800 \times \left(44.03^2\right)}{2 \times 9.8}$$

$$P = 262.7kW$$

The power produced by the turbine:

$$P = 262.7kW \times 0.90 = 236.4kW$$

General equation for vanes of a runner:

$$-F_{RX} = \rho A_J V_J \left[\eta\left(V_J - U\right)\cos\theta - \left(V_J - U\right)\right]$$

Velocity of the vane (U): $0.45V_J = 0.45 \times 44.03 \rightarrow U = 19.81$ m/s

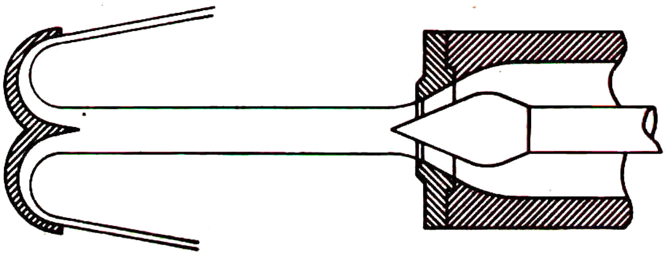


Figure 6-1 Deflection of jet by vane (Malibu HydroEngineering 2004. *Turbines and generators*. Retrieve from http://www.malibuhydro.com/engin.htm#gen)

$$-F_{RX} = (9800 \times 6.3 \times 10^{-3} \times 44.03)[0.95(44.03 - 19.81)\cos 165 - (44.03 - 19.81)]$$

$$F_{RX} = 126.25 \times 10^3 N$$

$$F_{RY} = \rho A_J V_J [\eta (V_j - U) Sin\theta$$

$$F_{RY} = (9800 \times 6.3 \times 10^{-3} \times 44.03)[0.95(44.03 - 19.81)\sin 165]$$

$$F_{RY} = 16.18 \times 10^3 N$$

$$F_R = \sqrt{\left(126250^2 + 16180^2\right)} \Rightarrow F_R = 127{,}280N$$

$$Tan^{-1} = \frac{16180}{126250} = 5.76^o$$

6.2 Wind turbine

Two blade propeller; Blade diameter of 51 m; Wind Speed (V_W) = 15m/s; Air Density (ρ)= 1.29 kg/m^3; Rotational speed of the rotor (n):28rpm; Maximum permitted shaft stress (σ)=55X10^6 N/m^2.

Tip-speed ratio (TSR)=?Torque (T)=?; Diameter of the turbine shaft (D_S)=? Electrical Power Generator (P_e)=? frequency (f)=?

Large Machines (100kW- 3MW) efficiency:

Turbine Efficiency (C_P) = 40-50% Assumed: 0.42

Gearbox Efficiency (η_{gb}) = 80-95% Assumed: 0.92

Generator Efficiency (η_g)= 80-95% Assumed: 0.90

Overall working efficiency (η)=0.42 X 0.92 X 0.90= 0.347

Where P_W = power in the wind:

$$\frac{r\omega}{V_W} = TSR = \frac{v}{V_W}$$ Where v is the instantaneous velocity of the blade tip.

$$\omega = \frac{2\pi n}{60} \quad \text{n} \rightarrow \text{rpm}$$

$$\frac{2 \times 28 \times \pi}{60} = \omega = 2.93\, {}^{rad}\!/_{s}$$

$$\frac{29 \times 2.93}{15} = TSR = 5.66$$

Now:

$$\eta = \frac{P_e}{P_w}$$ Where P_W = power in the wind

$$P_W = \frac{1}{2}\rho A V^3 \Rightarrow$$

$$\left(\frac{1}{2}\right)(1.29)\left(\frac{\pi \times 51^2}{4}\right)\left(15^3\right) = P_w = 4.44 \times 10^6\ W$$

$$P_W = T\omega \Rightarrow T = \frac{P_W}{\omega}$$

$$T = \frac{4.44 \times 10^6}{2.93} \Rightarrow T = 1.51 \times 10^6\ Nm$$

$$\sigma = \frac{Tr}{J} = \frac{Tr}{\frac{\pi r^4}{2}} \Rightarrow \sigma = \frac{2T}{\pi r^3} \quad Where\ J\ is\ the\ polar\ (area)$$

moment of inertia

$$r^3 = \frac{2T}{\pi\sigma} \Rightarrow$$

$$r = \sqrt[3]{\frac{2 \times 1.51 \times 10^6}{\pi \times 55 \times 10^6}} = 259.5 \times 10^{-3} m$$

$$D_s = 51.9cm \approx 52 \text{ cm}$$

Power:

$$P_W \times \eta = P_e = 4.44 \times 10^6 \times 0.347$$

$$P_e = 1.54 \times 10^6 W$$

Now frequency:

$$\frac{\omega}{2\pi} = f = \frac{2.93}{2\pi}$$

$$\Rightarrow f = 466 \times 10^{-3} Hz$$

6.3 Gas Turbine

Intake condition: $T_a = 283\ {}^0K$; $p_a = 1.0$ bar;

mass flow $\dot{m}_1 = 15 \frac{kg}{s}$

$$\text{Compressor : Pressure ratio } r_p = \frac{p_{02}}{p_{01}} = 4 \text{ bar,}$$

Isentropic efficiency η_{12} : 0.80

Fuel energy input: 42000 KJ / Kg

$$Combustion : Chamber\ \ pressure\ loss = 5\ per\ cent$$

$$(p_{03} = 0.95\ p_{02});\ \ efficiency\ \eta_B : 1.0$$

$$Fuel\ energy\ input : 42000\ \frac{\text{kJ}}{\text{kg}}$$

$$Turbine : Entry\ temperature = 1000^0 K$$

$$Isentropic\ efficiency\ \eta_{34} : 0.92$$

$$Air\ off\ \ take\ to\ cool\ shafts\ and\ discs : 0.25 \frac{Kg}{s}\ from\ \dot{m}_2$$

$$Power\ offtake\ to\ drive\ accesories = 20kW$$

$$Specific\ heat : C_p = 950 + 0.21T$$

$$R = gas\ cons\tan t\ \ for\ air = 287 \frac{J}{Kg^0K}$$

Calculation:

Compressor

$$p_{02} = r_{p12} \times p_{01} = 4\ bar$$

$$C_{p12} \text{ for cold air} = 1005 \ \frac{\text{j}}{\text{kg } ^\circ K}$$

$$C_p = \frac{R\gamma}{(\gamma - 1)} \Rightarrow \frac{C_p}{R} = \frac{\gamma}{(\gamma - 1)}$$

$$\frac{1005}{287} = 3.5 = \frac{\gamma}{(\gamma - 1)}$$

Isentropic

$$\left(\frac{T_{02'}}{T_{01}}\right)^{\frac{\gamma}{(\gamma - 1)}} = r_{p12} \Rightarrow \left(\frac{T_{02'}}{T_{01}}\right)^{3.5} = r_{p12}$$

$$\frac{T_{02'}}{T_{01}} = r_{p12}{}^{\frac{1}{3.5}} \quad \text{since } r_{p12} = 4 \Rightarrow \frac{T_{02'}}{T_{01}} = 4^{\frac{1}{3.5}}$$

$$\frac{T_{02'}}{T_{01}} = 1.485 \Rightarrow 1.485 \times 283 = T_{02'} = 420.26$$

$$T_{02'} - T_{01} = 420.26 - 283 = 137.3\ {}^0\text{C}$$

Then: $$\eta_C = \frac{T_{02'} - T_{01}}{T_{02} - T_{01}} = \frac{\Delta T_0'}{\Delta T_0}$$

$$\frac{T_{02'} - T_{01}}{\eta_C} = T_{02} - T_{01} = \frac{137.3}{0.80} = 171.62^0\mathrm{C}$$

$$171.62 + T_{01} = T_{02} = 171.62 + 283$$

$$\Rightarrow T_{OA}\ for\ combustion = 454.62^0 K$$

Expression for power:

$$P = \dot{m}\,\mathrm{c_p}\,\Delta\mathrm{T_0} \Rightarrow \mathrm{P_{12}} = \dot{\mathrm{m}}_1 C_{p12}\left(T_{02} - T_{01}\right)$$

$$15 \times 1005 \times \left(454.62 - 283\right) = \mathrm{P_{12}} = 2587.1\mathrm{x}10^3\ \mathrm{W}$$

Combustion

Airflow into the combustion system:

$$\dot{m}_2 = \dot{m}_1 - air\ oftake\ for\ cooling$$

$$15 - 0.25 = \dot{m}_2 = 14.75\ \frac{\mathrm{Kg}}{\mathrm{s}}$$

$$T_{03'} \rightarrow T_{0B} = 1000\ {}^0K \rightarrow T_{0B}\ burner\ outlet\ condition$$

$$1000 - 454.62 = T_{0B} - T_{0A} = 545.4\ {}^0C$$

$$T_{0B} - T_{0A} = Combustion\ \ temperature\ \ increase = 545.4\ {}^0C$$

For the value of the fuel/air ratio into the combustion system:

$$f/a = 1.1\frac{\left(T_{0B} - T_{0A} - 50\right)\left(1 + \frac{T_{0A}}{3250}\right)}{42000\,\eta_B}$$

$$f/a = 1.1\frac{\left(545.4 - 50\right)\left(1 + \frac{454.62}{3250}\right)}{42000\,(1)}$$

$$f/a = 0.0147$$

$$\dot{m}_f = fuel\ flow = f/a \times \dot{m}_2$$

$$0.0147 \times 14.75 = \dot{m}_f = 0.21\,kg/s$$

$$Outlet\ presure\ p_{03}:$$

$$0.95 \times p_{02} = p_{03} = 0.95 \times 4\,bar$$

$$p_{03} = 3.8\,bar$$

Turbine

$$\dot{m}_3 = \dot{m}_2 + \dot{m}_f$$

$$14.75 + 0.44 = \dot{m}_3 = 15.19\ \ kg/s$$

$$P_{34} = P_{12} + P_{Drive\,accesories} = \dot{m}_3 c_{p34}\left(T_{03} - T_{04}\right)$$

$$P_{34} = 2587.1\times10^3 + 20\times10^3 = 2607.1\times10^3$$

$$\Rightarrow 2607.1\times10^3 = 15.19\times\left(C_{p34}\right)\left(T_{03} - T_{04}\right)$$

$$\frac{2607\times10^3}{15.19\times C_{p34}} = \left(T_{03} - T_{04}\right)$$

$$C_{p34} = 950 + 0.21T_{03}\left\{T_{03} \rightarrow gas\ entry\ temperature\ to\ turbaine\right\}$$

$$C_{p34} = 950 + \left(0.21\times1000\right) = 1160\ \mathrm{j}/kg\ {}^0K$$

$$\frac{2607.1\times10^3}{15.19\times1160} = \left(T_{03} - T_{04}\right) = 147.95\ {}^0C$$

$$1000 - 147.95 = T_{04} = 852.04\ {}^0K$$

$$\eta_{34} = \frac{T_{03} - T_{04}}{T_{03} - T_{04'}} \Rightarrow \frac{T_{03} - T_{04}}{\eta_{34}} = T_{03} - T_{04'}$$

$$\frac{147.95}{0.92} = T_{03} - T_{04'} = 160.81\ {}^0C$$

$$T_{04'} = T_{03} - 160.81 \Rightarrow 1000 - 160.81 = T_{04'} = 839.20\ {}^0C$$

Now:

$$\frac{p_{03}}{p_{04}} = \left(\frac{T_{03}}{T_{04'}}\right)^{\frac{\gamma}{\gamma-1}} \Rightarrow \frac{3.8}{p_{04}} = \left(\frac{1000}{839.20}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{\gamma}{\gamma-1}=\frac{C_{p34}}{R}\Rightarrow\frac{1160}{287}=\frac{\gamma}{\gamma-1}=4.04$$

$$\left(\frac{1000}{839.20}\right)^{4.04}=2.03=\frac{3.8}{p_{04}}\Rightarrow p_{04}=1.871\,\text{bar}$$

p_{04} is the pressure that work (expand) in the power turbine.

Power Turbine

$$P_{45}=\dot{m}C_{p45}\Delta T_{45}$$

$$950+\left(0.21\times T_{04}\right)=C_{p45}=950+\left(0.21\times 852.04\right)\Rightarrow C_{p45}=1128.9\,\frac{j}{kg\,^{0}k}$$

$$\frac{p_{05}}{p_{01}}(typical\ value)=1.150\rightarrow p_{01}=1\,\text{bar}\Rightarrow p_{05}=1.150\,\text{bar}$$

$$\frac{p_{04}}{p_{05}}=\left(\frac{T_{04}}{T_{05'}}\right)^{\frac{\gamma}{\gamma-1}}\Rightarrow\frac{1.871}{1.15}=1.626=\left(\frac{852.04}{T_{05'}}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{\gamma}{\gamma-1}=\frac{C_{p45}}{R}\Rightarrow\frac{1128.9}{287}=\frac{\gamma}{\gamma-1}=3.93$$

$$1.626^{\frac{1}{3.93}}=\left(\frac{852.04}{T_{05'}}\right)\Rightarrow T_{05'}=752.90\ ^{0}k$$

$$852.04-752.90=T_{04}-T_{05'}=99.82\ ^{0}C$$

Assuming $\eta_{45} = \eta_{34} = 0.92$

$$\eta_{turbine(45)} = \frac{T_{04} - T_{05}}{T_{04} - T_{05'}} \Rightarrow 0.92 \times 99.82 = T_{04} - T_{05} = 91.83\ {}^{0}C$$

$$P_{45} = \dot{m}_3 \times C_{p45} \times \Delta T_{45}$$

$$15.19 \times 1128.9 \times 91.83 = P_{45} = 1.57\ MW$$

In this chapter, three systems - the Pelton turbine, wind turbine and gas turbine - were selected and in each case a mathematical model was developed to illustrate how rotordynamics machines work to generate power.

7. Discussion and Conclusions

7.1 Discussion

The research objectives posed for this thesis were: 1) to analyse the most important alternative energy systems that work with rotordynamics machines to generate power, 2) to explain the mathematical principles of rotordynamics and 3) to explain the generation of power using biofuels and their main emissions.

Objective 2 was explained in chapter 3 and objective 3 was analysed in chapter 5.

In answer to the first objective, this research shows that the main systems are hydropower turbines, wind power, geothermal energy, gas turbines, tidal energy, wave and ocean thermal energy, and biofuels. Experimental analysis was undertaken, with three specific cases being analysed: the pelton turbine, wind turbine and the gas turbine. Analysis of these cases was based on a scenario community of 900 houses and current statistics showing that the average New Zealand home uses 8MWh of energy every year. It is important to note that no energy system operates at 100% capacity, and in New Zealand, the average capacity for all forms of generation is 54%.

In the first case, as hydro schemes depend on the amount and source of water, the energy available depends on two variables: the flow rate and the drop in height between the inlet pipe and the turbine (the head). In the case of the Pelton turbine (Impulse turbine), which has a flow rate of 1 m^3/s, the practical power available is 1.6MW. Therefore, the amount of energy (kWh) produced would be:

$1.6 \text{ X } 10^3 \text{ kW X } 24\text{X } 0.54= 20.73 \text{ X } 10^3 \text{ kWh}$
1 year = $7.56 \text{ X}10^6$ kWh

Based on this scenario, the energy output would be sufficient to power in excess of 900 homes (approximately 945). However, in the event that the system experiences a reduction in the flow rate (for example due to seasonal flow variations) to 0.7 m^3 / s, the new practical power available would be 1.15 MW.

1.15 X 10^3 kW X 24X 0.54 = 14.90 X 10^3 kWh (energy generated per day)

1 year = 5.43 X10^6 kWh

With this new flow rate, the system would generate electricity to power well under 900 homes, namely 680 homes approximately. Most hydroelectric systems utilize dams for maintaining a reservoir of water, with water levels depending on the local climate. Thus, one drawback is that a drop in the flow rate is always a possibility.

In the case of the wind turbine, with a blade diameter of 51 meters, the turbine generates 1.54 X 10^3 kW. Assuming again a 54% capacity factor, to calculate the amount of energy produced by the turbine:

1.54 X 10^3 kW X 24X 0.54= 19.95 X 10^3 kWh
1 year = 7.28 X10^6 kWh

Here it can be seen that this energy would be sufficient to power approximately 910 homes.

However, in the event of increased energy demands to serve, say, 1100 homes in a year, the turbine would need to generate 8.8 X 10^6 kWh. With a diameter of 58m, the turbine would therefore generate 2.0 X 10^3 kW. If it has a capacity factor of 54%:

2 X 10^3 kW X 24X 0.54= 25.92 X 10^3 kWh
1 year = 9.46 X10^6 kWh

This shows that the resulting energy output would successfully power over 1100 homes. However, demand for greater power output would necessitate increased blade size and the cost of modern blades represents a considerable segment of the total cost of the system. Therefore, a clear understanding of energy requirements is necessary to select an appropriate and cost-effective model of turbine.

In the case of the gas turbine engine, combustion is a continuous process. In open-cycle engines, internal combustion of fuel in the airflow supplies heat to the compressed air. This process takes place at high constant pressure and it provides energy input. Part of this energy produces valuable work and part goes to the exhaust gas, usually as a heat.

In the process of burning fuel, it is necessary to transfer the energy from the fire to the hardware using appropriate gaseous working fluid. The thermodynamic cycle of induction, compression, heating, expansion and exhaust is the standard technique to handle the working fluid and, in the case of a gas turbine engine, the working fluid flows continuously, passing from one specific device to the following.

In this scenario, with a mass flow rate in the working fluid of 15 Kg/s, the gas turbine would generate 1.56 MW, which is, again, sufficient to power 900 homes. However, in the case of increased energy demands to serve, say, 1700 homes in a year, the turbine would need to generate 13.6 X 10^6 kWh. Thus, with a mass flow of 30 Kg/s, the turbine would generate 3.0 X 10^3 kW. The calculation is therefore:

3.0 X 10^3 kW X 24 X 0.54 = 38.88 X 10^3 kWh
1 year= 14.19 X 10^6 KWh.

This shows that the resulting energy output would successfully power over 1700 homes. However, again, in order to select the most appropriate and cost-effective turbine, a clear understanding of energy requirements is crucial.

7.2 Conclusions

There were three main objectives to this research. The first was to determine the main alternative systems that work with rotordynamics equipment. This research showed that the main alternative systems are hydropower turbines, wind power, geothermal energy, gas turbines, tidal energy, wave and ocean thermal energy, and biofuels. Three select cases were analysed - the pelton turbine, wind turbine and the gas turbine, based on a scenario community of 900 houses and the average New Zealand home using 8MWh per year.

This research showed that these three alternative systems depend on the availability of relevant natural resources (wind, water and natural gas), energy requirements and how they may be utilized. An analysis and comparison of hydropower, wind energy and natural gas, for example, showed that hydro systems can provide a stable flow of electricity as long as the flow of water is not interrupted. The wind turbine is also an option, but minimum height and cost factors need to be taken into account. The gas turbine is a third option, however, as biogas is a product of bioconversion, it needs to be extracted from diluted mixtures and this process increases operational costs and consumes energy.

Technological advances for power generation using renewable resources such as hydropower, geothermal energy, wind power, and ocean wave energy are an important consideration for the supply of electricity without environmental impact. Accordingly, further research and advancement in this area is vital to present day issues concerning climate change, energy security, and rising energy costs.

The second objective was to explain the mathematical principles of rotordynamics. Mechanical vibration concepts were reviewed followed by analysis of rotordynamics topics such as the Jeff rotor, fluid film bearings and magnetic bearings.

The third objective was to explain the generation of power using biofuels and their main emissions. This research showed that biomass can be used by power plants to generate electricity. In this process, burning biomass after gasification or direct burning are common practices. Wood, animal waste, harvest residues, landfill gas and vegetable oil are the main products used to generate power.

Fossil fuel combustion generates around 98% of carbon emissions. Renewable Energy Sources is the technology that offers hope for the reduction of carbon dioxide as well as decreasing the levels of environmental contamination.

Further research on biofuels for transport (road, off-road, fluvial, air) is recommended.

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Appendix

The analysis in this appendix is based on two books: Fluid mechanics and thermodynamics of turbomachinery (4rd ed.) by Dixon,S.L. (1998). and Gas Turbine Heat Transfer and Cooling Technology by Han, J., Dutta, S. & Ekkad, S. (2000).

Mechanical Energy

When an object is subjected to an external constant force and it moves a distance x in the direction of the force, the work done W is equal to the energy dissipated.

$$W = FX \tag{A.1}$$

The work or energy W has the unit of joules (J) if the distance is in meters (m) and the force in Newtons (N).

If a mass m moves in a straight line with constant velocity υ which is the change of its position in the unit of time:

$$\upsilon = \frac{dx}{dt} \quad \text{for small changes of x}$$

$$\upsilon = \frac{x}{t} \quad \text{for large changes of x} \tag{A.2}$$

If the velocity of the mass m changes in the unit of time, the mass has acceleration a:

$$a = \frac{dv}{dt} = \frac{d}{dt}\left(\frac{dx}{dt}\right) = \frac{d^2x}{dt^2} \tag{A.3}$$

When the linear velocity of the body of constant mass changes as a consequence of the application of a force, the resulting acceleration is proportional to the applied force:

$$F = ma = m\frac{dv}{dt} = m\frac{d^2x}{dt} = mv\frac{dv}{dx} \qquad \text{(A.4)}$$

The equation A.4 refers to Newton's Second law of Motion.

Linear momentum, an important physical property, combines mass **m** with velocity v:

$$Linear\ momentum = mv = m\frac{dx}{dt} \qquad \text{(A.5)}$$

Comparison between (A.4) and (A.5):

Force = time rate of change of linear momentum

$$F = m\frac{dv}{dt} = \frac{d}{dt}(mv) \qquad \text{(A.6)}$$

There are two types of energy associated with a mass **m**: potential energy linked with its position and kinetic energy connected with its motion. In a body of mass **m**, located at height **h** above a datum plane, the gravitational potential energy is given by:

$$W_{PE} = mgh \qquad \text{(A.7)}$$

Where g (gravitational acceleration) = 9.8 m/s^2 and mass **m** is in Kg and height **h** in meters, the potential energy W_{PE} is in joules.

The kinetic energy W_{KE} linked with the motion when a mass **m** is in linear motion at invariable velocity v is:

$$W_{KE} = \frac{1}{2} m v^2 \qquad \text{(A.8)}$$

From A.8, the momentum is given by the derivative of kinetic energy W_{KE} with respect to velocity:

$$\frac{dW_{KE}}{dv} = mv \qquad \text{(A.9)}$$

The kinetic energy and momentum comply with the Principle of Conservation of Energy, which states that energy cannot be created or destroyed, although it can be changed from one form to another. Therefore, the sum of all forms of energy remains constant in any insulated or closed system.

When a mass **m** moving between two locations is affected by a force **F**:

$$\begin{pmatrix} F \times distace \\ moved \end{pmatrix} = \begin{pmatrix} work\ done\ on \\ or\ against\ the \\ mass \end{pmatrix} = \begin{pmatrix} change\ kinetic \\ energy\ between \\ the\ two\ locations \end{pmatrix} \text{(A.10)}$$

Rotational Motion

Rotational equipment is vital to many energy conversion processes. For example, diesel engines usually integrate flywheels and water, and gas turbines work with a rotor that has the nature of a non-uniform flywheel.

In order to illustrate the principles of rotational motion, it is necessary to consider a concentrate mass **m** with circular movement at radius **r** around a fixed centre point.

The angular velocity ω in rad/s of the mass and the instantaneous tangential velocity v in m/s are components of the motion where:

$$v = \omega\, r \tag{A.11}$$

The centripetal force keeps the circular movement of the mass. The product of the external force **F** acting tangentially on the mass with the radius **r** is called the torque **T**:

$$T = F\, r = F\frac{v}{\omega} \tag{A.12}$$

The units of torque are Newton-meter (Nm). From the equation A.11, the linear acceleration of the mass is given by:

$$a = \frac{dv}{dt} = r\frac{d\omega}{dt} \tag{A.13}$$

Combining (A.12) and (A.13) direct to:

$$\begin{aligned} T &= F\, r \\ &= mar \\ &= m\frac{dv}{dt}r \end{aligned}$$

$$T = mr^2\frac{d\omega}{dt} = mr^2\alpha \tag{A.14}$$

The term α refers to the angular acceleration in rad/s^2.

In the same equation, the quantity **mr^2** is called polar moment of inertia **J** having the dimension kgm^2:

$$J = mr^2 = [mass][radius\ of\ giration]^2 \tag{A.15}$$

The features of (A.14) and (A.15) can be summarised as:

$$T = J\alpha = J\frac{dw}{dt} \qquad \text{(A.16)}$$

The link between the kinetic energy and rotational motion can be found by incorporating (A.11) into (A.8), in (A.15):

$$\frac{1}{2}mv^2 = W_{KE} = \frac{1}{2}mr^2\omega^2$$

$$W_{KE} = \frac{1}{2}J\omega^2 \qquad \text{(A.17)}$$

The energy of motion, which is also the work done on the rotating mass, has units of joules (J) or watt-seconds (Ws) when J is in kgm^2 and ω in rad/s.

GLOSSARY

Terms from: http://www.eia.gov/tools/glossary/index.cfm?id=A

Acid rain: Also called acid precipitation or acid deposition, acid rain is precipitation containing harmful amounts of nitric and sulphuric acids formed primarily by sulphur dioxide and nitrogen oxides released into the atmosphere when fossil fuels are burned.

Active power: The component of electric power that performs work, typically measured in kilowatts (kW) or megawatts (MW). Also known as "real power." The terms "active" or "real" are used to modify the base term "power" to differentiate it from Reactive Power.

Adverse Weather Conditions: Reduced stream flow, lack of rain in the drainage basin, or low water supply behind a pondage or reservoir dam resulting in a reduced gross head that limits the production of hydroelectric power or forces restrictions to be placed on multipurpose reservoirs or other water uses.

Alcohol: The family name of a group of organic chemical compounds composed of carbon, hydrogen, and oxygen. The series of molecules vary in chain length and are composed of a hydrocarbon plus a hydroxyl group; CH(3)-(CH(2))n-OH (e.g., methanol, ethanol, and tertiary butyl alcohol).

Average water conditions: The amount and distribution of precipitation within a drainage basin and the run off conditions present as determined by reviewing the area water supply records over a long period of time.

Biodiesel: A fuel typically made from soybean, canola, or other vegetable oils; animal fats; and recycled grease. It can serve as a substitute for petroleum-derived diesel or distillate fuel. For EIA reporting, it is a fuel composed of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM (American Society for Testing materials) D 6751.

Biofuels: Liquid fuels and blending components produced from biomass feed stocks, used primarily for transportation.

Biomass: Organic non-fossil material of biological origin constituting a renewable energy source.

Biomass gas: A medium Btu gas containing methane and carbon dioxide, resulting from the action of micro-organisms on organic materials such as a landfill.

Biomass waste: Organic non-fossil material of biological origin that is a by-product or a discarded product. Biomass waste includes municipal solid waste from biogenic sources, landfill gas, sludge waste, agricultural crop by-products, straw, and other biomass solids, liquids, and gases; but excludes wood and wood-derived fuels (including black liquor), biofuels feedstock, biodiesel, and fuel ethanol. **Note:** EIA biomass waste data also include energy crops grown specifically for energy production, which would not normally constitute waste.

By-product: A secondary or additional product resulting from the feedstock use of energy or the processing of non-energy materials. For example, the more common by-products of coke ovens are coal gas, tar, and a mixture of benzene, toluene, and xylenes (BTX).

Carbon cycle: All carbon sinks and exchanges of carbon from one sink to another by various chemical, physical, geological, and biological processes. Also see Carbon sink.

Carbon dioxide (CO_2): A colourless, odourless, non-poisonous gas that is a normal part of Earth's atmosphere. Carbon dioxide is a product of fossil-fuel combustion as well as other processes. It is considered a greenhouse gas as it traps heat (infrared energy) radiated by the Earth into the atmosphere and thereby contributes to the potential for global warming. The global warming potential (GWP) of other greenhouse gases is measured in relation to that of carbon dioxide, which by international scientific convention is assigned a value of one (1). Also see Global warming potential (GWP) and Greenhouse gases.

Carbon sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes.

Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).

Combined cycle: An electric generating technology in which electricity is produced from otherwise lost waste heat exiting from one or more gas (combustion) turbines. The exiting heat is routed to a conventional boiler or to a heat recovery steam generator for utilization by a steam turbine in the production of electricity. This process increases the efficiency of the electric generating unit.

Combined cycle unit: An electric generating unit that consists of one or more combustion turbines and one or more boilers with a portion of the required energy input to the boiler(s) provided by the exhaust gas of the combustion turbine(s).

Combined heat and power (CHP) plant: A plant designed to produce both heat and electricity from a single heat source. Note: This term is being used in place of the term "cogenerator" that was used by EIA in the past. CHP better describes the facilities because some of the plants included do not produce heat and power in a sequential fashion and, as a result, do not meet the legal definition of cogeneration specified in the Public Utility Regulatory Policies Act (PURPA).

Combined hydroelectric plant: A hydroelectric plant that uses both pumped water and natural stream flow for the production of power.

Combustion: Chemical oxidation accompanied by the generation of light and heat.

Combustion chamber: An enclosed vessel in which chemical oxidation of fuel occurs.

Conventional thermal electricity generation: Electricity generated by an electric power plant using coal, petroleum, or gas as its source of energy.

Cooling: Conditioning of room air for human comfort by a refrigeration unit (such as an air conditioner or heat pump) or by circulating chilled water through a central cooling or district cooling system. Use of fans or blowers by themselves, without chilled air or water, is not included in this definition of cooling.

Cooling pond: A natural or manmade body of water that is used for dissipating waste heat from power plants.

Cooling system: An equipment system that provides water to the condensers and includes water intakes and outlets; cooling towers; and ponds, pumps, and pipes.

Dam: A physical barrier constructed across a river or waterway to control the flow of or raise the level of water. The purpose of construction may be for flood control, irrigation needs, hydroelectric power production, and/or recreation usage.

Deforestation: The net removal of trees from forested land.

Depleted storage field: A sub-surface natural geological reservoir, usually a depleted gas or oil field, used for storing natural gas.

Electric energy: The ability of an electric current to produce work, heat, light, or other forms of energy. It is measured in kilowatthours.

Electric generation: See Gross generation and Net generation.

Electric generation industry: Stationary and mobile generating units that are connected to the electric power grid and can generate electricity. The electric generation industry includes the "electric power sector" (utility generators and independent power producers) and industrial and commercial power generators, including combined-heat-and-power producers, but excludes units at single-family dwellings.

Electric power plant: A station containing prime movers, electric generators, and auxiliary equipment for converting mechanical, chemical, and/or fission energy into electric energy.

Emissions: Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).

Energy: The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatthours, while heat energy is usually measured in British thermal units (Btu).

Energy efficiency, Electricity: Refers to programs that are aimed at reducing the energy used by specific end-use devices and systems, typically without affecting the services provided. These programs reduce overall electricity consumption (reported in megawatthours), often without explicit consideration for the timing of program-induced savings. Such savings are generally achieved by substituting technologically more advanced equipment to produce the same level of end-use services (e.g. lighting, heating, motor drive) with less electricity. Examples include high-efficiency appliances, efficient lighting programs, high-efficiency heating, ventilating and air conditioning (HVAC) systems or control modifications, efficient building design, advanced electric motor drives, and heat recovery systems.

Electricity: A form of energy characterized by the presence and motion of elementary charged particles generated by friction, induction, or chemical change.

Electricity demand: The rate at which energy is delivered to loads and scheduling points by generation, transmission, and distribution facilities.

Electricity generation: The process of producing electric energy or the amount of electric energy produced by transforming other forms of energy, commonly expressed in kilowatthours(kWh) or megawatthours (MWh).

Energy used in the home: For electricity or natural gas, the quantity is the amount used by the household during the365- or 366-day period.

Ethanol (C_2H_5OH): A clear, colourless, flammable alcohol. Ethanol is typically produced biologically from biomass feed stocks such as agricultural crops and cellulosic residues from agricultural crops or wood. Ethanol can also be produced chemically from ethylene.

Ether: A generic term applied to a group of organic chemical compounds composed of carbon, hydrogen, and oxygen, characterized by an oxygen atom attached to two carbon atoms (e.g., methyl tertiary butyl ether).

Facility: An existing or planned location or site at which prime movers, electric generators, and/or equipment for converting mechanical, chemical, and/or nuclear energy into electric energy a resituated or will be situated. A facility may contain more than one generator of either the same or different prime mover type. For a cogenerator, the facility includes the industrial or commercial process.

Fossil fuel: An energy source formed in the EarthRSQUO;s crust from decayed organic material. The common fossil fuels are petroleum, coal, and natural gas.

Fuel wood: Wood and wood products, possibly including scrubs and branches, etc, bought or gathered, and used by direct combustion.

Gas: A non-solid, non-liquid combustible energy source that includes natural gas, coke-oven gas, blast-furnace gas, and refinery gas.

Gas turbine plant: A plant in which the prime mover is a gas turbine. A gas turbine consists typically of an axial-flow air compressor and one or more combustion chambers where liquid or gaseous fuel is burned and the hot gases are passed to the turbine and where the hot gases expand drive the generator and are then used to run the compressor.

Generation: The process of producing electric energy by transforming other forms of energy; also, the amount of electric energy produced, expressed in kilowatthours.

Global warming: An increase in the near surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences, but the term is today most often used to refer to the warming some scientists predict will occur as a result of increased anthropogenic emissions of greenhouse gases.

Greenhouse effect: The result of water vapour, carbon dioxide, and other atmospheric gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent.

Greenhouse gases: Those gases, such as water vapour, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Grid: The layout of an electrical distribution system

Gross generation: The total amount of electric energy produced by generating units and measured at the generating terminal in kilowatthours (kWh) or megawatthours (MWh).

Heat pump (geothermal): A heat pump in which the refrigerant exchanges heat (in a heat exchanger) with a fluid circulating through an earth connection medium (ground or ground water). The fluid is contained in a variety of loop (pipe) configurations depending on the temperature of the ground and the ground area available. Loops may be installed horizontally or vertically in the ground or submersed in a body of water.

Kilowatthour (kWh): A measure of electricity defined as a unit of work or energy, measured as 1 kilowatt (1,000watts) of power expended for 1 hour. One kWh is equivalent to 3,412 Btu.

Liquid fuels: All petroleum products, natural gas liquids, biofuels, and liquids derived from other hydrocarbon sources (coal to liquids and gas to liquids). Not included are compressed natural gas (CNG), liquefied natural gas (LNG), and hydrogen.

Megawatt (MW): One million watts of electricity.

Methane: A colourless, flammable, odourless hydrocarbon gas (CH_4) which is the major component of natural gas. It is also an important source of hydrogen in various industrial processes. Methane is a greenhouse gas. See also Greenhouse gases.

Natural gas: A gaseous mixture of hydrocarbon compounds, the primary one being methane.

Net generation: The amount of gross generation less the electrical energy consumed at the generating station(s) for station service or auxiliaries. Note: Electricity required for pumping at pumped-storage plants is regarded as electricity for station service and is deducted from gross generation.

Nitrogen dioxide: A compound of nitrogen and oxygen formed by the oxidation of nitric oxide (NO), which is produced by the combustion of solid fuels.

Nitrogen oxides (NO_x): Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

Nitrous oxide (N_2O): A colourless gas, naturally occurring in the atmosphere. Nitrous oxide hasa 100-year Global Warming Potential of 310.

Non-biomass waste: Material of non-biological origin that is a by-product or a discarded product. "Non-biomass waste" includes municipal solid waste from non-biogenic sources, such as plastics, and tire-derived fuels.

Non-renewable fuels: Fuels that cannot be easily made or "renewed," such as oil, natural gas, and coal.

Ocean energy systems: Energy conversion technologies that harness the energy in tides, waves, and thermal gradients in the oceans.

Ocean thermal energy conversion (OTEC): The process or technologies for producing energy by harnessing the temperature differences (thermal gradients) between ocean surface waters and that of ocean depths. Warm surface water is pumped through an evaporator containing a working fluid in a closed Rankine-cycle system. The vaporized fluid drives a turbine/generator.

Organic waste: Waste material of animal or plant origin.

Power (electrical): An electric measurement unit of power called a voltampere is equal to the product of 1 volt and 1 ampere. This is equivalent to 1 watt for a direct current system, and a unit of apparent power is separated into real and reactive power. Real power is the work-producing part of apparent power that measures the rate of supply of energy and is denoted as kilowatts (kW). Reactive power is the portion of apparent power that does no work and is referred to as kilovars; this type of power must be supplied to most types of magnetic equipment, such as motors, and is supplied by generator or by electrostatic equipment. Voltamperes are usually divided by 1,000 and called kilovoltamperes (kVA). Energy is denoted by the product of real power and the length of time utilized; this product is expressed as kilowathours.

Power loss: The difference between electricity input and output as a result of an energy transfer between two points.

Power production plant: All the land and land rights, structures and improvements, boiler or reactor vessel equipment, engines and engine-driven generator, turbogenerator units, accessory electric equipment, and miscellaneous power plant equipment are grouped together for each individual facility.

Pyrolysis: The thermal decomposition of biomass at high temperatures (greater than 400° F, or 200° C) in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oxygenated oils), and gases (methane, carbon monoxide, and carbondioxide) with proportions determined by operating temperature, pressure, oxygen content, and other conditions.

Rankine cycle: The thermodynamic cycle that is an ideal standard for comparing performance of heat-engines, steam power plants, steam turbines, and heat pump systems that use a condensable vapour as the working fluid. Efficiency is measured as work done divided by sensible heat supplied.

Rankine cycle engine: The Rankine cycle system uses a liquid that evaporates when heated and expands to produce work, such as turning a turbine, which when connected to a generator, produces electricity. The exhaust vapour expelled from the turbine condenses and the liquid is pumped back to the boiler to repeat the cycle. The working fluid most commonly used is water, though other liquids can also be used. Rankine cycle design is used by most commercial electric power plants. The traditional steam locomotive is also a common form of the Rankine cycle engine. The Rankine engine itself can be either a piston engine or a turbine.

Renewable energy resources: Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

Renewable fuels (other): Fuels and fuel blending components, except biomass-based diesel fuel, renewable diesel fuel, and fuel ethanol, produced from renewable biomass. **Note:** This category "other" pertains to the petroleum supply data system.

Site energy consumption: The Btu value of energy at the point it enters the home, building, or establishment, sometimes referred to as "delivered" energy.

Thermal: A term used to identify a type of electric generating station, capacity, capability, or output in which the source of energy for the prime mover is heat.

Thermodynamics: A study of the transformation of energy from one form to another, and its practical application.

Turbine: A machine for generating rotary mechanical power from the energy of a stream of fluid (such as water, steam, or hot gas). Turbines convert the kinetic energy of fluids to mechanical energy through the principles of impulse and reaction, or a mixture of the two.

Utility generation: Generation by electric systems engaged in selling electric energy to the public.

Waste energy: Municipal solid waste, landfill gas, methane, digester gas, liquid acetonitrile waste, tall oil, waste alcohol, medical waste, paper pellets, sludge waste, solid by-products, tires, agricultural by-products, closed loop biomass, fish oil, and straw used as fuel.

Water turbine: A turbine that uses water pressure to rotate its blades; the primary types are the Pelton wheel, for high heads (pressure); the Francis turbine, for low to medium heads; and the Kaplan for a wide range of heads. Primarily used to power an electric generator.

Water wheel: A wheel that is designed to use the weight and/or force of moving water to turn it, primarily to operate machinery or grind grain.

Wind power plant: A group of wind turbines interconnected to a common utility system through a system of transformers, distribution lines, and (usually) one substation. Operation, control, and maintenance functions are often centralized through a network of computerized monitoring systems, supplemented by visual inspection. This is a term commonly used in the United States. In Europe, it is called a generating station.

Wind turbine: Wind energy conversion device that produces electricity; typically three blades rotating about a horizontal axis and positioned up-wind of the supporting tower.

Wood energy: Wood and wood products used as fuel, including round wood (cord wood), limb wood, wood chips, bark, saw dust, forest residues, charcoal, pulp waste, and spent pulping liquor.