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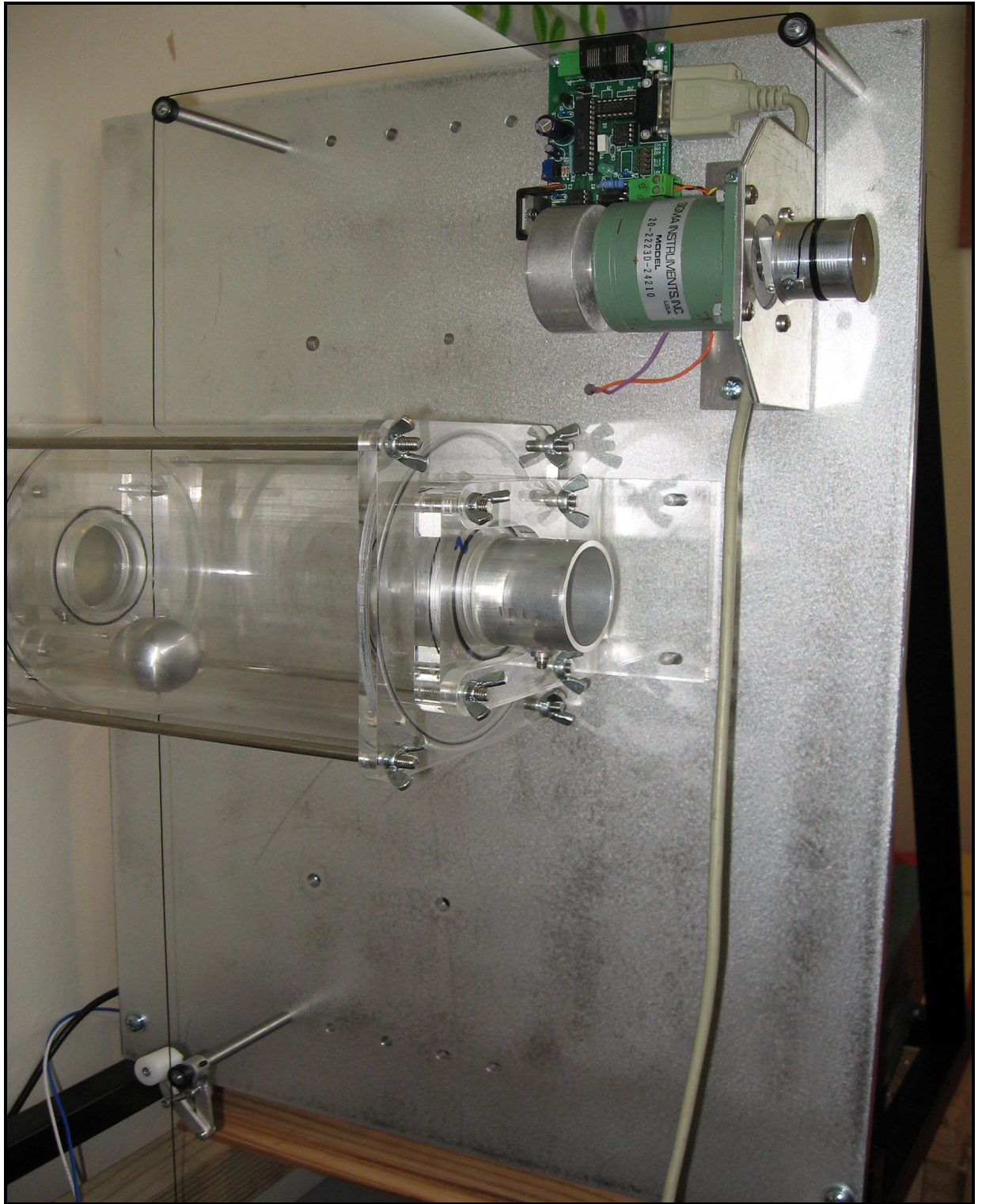
The application of Helmholtz resonance to determination of the volume of solids, liquids and particulate matter

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Pulley apparatus set up for mapping the resonant frequency versus sample location in the horizontal configuration

Abstract

The aim of this investigation was the creation of a high precision volume measurement device using the Helmholtz resonator principle, the purpose of which was to measure, without interference, liquids, solids and particulate samples. A previous study by Nishizu *et al.* (2001) suggested they achieved an accuracy of about $\pm 1\%$ of full scale, where full scale is 100% fill of the resonator chamber. Theory suggested that with careful design and measurement accuracy of approximately $\pm 0.1\%$ should be achievable.

A high precision resonator was designed using acoustic theory and drawn using SolidWorks™ computer aided design software. This was then built using a computerised numerical controlled milling machine. The resulting resonator was coupled to a 16-bit high-speed data acquisition system driven by purpose-made LabVIEW™ software. Using a resonant hunting method, repeatability was within $\pm 1\text{mL}$ for a 3L chamber and the accuracy was better than $\pm 3\text{mL}$, which is $\pm 0.1\%$ of full scale for liquid and solid samples.

Testing of particulate material gave results indicating complex behaviour occurring within the resonator. Accuracy of sub-millimetre granular samples was restricted to approximately $\pm 1\%$, and fill factors to about 50%. This reduction in accuracy was caused by a combination of energy absorption and resonant peak broadening. Medium sized particles, between 1mm and 15mm allowed measurement accuracies of approximately $\pm 0.5\%$. Larger samples, greater than 15mm in diameter, gave results with comparable accuracy to water and solids tested.

It was found that most materials required a post measurement curve fit to align predictive volume calculations. All samples were observed to have a predictive deviation curve with coefficients dependent on the material or general shape. This curve appeared to be a function of sample regularity and/or whether the sample has interstitial spaces. To achieve high measurement accuracy temperature compensation was required to negate drifts in sample measurement.

Chamber mapping was conducted using a spherical solid moved to precise locations, then making a three-dimensional frequency map of the inside of a dual port resonator. This showed the length extension term for the moving mass of air in the port penetrates roughly three times further than theory suggests. However, the influence of this extra ‘tail’ was found to be negligible when calculating sample volumes.

A new method of measuring volume was developed using Q profile shifting and ambient temperature information. Accuracies for this method were comparable to those found using the resonant hunting method. A significant advantage of the new method is a 2-3 second measurement time compared to approximately 40 seconds for the resonant hunting method. The Q profile shifting method allowed volume measurements on samples moving through a dual port resonator at speeds of up to 100mm/s.

Free fall measurements proved unsuccessful using existing methods, but variations in signal data for different sample sizes suggest the need for future investigation.

Follow-up studies may provide new interpretation models and methods for high-speed acquisition and analysis required to solve freefall measurements.

Precise temperature (speed of sound) and flange factor (responsible for port length extension) relationships were evaluated. The correction factor for the speed of sound with temperature was found to be marginally different to established theory using the Helmholtz equation due to temperature secondary effects in the port length extension factor. The flange factor, which determines port length extension, for the configurations used in this investigation was experimentally found to be approximately 5% less than theoretical values.

It was established that the sample to be measured must be within a certain region of the chamber for accurate volume measurements to be made. If the sample were larger than the bounded region the resonant frequency would no longer obey the Helmholtz relationship. This would thereby reduce the accuracy of the measurement. All samples irrespective of cross sectional area were found to alter the resonant frequency when they were over 85% of the chamber height.

An equalisation method termed environmental normalisation curve was developed to prevent environmental and loudspeaker deficiencies from colouring Q profiles used in Q profile shifting procedures. This was undertaken as Q profile shifting relies on consistency in the Q profile. The environmental normalisation curve was able to equalise external factors to within $\pm 0.4\text{dB}$. The environmental normalisation method could be used to post-process data or applied in real time to frequency generation.

The controlled decent Q profile shifting technique was refined further to be used in continuous measurements in a single port resonator. Samples could theoretically be measured up to 15% of full-scale fill before resonant peak predictability would compromise accuracy. Measurement times were from one to three seconds, depending on environmental temperature stability.

An alternative Helmholtz resonator was developed and investigated using an inverted port. This variant has potential applications for a seal-less chamber and port with rapid non-interference chamber access. Q factors for the inverted port resonator were found to be significantly less than tradition Helmholtz resonators. It is believed this is due to a larger boundary layer acoustic resistance occurring in the inverted port.

A variable chamber resonator was designed and built as a further development of the Helmholtz resonator volume measurement system, as the uncertainty of measurement is a function of resonant chamber size. Therefore, using the variable chamber resonator the chamber size could be customised to the sample size. In this way the uncertainty of measurement could be minimised. The variable chamber resonator was used with both the resonant hunting method and the Q profile shifting method.

Volume measurements on produce and minerals using the variable chamber resonator yielded results of similar accuracy to measurements on calibration samples. Each sample type displayed characteristics that would make specific calibration necessary. Both techniques were able to detect hidden void spaces, larger than 2% of the sample volume, and in punctured samples. Therefore, both methods may be viable for rapid sorting of produce and minerals.

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Table of contents

Abstract.....	i
Acknowledgements	iii
Table of contents	v
Figures and Tables.....	ix
Nomenclature	xvii
Basic equations.....	xix
Glossary	xxi
Chapter 1 Introduction and literature review.....	1
1.1 Introduction.....	3
1.2 Literature Review: Volume measurement.....	7
1.2.1 Experimental volume measurement using a Helmholtz resonator	7
1.2.2 Patent for Helmholtz volume measurement device	9
1.2.3 Experimental Helmholtz resonator with variable chamber size	9
1.2.4 Pycnometers	10
1.2.5 Commercial pycnometers	12
1.2.6 Commercial methods for sorting produce and minerals	12
1.2.7 Spheres in a resonant cavity.....	13
Literature review conclusions	14
Chapter 2 Helmholtz resonator theory	15
2.1Helmholtz resonator theory	17
2.1.1 Traditional Helmholtz resonator theory.....	17
2.1.2 Chirp frequencies	18
2.1.3 Non-ideal behaviour in the port: length extension.....	18
2.1.4 Non-ideal behaviour in the port: radiation resistance	21
2.1.5 Non-ideal behaviour in the port: viscosity and turbulence	22
2.1.6 Non-ideal behaviour in the port: heat conductive losses	23
2.1.7 Non-ideal behaviour in the port: relaxation time.....	24
2.1.8 Non-ideal behaviour in the port: non-linear effects.....	24
2.1.9 Non-ideal behaviour in the port: port placement	25
2.1.10 Non-ideal behaviour in the port: port shape	26
2.1.11 Non-ideal behaviour: chamber and port length	26
2.1.12 Non-ideal behaviour: chamber shape.....	27
2.1.13 Resonator chamber with many apertures.....	28
2.1.14 Analytical transmission and finite element analysis.....	29
2.1.15 Transcendental equations for resonance frequency determination.....	29
Key concepts in Helmholtz resonator design.....	31
Chapter 3 Resonance hunting for volume determination	33
3.1 Introduction and summary	35
3.2 Equipment and samples	37
3.2.1 Resonators.....	37
3.2.2 Microphones	38
3.2.3 Data Acquisition (DAQ) Hardware	39
3.2.4 Temperature sensors	39
3.2.5 Software	39
3.2.6 Pink noise.....	40
3.2.7 Chirps – Frequency sweep	40
3.2.8 Square wave	40
3.2.9 Loudspeaker	41

3.2.10 Pulley apparatus	41
3.2.11 Stepper-motor	43
3.2.12 Solid samples	43
3.2.13 Granular samples	43
3.2.14 Liquid samples	44
3.2.15 Acoustic barrier disks	44
3.3 Methods.....	45
3.3.1 Characterising the fabricated resonators	45
3.3.2 Repeatability of measurements using resonators	45
3.3.3 Temperature effects	45
3.3.4 Calibrating the asymmetric single port resonator	46
3.3.5 Effects of port symmetry	48
3.3.6 Effects of sample irregularities	48
3.3.7 Measurement on granular materials.....	49
3.3.8 Effects of air leaks on resonant frequency and Q factor	50
3.3.9 Effects of sample position on volume measurements.....	51
3.3.10 Controlled decent using a dual-port resonator and resonant hunting	51
3.3.11 Measurement of port flanging effects	52
3.4 Results	53
3.4.1 Characterising the fabricated resonators	53
3.4.2 Repeatability of measurements using resonators	54
3.4.3 Temperature effects	56
3.4.4 Calibrating the asymmetric single port resonator	58
3.4.5 Effects of port symmetry	62
3.4.6 Effects of sample irregularities	62
3.4.7 Measurement on granular materials.....	65
3.4.8 Effects of air leaks on resonant frequency and Q factor	73
3.4.9 Effects of sample position on volume measurements.....	75
3.4.10 Controlled decent using a dual-port resonator and resonant hunting	77
3.4.11 Measurement of port flanging effects	78
3.5 Discussion.....	81
3.5.1 Characterising the fabricated resonators	81
3.5.2 Repeatability of measurements using resonators	81
3.5.3 Temperature effects	83
3.5.4 Calibrating the asymmetric single port resonator	83
3.5.5 Effects of port symmetry	84
3.5.6 Effects of sample irregularities	85
3.5.7 Measurement on granular materials.....	86
3.5.8 Effects of air leaks on resonant frequency and Q factor	88
3.5.9 Effects of sample position on volume measurements.....	89
3.5.10 Controlled decent using a dual-port resonator and resonant hunting	90
3.5.11 Measurement of port flanging effects	90
Chapter 4 New methods in volume determination using Helmholtz resonance .91	
4.1 Introduction and summary	93
4.2 Equipment and samples	95
4.2.1 Variable chamber resonator (VCR)	95
4.2.2 Inverted port resonators	95
4.2.3 Buoyancy rig.....	96
4.2.4 Agricultural produce and mineral samples	96
4.3 Methods.....	99

4.3.1 Phase shift technique.....	99
4.3.2 Q profile shifting – Controlled decent	99
4.3.3 Q profile shifting – Free falling sample	101
4.3.4 Environmental Normalisation Curve (ENC)	102
4.3.5 Continuous Q Profile Shifting technique (QPS).....	102
4.3.6 Inverted port resonators	103
4.3.7 Variable chamber resonator (VCR)	103
4.3.8 Applications – Produce and mineral testing	104
4.4 Results	105
4.4.1 Phase shift technique.....	105
4.4.2 Q profile shifting – Controlled drop	105
4.4.3 Q profile shifting – Free falling sample	108
4.4.4 Environmental normalisation curve (ENC)	109
4.4.5 Continuous Q profile shifting technique.....	112
4.4.6 Inverted port resonators	116
4.4.7 Variable chamber resonator (VCR)	118
4.4.8 Applications – Produce and mineral testing	122
4.5 Discussion.....	127
4.5.1 Phase shift technique.....	127
4.5.2 Q profile shifting – Controlled drop	127
4.5.3 Q profile shifting – Free falling sample	128
4.5.4 Environmental normalisation curve (ENC)	129
4.5.5 Continuous Q profile shifting technique.....	130
4.5.6 Inverted port resonators	131
4.5.7 Variable chamber resonator (VCR)	131
4.5.8 Applications – Produce and mineral testing	132
Chapter 5 Conclusions and recommendations.....	135
5.1 Conclusions.....	137
5.1.1 Characterising the fabricated resonators.....	137
5.1.2 Repeatability of measurements using resonators	137
5.1.3 Temperature effects	138
5.1.4 Calibrating the asymmetric single port resonator	138
5.1.5 Effects of port symmetry	138
5.1.6 Effects of sample irregularities	138
5.1.7 Measurement of granular materials	139
5.1.8 Effects of air leaks on resonant frequency and Q factor	139
5.1.9 Effects of sample position on volume measurements.....	139
5.1.10 Controlled decent and free falling sample using a dual-port resonator	140
5.1.11 Environmental normalisation curve (ENC)	140
5.1.12 Continuous Q profile shifting technique.....	140
5.1.13 Inverted port resonators	141
5.1.14 Variable chamber resonator (VCR)	141
5.1.15 Applications – Produce and mineral testing	141
5.2 Recommendations	143
5.2.1 Energy in resonance, improving the Q factor	143
5.2.2 Thermal heating and temperature inside the resonator	143
5.2.3 Broadband noise from particle reemission of sound.....	143
5.2.4 Effects of particle shape when testing granular materials	143
5.2.5 Phase shifting method of measuring sample volume.....	143
5.2.6 Alternate methods for volume measurements of moving samples	143

5.2.7 Measurement of surface hardness and structure	144
5.2.8 Energy impulse response	144
Appendix A Mathematics of acoustics	145
1. The wave equation	145
2. Solutions to the wave equation for Helmholtz resonator	147
3. Mechanical Power and Q factor for a resonator	149
4. Mechanical piston radiator	150
5. Directivity of a piston source	153
6. Pressure at the piston source	154
7. Radiation impedance	157
8. Flanged and un-flanged ports	158
9. Mechanical resistance caused by boundary layer	159
10. Mechanical stiffness caused by an orifice	162
11. Acoustic transmission effects	162
12. Lumped parameters	168
13. Diffraction from edge effects	169
Appendix B Software descriptions and functional block diagrams	171
1. Resonant hunting	171
2. Broad frequency scanner	172
3. Chamber mapping using resonant hunting	173
4. Q profile shifting	174
State 1 – Resonant hunting on empty chamber	174
State 2 – Generate Q profile	175
State 3 – Perform Q profile shifting	176
5. Continuous Q profile shifting	177
State 3 – Continuous Q profile shifting	177
6. VCR Q profile shifting	178
State 1 – Acquire Q profile	178
State 2 – Dynamic Q profile shifting	179
State 3 and 4 – Create and check an ENC profile	180
Appendix C Loudspeaker Parameters	181
1. Loudspeaker design considerations	181
2. Loudspeaker enclosure design	181
3. Noise cancellation and echo suppression	182
4. Loudspeaker lobes and interference	183
Appendix D Calibrations	187
1. Density measurements of marbles used in granular testing	187
2. Calibration of variable chamber resonator, SMC LXPB200 linear actuator	187
3. Anechoic chamber calibration of microphone and loudspeaker	188
4. Buoyancy uncertainty due to balance deflection	193
Appendix E Working drawings and data sheets	195
Drawings for primary Helmholtz resonator:	197
Speaker enclosure drawings:	209
Drawings for variable chamber resonator:	212
Drawings for volume buoyancy rig:	222
Data sheets	224
References	225

Figures and Tables

Figure 1.1.1	Historical Resonators' from Notre Dame Indiana, http://physics.kenyon.edu (last viewed May 2008)	3
Figure 1.1.2	Cross section of historical resonator with listening orifice at rear of chamber. 4	
Figure 1.2.1	Schematic of automatic continuous volume measurement system, Nishizu <i>et al.</i> (2001).	7
Figure 1.2.2	Schematic of Helmholtz resonator fuel tank designed to be used in micro-gravity conditions, Nakano <i>et al.</i> (2006).	8
Figure 1.2.3	a) Helmholtz resonator designed for measuring a human's volume. b) Super position of whistle frequency onto Helmholtz frequency (Johnson Jr., 1995). 9	
Figure 1.2.4	Variable volume Helmholtz resonator designed and implemented by De Bedout <i>et al.</i> (Left) top view, (right) side view (De Bedout <i>et al.</i> , 1996).	10
Figure 1.2.5	Diagram of a constant-volume gas pycnometer. The sample- chamber and the tank, initially filled with gas at two different pressures, are connected by opening valve 'Z' (from Tamari 2004).	11
Figure 2.1.1	a) Simple ideal resonator showing moving mass of air in port compressing air in chamber volume and springing back due to the increased pressure in the chamber. b) Equivalent mass spring system.	17
Figure 2.1.2	Flange material will alter the virtual or effective port length.	18
Figure 2.1.3	Port placed eccentrically with respect to the chamber centre.	25
Figure 2.1.4	Chamber with tapered conical port.	26
Figure 2.1.5	Sinusoidal representation of pressure within chamber occurring when dimensions of the resonator are a significant fraction of the resonant frequency wavelength.	27
Figure 2.1.6	Three methods for determination of resonant frequency using traditional ($1/kL$), improved traditional ($1/kL-[kL]/3$) and transcendental ($\cot[kL]$). 31	
Figure 3.2.1	a) Photo of standard single asymmetric port resonator with blanking plate on bottom face having a 3L chamber (140mm internal diameter), 170mm long port with an internal radius of 44mm and b) schematic diagram.	37
Figure 3.2.2	A) Single 170mm asymmetric port plate B) 51mm asymmetric port plate C) 170mm symmetric port plate	38
Table 3.2.1	Fourteen possible resonator combinations possible using available chamber sizes, port lengths and port types.	38
Figure 3.2.3	Microphone locations on resonant chamber, able to measure port frequency and chamber frequency independently.	39
Figure 3.2.4	A) Schematic of hardware components used in experimental setup. B) Resonator alignment and distance from speaker.	39
Figure 3.2.5	A) Decaying regular spacing of harmonic frequencies present in square wave. B) Expected amplification of harmonic near Helmholtz resonant frequency.	41
Figure 3.2.6	Vertical arrangement of dual port resonator showing pulleys above and below to locate sample.	42
Figure 3.2.7	Horizontal arrangement of dual port 3L resonator showing pulleys above and below to locate sample. Also shown are placement holes for pulley support posts allowing multiple horizontal placements to be investigated.	42

Table 3.2.2	Bulk density and particle density information for granular materials. ‘*’ indicates approximate only.....	43
Table 3.2.3	Change in water density with temperature (Lide, 1990).....	44
Figure 3.3.1	Photo (left) and diagram (right) of water filling of 3L chamber with 170mm, asymmetric port used for volume calibration.	47
Figure 3.3.2	(a): Flanged internal and un-flanged external port, asymmetric. (b): Un-flanged internal and un-flanged external port, symmetric.....	48
Figure 3.3.3	A) Photograph of one of the six flat disks (20mm diameter) used to isolate surface area effects from volume effects. B) Diagram of resonator housing a disk of variable size and position.	49
Figure 3.3.4	A) Photograph of the adjustable piston within chamber and B) Schematic diagram. C) Photo of embedded magnet within piston used for retaining steel coated disks. D) Photo of ballotini coated disk.	50
Figure 3.3.5	(Left) five positions for a spherical sample moving through the resonator vertically. (Right) horizontally adjusted spherical sample. Both configurations are driven by a stepper motor to create resonant mapping characteristics for the dual port resonator.	51
Figure 3.3.6	Flange material added resonator port. Flange material will alter the virtual or effective port length.	52
Figure 3.4.1	Attenuation in peak amplitude caused by changing experimental environment, where ‘A’ and ‘B’ are door A and B and ‘O’ and ‘C’ are open and closed. 3L chamber with a 170mm long, 22mm radius asymmetric port.....	54
Table 3.4.1	Comparison of predicted Q factors, Equation (No.25), and actual measured Q factors, Equation (No.24), from Basic Equations. Q factors were evaluated for various chamber and port configurations at 20 degrees C.....	55
Figure 3.4.2	Resonant Frequency versus amplitude for increasing water fill level indicating changes in peak sound level. Tests used 3L chamber with 22mm radius, asymmetric, 170mm long port.	56
Figure 3.4.3	Empirical, using the Helmholtz equation, and standard theoretical speed of sound gradient for changes in ambient temperature for 3L chamber with 170mm port.....	57
Figure 3.4.4	Changing value of the Helmholtz constants (α) for increasing temperature using a 3L chamber with 170mm port.	57
Figure 3.4.5	Deviation difference in volume for increasing chamber fill between predicted volume using Helmholtz equation with and without temperature compensation. Tests used water, 3L chamber with 22mm radius, asymmetric, 170mm long port.....	58
Figure 3.4.6	Calibration plot of water fill volume versus actual and predicted resonant frequency (Res Freq). Tests used 3L chamber with 22mm radius, asymmetric, 170mm long port.	59
Figure 3.4.7	Second order curve fit of predicted volume deviation from actual volume. Tests used water, 3L chamber with 22mm radius, asymmetric, 170mm long port.	59
Figure 3.4.8	High Q factor for water calibration tests up to fill of 2500mL. Tests used 3L chamber with 22mm radius, asymmetric, 170mm long port.	60
Figure 3.4.9	Comparison of vertical and horizontal volume deviation with water filling using 3L chamber with 22mm radius 170mm long asymmetric port.	60
Figure 3.4.10	Parabolic curve fit of predicted volume deviation from actual volume using solid piston. Tests used 3L chamber with 22mm radius, asymmetric, 170mm long port.	61

Figure 3.4.11	Deviation of predicted volume from actual volume using water fill data for various chamber volume sizes. Tests used 1, 2 and 3L chambers with 22mm radius, asymmetric, 170mm long port.	61
Figure 3.4.12	Second order curve fit of predicted volume deviation from actual volume using symmetric port. Tests used water, 3L chamber with 22mm radius, symmetric, 170mm long port.	62
Figure 3.4.13	Curves of predicted volume deviation from actual volume using individual spherical samples and large cubic blocks. Tests used 3L chamber with 22mm radius, asymmetric, 170mm long port.	63
Figure 3.4.14	Curves of predicted volume deviation from actual volume using 1, 2 and 3L chambers with individual spherical samples. Tests used 3L chamber with 22mm radius, asymmetric, 170mm long port.	64
Figure 3.4.15	Frequency deviation plot for various disks having different cross sectional area in 3L chamber with 170mm port.....	64
Figure 3.4.16	Plot showing the maximum height a disk can extend into the chamber based on it's cross sectional area percentage to that of the chamber's cross sectional area.	65
Figure 3.4.17	Comparison of actual volume versus predicted particle volume for granular materials tested. Tests used 3L chamber with 22mm radius, 170mm asymmetric port.	66
Figure 3.4.18	Comparison of actual volume versus predicted volume for plastic pallets agricultural granular materials tested. Tests used 3L chamber with 22mm radius, 170mm asymmetric port.	67
Figure 3.4.19	Q factor with increasing particle fill fraction. Using a 3L chamber, 22mm radius, 170mm asymmetric port.	68
Figure 3.4.20	Attenuation with increasing particle fill level for marbles, ballotini and sand. Using a 3L chamber, 22mm radius, 170mm asymmetric port.....	69
Figure 3.4.21	Broad spectrum frequency sweep as measured in the port with three fill fractions of sand. Using a 3L chamber, 22mm radius, 170mm asymmetric port.	70
Figure 3.4.22	Broad spectrum frequency sweep as measured in the chamber with three fill fractions of sand. Using a 3L chamber, 22mm radius, 170mm asymmetric port.	70
Figure 3.4.23	Change in linear curve fitted slope for changing particle size. Using a variable 3L chamber, 22mm radius, 170mm asymmetric port.	71
Figure 3.4.24	Logarithmic trend of Q factor for changing particle size measured at 25% fill. Using a variable 3L chamber, 22mm radius, 170mm asymmetric port.	71
Figure 3.4.25	Comparative Q factor testing with various granular coated piston surfaces. Using a variable 3L chamber, 22mm radius, 170mm asymmetric port.	72
Figure 3.4.26	Experimental differences in volume predictive deviation due to piston coating materials. Using a variable 3L chamber, 22mm radius, 170mm asymmetric port.	73
Figure 3.4.27	Observed linear increase in resonant frequency due to an increasing number of air leaks in the resonant chamber. Using a 3L chamber, 22mm radius, 170mm asymmetric port.	73
Figure 3.4.28	Data fitted with logarithmic decreasing Q factor due to an increasing number of air leaks in the resonant chamber. Using a 3L chamber, 22mm radius, 170mm asymmetric port.	74

Figure 3.4.29	Data fitted with second order curve for rise in frequency with increasing leak diameter. 3L chamber with 170mm long port having 22mm radius.	74
Figure 3.4.30	Q factor with increasing leak diameter fitted with a second order curve. 3L chamber with 170mm long port having 22mm radius.....	75
Figure 3.4.31	Frequency chamber mapping using a 42mL aluminium sphere moved in the radial direction in 1mm steps at 5 positions along the chamber's length. The frequency has been normalised and temperature corrected. Also shown is the 3L chamber indicating orientation of mapping, width being radial movement and horizontal being chamber length.	76
Figure 3.4.32	Frequency chamber mapping using a 42mL aluminium sphere moved in an axial direction in 1mm steps along the chamber's length. Using a 3L chamber with two 22mm radius, 51mm asymmetric ports.....	77
Figure 3.4.33	Enlargement of 'stable' region in figure 4.32. Plot shows change in mL from a central value of 3168mL at 145mm displacement. Using a 3L chamber with two 22mm radius, 51mm asymmetric ports.....	77
Figure 3.4.34	Effects of various flange sizes on resonant frequency used to evaluate port length extension. Measurements taken with 3L resonator having two different port lengths, 51mm and 170mm.....	78
Figure 4.2.1	Variable chamber resonator, 1.6L – 3.5L with 175mm port. Shown are linear actuator placement and movable floor plate allowing sample insertion....	95
Figure 4.2.2	Inverted port resonator with removable port piece allowing easy access to chamber.....	96
Figure 4.2.3	Buoyancy rig used to either suspend sample or provide forced immersion for samples less dense than water.	96
Table 4.2.1	Various produce and mineral samples used in variable chamber resonator using Q profile shifting.	97
Figure 4.3.1	Software adjustments to the Q profile required to make predictive volume measurements. A is the frequency shift due to temperature change, B the frequency shift associated with a volume change and D the total change in frequency that is used to predict the new resonant frequency. C is the amplitude change proportional to the change in microphone level at the initial resonant frequency.....	100
Figure 4.4.1	Q profiles for four chamber configurations, each using a different sized sphere. Using a 3L chamber with two 22mm radius, 51mm asymmetric ports.	105
Figure 4.4.2	Resonant peak with increasing sample size for Q profile shifting. Tests used a 3L chamber with two 22mm radius, 51mm asymmetric ports.	106
Figure 4.4.3	Reduction in RMS amplitude as samples pass through the chamber at 80mm/s. Transition dips are present as the samples pass through the ports. Using a 3L chamber with two 22mm radius, 51mm asymmetric ports.....	106
Figure 4.4.4	Comparison between spline fit and 5 th order polynomial using an empty chamber. 3L chamber with two 22mm radius, 51mm asymmetric ports.	107
Figure 4.4.5	Changes in descent speed for an aluminium sphere of 42mL. Speeds 1, 5 and 10 are 28mm/s, 50mm/s and 100mm/s respectively. Tests used a 3L chamber with two 22mm radius, 51mm asymmetric ports.....	108
Figure 4.4.6	a) Free fall data for 9mL and 23mL spheres. 9mL sphere measurement at 0.1s and 23mL measurement time at 0.25s b) comparison of slower descent speed at 60mm/s. Tests used a 3L chamber with two 22mm radius, 51mm asymmetric ports.....	109

Figure 4.4.7	Corrected Q factor curve using <i>ENC</i> .	109
Figure 4.4.8	Comparison of Q factor curve dynamically adjusted with <i>ENC</i> data and the same Q factor curve post processed using the <i>ENC</i> data.	110
Figure 4.4.9	Stability and linear shifting of environmental profile with changing temperature between 60Hz-100Hz.	110
Figure 4.4.10	Resonant peak amplitudes for various chamber fill levels and the <i>ENC</i> profile.	111
Figure 4.4.11	Q profiles for increasing fill with <i>ENC</i> corrected curves using a 3L chamber and 51mm port with increasing fill level using water.	112
Figure 4.4.12	Five repeat measurements of the Q profile and the environmental curve at 17.0°C showing negligible variation.	112
Figure 4.4.13	Temperature stability tests at T1 (21.9°C) and T2 (13.6°C) using a 3L chamber with a 51mm port and a 278mL steel sphere sample.	113
Figure 4.4.14	Temperature stability: Sound pressure level deviation for the empty chamber and for a 278mL spherical displacement sample. Resonator has 3L chamber with 51mm long, 44mm diameter port.	113
Figure 4.4.15	Q profile stability profiles taken at constant temperature and using 278mL steel sphere sample showing profile insensitivity to volume change. Also shown is a frequency-shifted profile of the empty chamber to allow direct comparison. The chamber was 3L and port 51mm.	114
Figure 4.4.16	Q profile stability: associated sound pressure level deviation for a 278mL spherical displacement sample. Resonator has 3L chamber with 51mm long, 44mm diameter port.	114
Figure 4.4.17	Volume deviation data and second order polynomial fitted curves for differing sample shape using the continuous <i>QPS</i> method. Resonator has 3L chamber with 51mm long, 44mm diameter port.	115
Figure 4.4.18	Continuous <i>QPS</i> deviation volume from true volume using a generic correction factor on water fill, sphere and cube volume. Resonator has 3L chamber with 51mm long, 44mm diameter port.	116
Figure 4.4.19	Environmentally normalization curve, corrected curve and inverted port resonator Q profiles curves with three port insert plug configurations.	117
Figure 4.4.20	Boundary layer to port area becomes substantial for the inverted port resonator necessitating a large port area.	118
Figure 4.4.21	Deviation volume and second order fitted curves, implemented with <i>VCR</i> using <i>QPS</i> , when calibrating for a piston, spheres and cubes. <i>VCR</i> resonator has 3.5L chamber with 175mm long, 44mm diameter port.	119
Figure 4.4.22	<i>VCR</i> deviation volume from true volume using a generic correction factor on piston, sphere and cube volumes. <i>VCR</i> resonator has 3.5L chamber with 175mm long, 44mm diameter port.	119
Figure 4.4.23	<i>VCR</i> volume deviation from true volume using a specific second order correction on piston, sphere and cube volumes. Resonator has 3.5L chamber with 175mm long, 44mm diameter port.	120
Figure 4.4.24	<i>VCR</i> with dynamic <i>QPS</i> of 133mL sample showing original (empty), predicted and measured Q profiles. Resonator has 3.5L chamber with 175mm long, 44mm diameter port.	121
Figure 4.4.25	Plot of amplitude deviation with changing frequency for 133mL sample, predicted and actual Q profiles. Resonator has 3.5L chamber with 175mm long, 44mm diameter port.	121

Figure 4.4.26	VCR with dynamic <i>QPS</i> of 215mL cube sample showing original (empty), predicted and measured <i>Q</i> profiles. VCR resonator has 3.5L chamber with 175mm long, 44mm diameter port.	122
Figure 4.4.27	Plot of amplitude deviation with changing frequency for 215mL cube sample, predicted and actual <i>Q</i> profiles. VCR resonator has 3.5L chamber with 175mm long, 44mm diameter port.	122
Figure 4.4.28	Produce tests displaying the deviation of the predicted volume from the actual volume. VCR resonator has 3.5L chamber with 175mm long, 44mm diameter port.	123
Figure 4.4.29	Mineral tests displaying parabolic deviation of greywacke and linear deviation of schist samples. VCR resonator has 3.5L chamber with 175mm long, 44mm diameter port.	123
Figure 4.4.30	Comparison of two mineral sample types and two produce sample types as measured in VCR with 3.5L chamber volume.	124
Figure 4.4.31	Greywacke and schist samples as measured in VCR with chamber volume of 2L with low deviation in volume measurement.	125
Figure 4.1	Pressure at distance <i>R</i> from surface element caused by a piston radiator.	152
Figure 5.1	Pressure decay from axial direction extending over <i>x</i> , where <i>x</i> is defined as <i>kasin</i> (<i>θ</i>).	154
Figure 6.1	Piston face occupied by two arbitrary surface elements <i>dS</i> and <i>dS'</i> and their geometric relations	155
Figure 7.1	The Resistive and reactive coefficients for increasing <i>ka</i> and the first four term approximations for the Bessel and Struve functions.....	157
Figure 9.1	Velocity profile from internal port surface boundary. Arrows indicate velocity direction and magnitude. The boundary grows linearly with length. ..	160
Figure 11.1	Sound source driving into impedance <i>Z</i> ₁ which then changes to impedance <i>Z</i> ₂ . The distance <i>d=L-x</i> for considering pressure and velocity as a function of the distance from the impedance change.....	165
Figure 4.1a	Polar plot of sound intensity for an 8" speaker at 100Hz	183
Figure 4.1b	Polar plot of sound intensity for an 8" speaker at 500Hz	183
Figure 4.1c	Polar plot of sound intensity for an 8" speaker at 1kHz	184
Figure 4.1d	Polar plot of sound intensity for an 8" speaker at 5kHz	184
Figure 4.2	Interference caused by reradiating by sharp edges within proximity of sound source (fringing).	185
Figure 2.1	The SMC LXPB200 linear actuator diagram showing where calibration measurements were taken.	187
Figure 2.2	<i>Q</i> factor tests of VCR when dry and with a 50mL thin water film covering the piston.	188
Figure 3.1	Broad frequency sweep of anechoic chamber and two positions used in non-anechoic environment. Measurements made with PCB 103A microphone mounted 30 degree off axis at 0.5m. Position 2 taken atop of VCR resonator with port plug 50 degrees off axis at 0.5m.....	189
Figure 3.2	Broad frequency sweep comparison between PCB 103A microphone, <i>Realistic</i> sound meter and <i>Quest</i> sound meter taken in anechoic chamber. Fast sweep, 2Hz/sec.....	190
Figure 3.3	Broad frequency sweep deviation from the PCB 103A microphone for the <i>Realistic</i> sound meter and <i>Quest</i> sound meter taken in anechoic chamber. Fast sweep, 2Hz/sec	190

Figure 3.4	Narrow frequency sweep comparison between PCB 103A microphone, <i>Realistic</i> sound meter and <i>Quest</i> sound meter taken in anechoic chamber. Slow sweep, 0.2Hz/sec.....	191
Figure 3.5	Narrow frequency sweep deviation comparison between <i>Realistic</i> sound meter and <i>Quest</i> sound meter taken in anechoic chamber. Slow sweep, 0.2Hz/sec.....	191
Figure 3.6	Calibration tests using 1Vpp and 2Vpp signals generated by DAQ, demonstrating a 3dB change in level as measured in the port. Also shown is a corrected output profile using <i>ENC</i> data at -37dB.	192
Figure 3.7	Output from the <i>Realistic</i> sound meter and PCB 103A microphone in experimental environment. Amplitude is referenced to a 90dB level (0dB = 90dB).	192
Figure 3.8	Anechoic chamber <i>VCR</i> volume deviation from true volume using a specific correction factor on piston volumes. Resonator has 3.5L chamber with 175mm long, 44mm diameter port.....	193
Figure 4.1	Scale deflection tests for establishing buoyancy uncertainty due to the immersion stem.	194
	Complete Helmholtz resonator assembly with dual ports and pulley back plate assembly.....	208
	Pinch roller assembly.....	208
	Complete Assembly of variable chamber resonator	221

Nomenclature

a	Primary radius , polynomial coefficient (with subscript)	(m)
BL	Boundary layer	(m)
c	Speed of sound	(m/s)
c_p	Specific heat, constant pressure	(J/kg.K)
c_v	Specific heat, constant volume	(J/kg.K)
c_0	Speed of sound (STP)	(m/s)
d	Diameter	(m)
D	Energy density	(W.s/m ³)
f	Force	(N)
$freq$	Frequency	(Hz)
i	Complex notation	-
I	Intensity	(W/m ²)
k	Wave number	($k = \omega/c$)
L	Length	(m)
l_p	Port length	(m)
l_p'	Total port length	(m)
L_{mfp}	Mean free path length	(m)
Δl	Port length extension	(m)
m	Mass	(kg)
M	Mean molecular weight	(kg)
M_{mol}	Molar mass	(kg)
n	Number of moles	-
N	Number of molecules	-
p	Particular pressure	(Pa)
p_0	Pressure at STP	(Pa)
P_0	Primary pressure	(Pa)
δp	Excess pressure	(Pa)
P_r	Prandtl number	-
Q	Quality factor	-
Q_s	Strength of source	-
r	Primary distance from source	(m)
R	Secondary distance from source, Reflection ()	(m)
R_a	Acoustic resistance	(N.m/s ⁵)
R_m	Mechanical resistance	(N.m/s)
R_r	Radiation resistance	(N.m/s)
$R_{reflect}$	Reflective coefficient	-
R_c	Gas constant	(8.31 J/mol.K)
R_N	Reynolds number	-
S	Surface	(m ²)
s	Cross sectional area	(m ²)
ST	Sweep time	(s)
t	Time	(s)
T	Wave period	(s)
T_{emp}	Temperature	(K)
$T_{transmit}$	Transmission coefficient	(m/s)
U_0	Primary velocity	(m/s)
U_s	Specific velocity	(m/s)
U_v	Volume velocity	(m ³ /s)

V	Volume	(m ³)
w	Sample volume	(m ³)
X_a	Acoustic reactance	(N.m/s ⁵)
X_m	Mechanical reactance	(N.m/s)
X_r	Radiation reactance	(N.m/s)
Y	Thermal conductivity	(W/m.K)
Z	Characteristic impedance	(N.m/s ³)
Z_a	Acoustic impedance	(N.m/s ⁵)
Z_m	Mechanical impedance	(N.m/s)
Z_r	Radiation impedance	(N.m/s)
Z_s	Specific impedance	(N.m/s ³)

Greek symbols

α	Helmholtz equation constant	(Hz/K)
β	Temperature gradient compensation	-
δ	Length extension factor	(m)
γ	Adiabatic gas ratio	(c _p /c _v)
θ	Primary angle	(radians)
λ	Wavelength	(m)
μ	Viscosity	(N.s/m ²)
ρ	Particular air density	(kg/m ³)
ρ_0	Density at STP	(kg/m ³)
$\delta\rho$	Excess density	(kg/m ³)
ς	Power reflective coefficient	-
σ	Secondary radius	(m)
τ	Power transmission coefficient	-
ν	Kinematic viscosity	(m ² /s)
ν_{rms}	Root mean squared velocity	(m/s)
φ	Secondary Angle	(radians)
ψ	Tertiary angle	(radians)
ω	Angular frequency	(radians/s)
Ω	Approximation function	-

Subscripts

$+$	Incident	$-$	Reflected
0	Initial value	$1,2$	Later values, coefficient number
c	Chamber	e	Extension
H	High	i	inner
n	Value in	$inst$	Instantaneous
L	Low	max	Maximum
min	Minimum	o	outer
Out	Value out	p	Port
t	Transmitted	T	Temperature
$Therm$	Thermal	$Visc$	Viscous

Vector quantities are represented by either a cap or in **bold**.

Basic equations

Particular pressure: $p = \rho_0 c U_0$ (1)

Volume velocity: $U_v = S U_s$ (2)

Acoustic impedance: $Z_a = p / U_v = Z_s / s_p$ (3)

Specific impedance: $Z_s = p / U_s$ (4)

Mechanical impedance: $Z_m = f / U_s$ (5)

Radiation impedance: $Z_r = Z_a s_p^2 = Z_s s_p$ (6)

Characteristic impedance: $Z = \rho_0 c$ (7)

Acoustic intensity for a sphere: $I = p^2 / 2 \rho_0 c$ (8)

Acoustic power for a sphere: $W = 4 \pi a^2 I$ (9)

Sound energy density: $D = p^2 / \rho_0 c^2 = p^2 / \rho_0$ (10)

Acoustic intensity level (dB): $Intensity = 10 \log_{10} \left(\frac{I_{out}}{I_{in}} \right)$ (11)

Acoustic power level (dB): $power = 10 \log_{10} \left(\frac{W_{out}^2 \rho_0 c}{\rho_0 c W_{in}^2} \right)$ (12)

Specific resistance derivation: $power = 10 \log_{10} \left(\frac{W_{out}^2 R_s^{in}}{R_s^{out} W_{in}^2} \right)$ (12a)

$$power = 20 \log_{10} \left(\frac{W_{out}}{W_{in}} \right) + 10 \log_{10} \left(\frac{R_s^{in}}{R_s^{out}} \right)$$

Sound pressure level (dB): $power = 20 \log_{10} \left(\frac{p}{p_{ref}} \right)$ (13¹)

Excess pressure: $\delta p = p - p_0$ (14)

¹ P_{ref} is a predefined reference pressure of 2x10⁻⁵Pa for hearing and liquids or 0.1Pa for transducer calibration.

Excess density: $\delta\rho = \rho - \rho_0$ (15)

The specific velocity: $U_s = U_0 e^{i\omega t}$ (16)

The specific pressure: $p = P_0 e^{i\omega t}$ (17)

Strength of spherical Source: $Q_s = 4\pi a^2 U_0$ (18)

Forward travelling wave: $p = ZU_s$ (19)

Backward travelling wave: $p = -ZU_s$ (20)

Standard Helmholtz equation

$$\omega_{res} = 2\pi freq = c \sqrt{\frac{s_p}{(V - w)(l_p + \Delta l)}} \quad (21)$$

Sample volume Helmholtz equation

$$w = V - \frac{s_p}{(l_p + \Delta l) \left(\frac{2\pi freq}{\beta c} \right)^2} \quad (22)$$

Temperature correction for speed of sound

$$c_0 = \sqrt{\gamma \frac{P_0}{\rho_0}} = \sqrt{\frac{\mathcal{R}_c T_{emp}}{M}} \quad (23)$$

Measured Q factor equation $Q = \frac{\omega}{(\omega_H - \omega_L)}$ (24)

Theoretical Q factor for a Helmholtz resonator

$$Q = \frac{\omega m}{R_m} = 2\pi \sqrt{\frac{l_p^3 V}{s_p^3}} \quad (25)$$

Glossary

Attenuation	Difference in sound pressure level between two points
BL	Boundary Layer
BEM	Boundary Element Model
Chamber	Main body of resonator in which sample volume is measured
Characteristic impedance	Measure of acoustic resistance in the far field
Chirp	A narrow frequency sweep
CSA	Cross Sectional Area
dB	Decibels, measure of relative sound level
ENC	Environmental Normalisation Curve
Excess pressure	Differential pressure to the density at STP
Excess density	Differential density to the density at STP
Far field	Distance at which sound level is uniform
Flange factor	Multiplying factor for determining port length extension
FFT	Fast Fourier Transform
FEM	Finite Element Model
Helmholtz resonator	Resonator consisting of chamber and port
Interstitial space	Space between adjacent particles in a granular bed
IIR	Infinite Impulse Response (Digital filter)
Length extension	Extra distance the air in port moves beyond physical port length
Mechanical impedance	Combined mechanical resistance and reactance
Mechanical resistance	Sum of all real resistive components in the resonant system
Mechanical reactance	Sum of all imaginary force components in the resonant system
Near field	Distance where localised effects make sound levels non-uniform
Neck	Alternative name for port
Particular pressure	The instantaneous pressure of an oscillatory pressure wave
Pink noise	Random frequencies having equal power
Port	Tube of smaller CSA than chamber connecting chamber to a secondary impedance region (usually an open environment)
Primary pressure	The maximum pressure in an oscillatory pressure wave
Primary velocity	The maximum velocity in an oscillatory wave
Q factor	Quality factor, quality of resonance
QPS	Q Profile Shifting
Radiation impedance	Combined radiation resistance and reactance
Radiation resistance	Measure of the real resistive losses from the port
Radiation reactance	Measure of the imaginary forces in the port
Reflective coefficient	Reflected component based on the ratio change of two impedance mediums
RMS	Root Mean Squared (geometric average)
RTD	Resistive Temperature Device
Specific velocity	The instantaneous velocity of an oscillatory wave

SPL	Sound Pressure Level (dB)
STP	Standard Temperature and Pressure (15°C, 1.01x10 ⁵ Pa)
SWR	Standing Wave Ratio (maximum over minimum pressure)
Transmission coefficient	Transmitted component based on the ratio change of two impedance mediums
VCR	Variable Chamber Resonator
White noise	Random frequencies having random power