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Investigating Broadband Acoustic Absorption Using Rapid Manufacturing

By

Oliver Godbold

Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

April, 2008

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Abstract

The reduction of nuisance noise and the removal of unwanted sound modes within a room or component enclosure are accomplished through the use of acoustic absorbers. Sound absorption can be achieved through conversion of the kinetic energy associated with pressure waves, into heat energy via viscous dissipation. This occurs within open porous materials, or by utilising resonant effects produced using simple cavity and orifice configurations. The manufacture of traditional porous and resonant absorbers is commonly realised using basic manufacturing techniques. These techniques restrict the geometry of a given resonant construction, and limit the configuration of porous absorbers. The aim of this work is to exploit new and emerging capabilities of Rapid Manufacturing (RM) to produce components with geometrical freedom, and apply it to the development of broadband acoustic absorption. New and novel absorber geometric configurations are identified and their absorption performance is determined. The capabilities and limitations of RM processes in reproducing these configurations are demonstrated.

The geometric configuration of RM resonant absorbers is investigated. Cavity modifications aimed at damping the resonant effect by restricting the motion of cavity air, and adding increased viscous resistance are explored. Modifications relating to cavity shape, the addition of internal perforations and increased cavity surface area have all been shown to add acoustic resistance, thereby increasing the bandwidth of absorption. Decreasing the hydraulic radius of the cavity cross section and reducing internal feature dimensions provide improved resistance over conventional configurations. Process limitations were identified which produce definable limits to the complexity of the cavity shape and the dimensions of internal features. Incorporation of internal cavity fins was identified as the most successful geometric modification, being capable of providing measurable improvements in resistance of 195 Pa s m⁻¹ without incurring intolerable fabrication issues.

The use of RM in the fabrication of acoustic absorbers required characterisation of the acoustic properties of various RM materials. Processes such as Stereolithography and Selective Laser Sintering produce highly dense topologies with low porosity resulting
in highly reflective acoustic properties, offering low porous absorption. However, the
processes themselves were explored to identify characteristics which could introduce
porosity during fabrication. Modification of the track width and raster spacing
parameters relating to Fused Deposition Modelling (FDM), for example, resulted in a
method of producing controllable porous topologies. Different process configurations
demonstrated a range of acoustic properties. Fabricated FDM samples, 20mm thick
with 5% porosity, demonstrated porous absorption at and above 1600Hz. More open
configurations were better suited to providing acoustic resistance. These configurable
topologies demonstrated high levels of added resistance to resonant absorption,
providing the greatest improvement to resonant absorption bandwidth.

The absorption of the investigated acoustic absorbers was compared against existing
theoretical models to derive functional parameters to assist their incorporation in
further absorber designs. This comparison was also used to evaluate the suitability of
the existing theories in predicting the absorption of these novel absorber
configurations.

A combination of geometric forms were identified and applied to produce a dual layer
broadband resonant absorber, fabricated using different FDM porous topologies. This
configuration yields a bandwidth of resonant absorption distributed over 3 octaves,
comparable in performance to existing microperforated panel broadband absorbers.
The resonant absorption is complemented with higher frequency porous absorption
over 3000Hz.

This work introduces a novel empirical approach to investigating how changes in
resonant absorber cavity geometry can be exploited to add acoustic resistance. A
method of producing configurable porous topologies is also presented, allowing
control of the acoustic properties through changes to FDM process parameters. The
work has identified the potential in exploiting the relationship between process
parameters and acoustic response, and demonstrates how this could be developed into
a method of directly fabricating topologies with customised acoustic properties.
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List of Symbols and Abbreviations

\( a \) Orifice radius

\( C_a \) Total surface area of the cavity boundary

\( C_l \) Length of the cavity cross section perimeter

\( C_p \) Specific heat capacity at constant pressure

\( C_v \) Specific heat capacity at constant volume

\( c \) Speed of sound

\( D \) Equivalent diameter of a cylindrical cavity of volume \( V \)

\( D_p \) Spacing between adjacent perforations

\( d \) Depth of cavity / air gap

\( d_f \) Fibre diameter

\( d_n \) Well depth of the \( n \)th well.

\( F \) Complex driving force

\( F(\omega) \) Frequency dependent dynamic tortuosity function

\( F'(\omega) \) Frequency dependent bulk modulus function

\( f \) Applied frequency

\( f_r \) Resonant frequency

\( H \) Transfer function

\( J_0 \) Bessel function of the first kind, zeroth order

\( J_1 \) Bessel function of the first kind, first order

\( K_{\text{eff}} \) Effective bulk modulus

\( k \) Wavenumber

\( k_m \) Mass reactance coefficient

\( k_r \) Resistance coefficient

\( k_s \) Tortuosity

\( k_t \) Perforate constant

\( k_{\text{eff}} \) Dynamic tortuosity

\( L \) Distance to the test specimen

\( l \) Neck length

\( \Delta l \) Neck length end correction

\( \Delta l_i \) Internal orifice neck length end correction
$\Delta l_e$ External orifice neck length end correction

$l_p$ Equivalent perforation length

$M$ Mass

$M_z$ Panel surface mass

$N$ Sample size

$N_p$ Prandtl number

$n$ Number of data points

$P$ Sound pressure

$P_0$ Atmospheric pressure

$P_a$ Random uncertainty

$P_p$ Internal perforation position

$P_r$ Internal perforation radius

$Q$ Quality factor

$R$ Added resonator resistance

$R_s$ Orifice radiation resistance

$R_t$ Viscous resistance over an infinite plane

$R_v$ Viscous orifice resistance

$r$ Reflection coefficient

$S$ Orifice cross sectional area

$S_a$ Standard deviation

$s$ Spring stiffness

$s_p$ Pore shape constant

$t$ Material thickness

$t'$ $t$ – distribution value

$U$ Volume velocity

$V$ Cavity volume

$W$ Absorption bandwidth

$X$ Volumetric displacement

$x$ Perforation separation

$x_f$ Internal cavity fin spacing

$x_i$ Arbitrary theoretical value

$x_t$ Arbitrary measured value

$y$ Distance to the pressure minima

$Z$ Specific impedance
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_0$</td>
<td>Characteristic impedance of air</td>
</tr>
<tr>
<td>$Z_{ac}$</td>
<td>Acoustic impedance</td>
</tr>
<tr>
<td>$Z_c$</td>
<td>Porous material characteristic impedance</td>
</tr>
<tr>
<td>$Z_p$</td>
<td>Perforated layer impedance</td>
</tr>
<tr>
<td>$Z_s$</td>
<td>Impedance of cavity space</td>
</tr>
<tr>
<td>$Z_{real}$</td>
<td>Real part of impedance</td>
</tr>
<tr>
<td>$Z_{imaginary}$</td>
<td>Imaginary part of impedance</td>
</tr>
<tr>
<td>$z_1$</td>
<td>Distance to Mic 1</td>
</tr>
<tr>
<td>$z_2$</td>
<td>Distance to Mic 2</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Absorption coefficient</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of specific heat capacities</td>
</tr>
<tr>
<td>$\delta_v$</td>
<td>Viscous boundary layer thickness</td>
</tr>
<tr>
<td>$\delta_t$</td>
<td>Thermal boundary layer thickness</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Porosity or fraction open area</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Dynamic viscosity</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Phase change</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>Angle of incident sound</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>Weighted pore characteristic length</td>
</tr>
<tr>
<td>$\Lambda'$</td>
<td>Weighted pore characteristic length</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Kinematic viscosity of air</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Displacement of air in the resonator neck</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Air density</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>Bulk density</td>
</tr>
<tr>
<td>$\rho_{eff}$</td>
<td>Effective density</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>Fibre material density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Flow resistivity</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Fractal iteration</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
</tr>
<tr>
<td>$\omega_r$</td>
<td>Resonant angular frequency</td>
</tr>
<tr>
<td>$\Delta \omega$</td>
<td>Resonant frequency width</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>dB</td>
<td>Decibels</td>
</tr>
<tr>
<td>DLP</td>
<td>Digital Light Processing</td>
</tr>
<tr>
<td>FDM</td>
<td>Fused Deposition Modelling</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>HR</td>
<td>Hydraulic Radius</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating Ventilation and Air Conditioning</td>
</tr>
<tr>
<td>LENS</td>
<td>Laser Engineered Net Shaping</td>
</tr>
<tr>
<td>LOM</td>
<td>Laminated Object Modelling</td>
</tr>
<tr>
<td>MDF</td>
<td>Medium Density Fibreboard</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean Squared Error</td>
</tr>
<tr>
<td>PC</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>RM</td>
<td>Rapid Manufacturing</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RS</td>
<td>Raster Spacing</td>
</tr>
<tr>
<td>RW</td>
<td>Raster Width</td>
</tr>
<tr>
<td>SLA</td>
<td>Stereolithography</td>
</tr>
<tr>
<td>SLS</td>
<td>Selective Laser Sintering</td>
</tr>
<tr>
<td>SWR</td>
<td>Standing Wave Ratio</td>
</tr>
<tr>
<td>TL</td>
<td>Transmission Loss</td>
</tr>
</tbody>
</table>
Acknowledgements

This work has been enabled through the funding provided by the Engineering and Physical Sciences Research Council (EPSRC) via the Innovative Manufacturing and Construction Research Centre (IMCRC) at Loughborough University. I am indebted to these organisations for giving me the opportunity to conduct this research. I am also grateful to the Royal Academy of Engineering (RAE) for their additional financial support allowing me to disseminate my work at the 19th International Congress on Acoustics ICA 2007, Madrid. I am grateful to Dr Rupert Soar and Dr Richard Buswell from Loughborough University, and Professor Jian Kang from the University of Sheffield, for their supervision, support, knowledge and direction. Further appreciation must go to the University of Sheffield for use of their acoustic test equipment. My gratitude must also go to the various members of the Rapid Manufacturing Research Group (RMRG) at Loughborough University for their help and support, in particular the technicians who assisted in the fabrication of the test samples. Thanks must also go to the administrative and clerical staff within the Wolfson School of Mechanical and Manufacturing Engineering. Finally I would like to thank my family and friends for their support and understanding over the past three years.
Chapter 1

Introduction

The control of unwanted noise and the absorption of sound energy are relevant to many different engineering applications. Traditional solutions are generally either based on the bulk absorbing properties of certain porous materials for high frequencies, or on resonance with carefully designed structures tuned to lower frequencies. The design and manufacture of commercial resonant structures has had relatively little development to date. Many developed solutions utilise additional resistive materials or accurate sub-millimetre features to achieve satisfactory absorption characteristics. Much of the research to date has been concerned with predicting their absorption, and the effects of simple changes in geometry on the resonant frequency.

Over the past 20 years, digitally driven, additive manufacturing processes have been developed. Originally used for the production of prototype models, these technologies are now being applied directly to manufacturing. Both the processes and materials are continuously improving, and their application and scope is expanding. There are certain design and geometric advantages that make these processes attractive for particular applications. Reduction of design constraints and complexity of geometry increases the potential for acoustic structures incorporating complex geometries and internal features, not currently viable with conventional manufacturing techniques. The discrete deposition or consolidation methods, coupled with layer based fabrication, offer scope to produce topologies with reduced density and increased porosity, with potential acoustic applications. This work investigates the design and manufacture of acoustic absorbers incorporating resonant geometric features and improved porous configurations, to demonstrate improved performance as broadband acoustic absorbing devices.
1.1 Acoustics

The presence of noise and sound influences every field of engineering. Acoustics can loosely be defined as the generation, transmission, and reception of energy in the form of vibrational waves in matter (Kinsler et al. 1982). The radiation of vibrational energy in compressible gasses (such as air) causes pressure variations that fluctuate sinusoidally, these compressional waves are perceived aurally as sound. Typically the human ear is sensitive to oscillatory frequencies between 20 and 20,000 Hz in air (Smith, Peters & Owen 1996); however prolonged exposure to sustained sound levels and unstructured nuisance noise can have physical and psychological effects over and above that of annoyance. Human perception of generated sounds gives feedback on the environment status. The time taken for a produced sound to decay by 60dB (known as the reverberation time), and the reflective properties of an enclosure’s surfaces, provides a non-visual perception of space. The absorption of airborne sound energy affects how sound is reflected off a surface, altering the reverberation time of any associated enclosure. These factors influence how sound propagates within an enclosure, affecting the perceived clarity of sound reproduction or speech.

When the oscillating air particles associated with a compressional airborne sound wave strike a solid surface the energy may be transmitted, reflected or absorbed by the surface. The relative magnitude of any one of these phenomena is dependent on the acoustic properties of the solid surface. The transmission of sound energy through a solid material is largely due to the propagation of structure-borne bending waves. The magnitude of these bending waves through a solid structure can be reduced by increasing the mass that the wave has to displace, or through the decoupling of surfaces to reduce the transmission paths. Airborne sound transmission presents a more complicated problem due to the intrinsic enveloping presence of the transmission medium. To reduce the transmission of compressional sound waves in a gas; the sound energy may be reduced through dissipation into heat energy, commonly referred to as acoustic absorption. A great deal of work has been carried out to understand and define airborne acoustics mathematically (Mechel, Munjal 2002, Rayleigh 1945) to aid the development of acoustic absorption methods. There are, however, many recognised unpredictable variables that can affect the propagation
of compressional sound waves in a gas. This has often led to greater uncertainty in calculations when compared, for example, to electromagnetic wave systems. These uncertainties introduce discrepancies between theoretical and experimental results.

1.2 Airborne Sound Energy Absorption

The application of sound energy absorption can be used in the control of problematic noise or to enhance sound production or reproduction. It usually occurs through the transformation of energy within the oscillating air particles, into heat. This occurs through viscous shear forces within the gas as it experiences viscous drag over a solid surface. Acoustic absorption can be produced by forcing the oscillating air through restrictions or porous structures such as open celled foams or fibrous materials. Energy conversion into heat takes place over the large internal surface area of the absorber. Resonant cavity absorbers, comprising a mass element and an enclosed volume, have much less surface area to dissipate energy. Absorption is achieved by increasing the magnitude of oscillations, which occurs when the incident frequency of air oscillations matches, for example, the resonant frequency of a combined orifice / volume configuration.

Absorption using solid porous structures is only effective if the internal air inclusions are interconnected, allowing compressional sound waves to propagate into the pores of the material. Material density, internal pore surface area and the complexity of the interconnections are the influential physical characteristics affecting the absorptive properties. Absorption is only effective if the pressure maximum (and consequently maximum air velocity) of the incident wave is present within the porous structure. Therefore the thickness of the material determines the lower frequency absorption limit making porous materials more suited to higher frequencies. The configuration of resonant absorber elements allow lower frequency absorption to be achieved, although absorption only takes place over the narrow frequency range when the incident sound frequency matches the resonant frequency. This is determined by the enclosed air volume, and either panel mass per unit area (membrane absorbers), or the mass of air contained within an orifice (cavity absorbers).
High frequency sound energy absorption within porous structures can be easily realised using common fibrous materials and open celled foams. Much applied research has focused on producing low frequency acoustic absorption without the reliance on large thicknesses of porous material. Slowing the motion of air oscillations within resonant acoustic absorbers dampens the resonant effect, broadening the frequency bandwidth of effective absorption. Within cavity absorbers this is achieved by increasing the resistive viscous shear forces through the introduction of porous structures or sub-millimetre features.

Advanced, resonant absorbers (Cobo, Fernandez & Doutres 2003, Orduña-Bustamante, Nelson 1992), based on the use of active loudspeakers to modify the pressure oscillations of the enclosed air volume, have been shown to improve acoustic energy absorption characteristics, although rapid signal sampling, analysis, signal inversion and amplification in real time limit their applicability.

Much theoretical modelling of the basic acoustic absorption methods has been carried out, allowing prediction of their absorption properties. These theories use physical properties relating to flow characteristics and absorber geometry to derive values of impedance and the absorption at different frequencies. These predictions can then be used in the design of absorbers to address certain problematic frequencies, or to act over a range of frequencies.

1.2.1 The Function of Geometry in Sound Energy Absorption

The characterisation of porous sound absorbing materials includes consideration of the pore shape and size, as well as the percentage of solid material to air, and the complexity of the propagation path through the material. Each of these physical characteristics has an effect on the absorption properties; however accurate characterisation is reliant on material quality and homogeneity which is limited by the random distribution of pore shapes and size, resulting from their manufacturing methods. This results in uncertainty in the prediction of their absorption (Horoshenkov et al. 2007).
Low frequency resonant absorbing structures can be tuned to absorb sound energy of specific frequencies through the selection of specific design dimension relationships. The size and shape of the enclosed air volume and orifice associated with resonant cavity absorbers can also affect the resonant frequency (Alster 1972). Further geometric development incorporating sub-millimetre orifice diameters (Maa 1998) encourages viscous flow within the orifice, achieving high resistance to the resonant oscillations, and increasing resonant absorption bandwidth. Other literature also suggests that the geometry of the cavity enclosing the air volume, can affect the resonator resistance (Ilinskii, Lipkens & Zabolotskaya 2001, Sapoval, Haeberlé & Russ 1997).

1.3 Rapid Manufacturing Advantages

A family of additive fabrication technologies, traditionally referred to as Rapid Prototyping, has evolved over the past 20 years into Rapid Manufacturing (RM). This development has led to improvements in build speeds, larger build sizes and improved physical properties of the produced parts, making them suitable for end use products and not confined to use as prototypes (Hopkinson, Hague & Dickens 2006, Pham, Dimov 2003). The additive, layer-by-layer, Computer Aided Design (CAD) driven fabrication method embraced by many RM processes enables complicated geometries to be produced without the constraints associated with many traditional manufacturing processes, such as draft angles or the requirement for tool clearance. This offers much more design freedom allowing intricate internal features and complicated forms. The selective placement of solid material, and the layering of consecutive cross sections, can both give rise to porosity. This may be undesirable for applications where part strength or density is required, but has potential value for porous acoustic applications.
The advantages of RM over traditional methods are:

- More design freedom, allowing manufacture-to-design;
- no limitations due to tooling requirements;
- more complicated or customised geometries are possible requiring no additional machine operator skill over that required for simple geometries;
- minimal labour and a constant material costs making the location of manufacture unimportant.

The development of applications that exploit these advantageous features is an expanding area of research that aims to produce products with added value or improved performance. An application to the field of acoustic absorption is the area investigated within this thesis.

RM processes can be employed to investigate the geometry of acoustic absorbers. The larger feature sizes of resonant cavity absorbers lend themselves to fabrication using RM, allowing an investigation of resonator geometry to be conducted. Similarly the potential for producing porous topologies using RM has significant implications to acoustic absorption.

1.4 Aims and Objectives

The aims of this work are to investigate the incorporation of RM design freedoms to resonant acoustic absorbers, and ascertain if acoustically significant porous topologies can be fabricated using RM. This work aims to develop a single material broadband absorbing structure that is comparable in performance to existing solutions requiring multiple materials or the fabrication of sub-millimetre features, e.g. a microperforated panel. The limitations and constraints of the technology will also be identified and related to absorber performance.
The objectives of this work are to:

- Ascertain the potential application of RM to acoustic absorption;
- investigate resonant absorption bandwidth improvements through the modification of resonant absorber cavity geometry;
- investigate the fabrication of porous topologies using RM, with an aim to achieve porous absorption and acoustic resistance;
- derive absorption characteristics and important parameters of RM acoustic absorbing structures;
- develop a RM enabled single material broadband acoustic absorber, comparable in performance to existing broadband absorbers.

1.5 Thesis Structure

An investigation addressing the application of RM to acoustic absorption is presented within this thesis. The investigation takes an iterative approach, using findings from previous chapters to develop ideas, test methods and test geometries. The structure of the thesis is as follows:

- A critical review of current acoustic absorbing / noise reducing methods, and Rapid Manufacturing processes and materials is presented (Chapter 2);
- following the identification of areas of significance from Chapter 2, the detailed theory and design of resonant and porous absorbers is described. Areas with potential for enhancing performance through geometrical form and fabrication freedom are identified. (Chapter 3);
- the theoretical background from Chapters 2 and 3 is used to develop an investigation into the configuration of resonant acoustic absorbers. Geometric cavity modifications are developed aimed at adding acoustic resistance. Performance is evaluated through absorption bandwidth improvements (Chapter 4);
• the acoustic implications of porosity produced using RM processes are investigated. Porous absorption and acoustic resistance are both addressed (Chapter 5);

• the theoretical models from Chapter 3 are used to evaluate the absorption of the results in Chapters 4 and 5. A novel derivation approach is adopted to ascertain resonant absorber model parameters from the measured absorption. These parameters, together with porous absorption predictions are then used in the development of a broadband RM absorber, whose performance is compared to theoretical predictions and existing broadband absorption performance (Chapter 6);

• conclusions are drawn from the conducted work and areas are suggested for further work or investigation. Practical implications are also considered (Chapter 7).
Chapter 2

Theoretical Background

Sound, from a human perspective, is an interpretation by the ear of longitudinal pressure waves, transmitted via disturbances within a compressible fluid (e.g. air or water). These disturbances displace the eardrum, the movements of which are transmitted via the Ossicles (a series of three bones) to the inner ear, where the auditory nerve detects the movement of hair cells within the fluid filled Cochlea, sending nerve impulses to the brain. For an average young person, an airborne vibrational disturbance is interpreted as sound if its frequency lies in the range of about 20 to 20,000 Hz. Eardrum displacements one-tenth the diameter of a hydrogen molecule can be detected (Kinsler et al. 1982). When sounds are perceived as annoying or uncomfortable, we generally regard this as noise. Nuisance noise, aside from annoyance, can also have adverse health effects, the most obvious being disturbance of sleep\(^1\), but there is also evidence of ischaemic heat disease and decreased performance of school children (Institute for Environment and Health 1997).

In buildings, especially residential housing, noise nuisance has become a significant issue, indicated by the trebling of domestic nuisance noise complaints between 1988 and 1998 (Simons, Waters 2004). The presence of external environmental noise within a room is mainly dependent on the construction of the walls of the building and their associated transmission loss properties. Airborne transmission of environmental noise is also possible (through ventilation systems for example), if sound paths are unhindered by acoustic absorbing measures. Recent legislation has placed regulations limiting the permissible amount of sound transmission between dwellings, and placing

\(^1\) Disturbance of sleep can reduce sleep quality: premature awakening, changes in sleep stages and time taken to fall asleep. Performance and mood may both be lowered following sleep disturbance by noise.
a minimum requirement of 45dB sound insulation on separating walls and floors (Office of the Deputy Prime Minister 2003).

The sound type and level that constitutes nuisance noise is inherently hard to quantify. However, the key factors are the noise sensitivity of the listener and the circumstances in which the noise is heard. The acceptability of different sounds is largely subjective, but the general acceptability of a sound of constant frequency can be established using noise rating curves\(^2\). These curves only apply to steady constant noise such as that produced by building services. In general, low frequency sounds are much more acceptable than higher frequencies. A noise rating value of 20 is indicative of a location such as an opera hall, or sound studio whereas a value of 45 might be indicative of a machine room, laundry room or busy canteen (The Chartered Institution of Building Services Engineers 1999).

The evaluation of the acceptance of fluctuating noise such as that produced by road vehicles, construction noise, rail traffic or aviation noise cannot be described by a single noise rating or decibel value as they constantly vary in character and level. Instead, fluctuating noise acceptance is often determined using indices based on decibel (dB) levels. For example, road noise acceptance is based on a statistical sound level being exceeded for more than 10% of a given time (Fry 1988).

Tackling the source of mechanically produced nuisance noise is one method of noise reduction. Complete acoustic isolation can be a difficult task to achieve, although significant noise reduction can be accomplished through careful consideration of the stiffness and resonant modes of machine parts / enclosures, and the application of increased damping and vibration isolating measures (Smith, Peters & Owen 1996). These strategies cannot always be fully implemented if the flow of air is an important factor in the operation of a machine. The sound that propagates within tubes or ducts e.g. exhaust pipes, compressors or pumps and air ducts from Heating Ventilation and

\(^{2}\) The noise rating value is determined by plotting measured sound pressure levels against a set of noise rating curves whose contours have been subjectively defined to represent sound of equal loudness at different frequencies. The highest curve intersected by the measured results determines the noise rating value.
Air Conditioning (HVAC) systems, is often radiated into occupied spaces and can be a source of annoyance (Reynolds 1981). The low frequency absorption ability of resonant cavity absorbers finds their extensive use within these systems (Munjal 1987). They can be applied as side branches to absorb sound energy whilst maintaining air flow. Lightweight porous absorbers are often used to reduce the external noise within an enclosure. Examples of such applications are sound absorbing passenger vehicle trim or lightweight double wall partitions within buildings (Fahy 2001, Simons, Waters 2004).

The application of acoustic absorption used to control the noise in rooms and buildings can reduce overall noise levels that may otherwise cause hearing damage or impede speech intelligibility (Cox, D'Antonio 2004). In addition to controlling unwanted noise within a room, the application of acoustic absorption to a room can be used to tailor a room for specific acoustic applications. The rate of decay once a sound source has stopped is governed by the sound absorbing characteristics of the boundary surfaces, the air filling the space, and the objects within the space (British Standards Institute 2003). The reverberation time of a room is the time taken for the sound energy produced by a source to decay by 60dB. A long reverberation time will mean that the sound level of a single syllable will not have decayed sufficiently by the time the next arrives, resulting in a messy confusing sound. In particular, lower level consonants are often masked by more prominent preceding syllables (Everest 2001). A short reverberation time will give good speech intelligibility, and it can also help to reduce sound transmission between workstations in an open plan office. However high absorption will reduce the transmission of the sound within the room, inhibiting sound distribution (Fry 1988). Usually a room with little absorption and a long reverberation time has a very lively feel to it, whereas a room with high absorption can feel dead. The ‘feel’ of the room not only affects the intelligibility of any sound produced within the room, but can also affect the sense of well-being of the occupants (Smith, Peters & Owen 1996). Control of these effects is important within rooms intended for sound reproduction (such as cinemas or listening auditoria), or sound production (such as recording studios and theatres). It is especially important in large rooms with no acoustical amplification, such as a concert hall (Smith, Peters & Owen 1996).
Not all absorber types are suitable to all applications; porous absorbers are susceptible to blockage by particles and are generally only feasible for high frequency absorption, as low frequencies have long wavelengths meaning pressure maxima are less likely to propagate sufficiently into a porous material to achieve significant absorption. They are also hard to clean, presenting hygiene issues and can release fibres into the air. Their inherent fragility affects durability, particularly in physically harsh surroundings. They also introduce environmental issues, principally in their recyclability. Resonant type absorbers can address low frequency problems but the range over which they are effective is narrow. Their cavities can trap water, dust and insects, presenting hygiene issues (Fuchs 2001).

2.1 Sound Propagation

The propagation of sound energy is largely dependent on the medium through which it travels. The speed at which sound energy travels and its dissipation varies between solids, liquids and gases. Further, it is also dependent on specific material properties such as compressibility, inertia and temperature. As a wave travels, the particles of the medium vibrate to produce changes in density and pressure in the direction of the wave motion (Serway, Beichner 2000). Propagation of sound through solids and gasses are mainly considered in architectural and engineering applications.

Solid materials are capable of supporting shear as well as compressional stresses, although due to the strong intermolecular forces resisting compression, purely compressional longitudinal sound wave propagation is of negligible importance (Bies, Hansen 2003). The sound transmission from a sound source, within a solid medium is largely due to the propagation of structure-borne bending waves, which are a combination of shear and compressional waves. These may be induced in a structure by the direct vibration of the sound source, or by airborne waves striking an enclosure’s surface. The bending waves propagate through the solid material and re-radiate on the other side. The intensity of the transmitted sound is dependent on (Fry 1988):
- Frequency of the sound;
- intensity of the sound;
- angle of incidence of the sound wave on the wall;
- dimensions of the wall;
- mass and stiffness of the wall;
- amount of damping in the wall.

The most common method of reducing the sound transmission through a panel is to increase its mass, as more sound energy is required to induce vibrations in a heavy structure with high inertia. The transmission loss of the panel is related to its mass per unit area and the frequency being applied. The transmission loss $TL$ (dB) for an acoustic wave of normal incidence, can be approximated using the following formula (Bies, Hansen 2003),

$$TL = 10 \log_{10} \left[ 1 + \left( \frac{\pi f M}{\rho c} \right)^2 \right],$$

where $f$ (Hz) is the applied frequency, $M$ (kg m$^2$) the surface mass, $\rho$ (kg m$^{-3}$) the density of air and $c$ (m s$^{-1}$) the speed of sound in air.

Therefore, for a given material and environment, the sound transmission loss is dependent on the thickness of the panel and the incident frequency. However, this only holds true for a certain range of frequencies, dependent on different physical properties of the wall. At very low frequencies the panel tends to move as a membrane; transmission loss is affected by resonance at the natural frequencies of the panel which is dependent on the panel stiffness (Fry 1988). At very high frequencies an effect known as coincidence influences the transmission loss. This effect reduces the panel transmission loss when the frequency of induced longitudinal bending waves within the panel, matches the frequency of the incident sound. This effect is controlled by the damping characteristics and the stiffness of the panel. Under resonance and coincidence the partition experiences 'free' vibration, consequently leading to increased sound transmission. As with all vibratory systems, the introduction of damping reduces the amplitude of the vibrations by producing heat.
during the overcoming of internal frictional forces associated with damping. This consequently reduces the energy transferred. This can be applied to walls by the addition of a mastic like material with high hysteresis losses to one side of a wall panel (Sharland 1988).

The transmission of sound energy within a wall or structure can be reduced if the number of paths, for structure borne bending waves to travel through to the external surface, is minimised. The simplest method of implementing this strategy in buildings is to stagger the studs to which the wall panels are fixed to. This leaves the perimeter as the only common support between opposing panels. Alternatively constructing two independent frames mechanically and acoustically independent of one another, creating a double wall partition, can further reduce the amount of coupling between wall surfaces (Bies, Hansen 2003). To further decouple wall surfaces, resilient bars can be used to mount the wall panels onto the studs. They reduce the amount of vibration transmitted from the panels to the studwork by eliminating direct contact between the two.

The reduction of airborne sound energy is a more difficult task than that of structure borne sound energy, because the abundance of the transmission medium can hamper efforts to isolate problems. Reduction of airborne sound energy can be achieved by converting sound energy into heat energy.

All sound energy is ultimately converted into heat energy. This may occur within the transmission medium itself, or through interactions at boundaries with other materials. In air, energy conversion is mostly attributable to molecular relaxation, which is heavily dependent on humidity. Relative motion between molecules during compression and expansion gives rise to viscous frictional energy conversions, while losses due to heat conduction and molecular energy exchanges are also accountable. Sound energy reduction through conversion to heat energy is known as sound absorption. The sound absorption of air (decibels per metre) is approximately proportional to the square of the frequency; however, this only becomes significant for very high frequencies (Smith, Peters & Owen 1996).
As airborne sound propagates over a surface, viscous flow is induced near the boundary. The layer of particles adjacent to the surface has zero velocity, while the particles a finite distance away oscillate freely. This distance is known as the viscous boundary layer, depicted in Figure 2.1. As with the sound absorption within air, the relative motion between air molecules as a result of fluid viscosity produces friction, converting kinetic energy into heat energy. The amount of viscous energy conversion is greater than that produced in free air, as the relative particle velocities are greater.

Figure 2.1: Oscillatory viscous flow over a surface.

2.2 Sound Energy Absorption

The magnitude of acoustic energy conversion via viscous friction is generally very small. Maximising these conversions is the key to the successful absorption of airborne sound energy. This can be achieved by increasing the surface area that the air oscillates over (adopted by open celled porous materials), or increasing the magnitude of the air oscillations over a surface (adopted by resonant absorbers). The fraction of incident sound energy that is absorbed by a material is known as the dimensionless absorption coefficient $\alpha$ (-).

2.2.1 Porous Absorption

Porous absorbers consist of many interconnecting pores through which air can move. Pore sizes for optimal absorption are typically in the order of 0.1mm (Wang, Lu 1999). As a sound pressure wave is forced through the many narrow airways, viscous frictional energy conversion takes place between the air particles, causing energy to
be dissipated in the form of heat. Changes in flow direction, and expansion / contraction into the varying cross sections of irregular pores, cause a momentum reduction in the direction of wave propagation, adding to the sound energy reduction (Beranek, Vér 1992). Further losses occur at lower frequencies through thermal energy conduction into the absorber material as air undergoes thermal fluctuations caused by the oscillating changes in pressure (Zwikker, Kosten 1949).

Common absorber materials are glass fibre, rock wool and open cell foams (Figure 2.2). However, other compositions based on granular materials, including sands and soil, can also achieve porous absorption (Voronina, Horoshenkov 2003). Commonly used closed cell foams such as expanded polystyrene, do not necessarily make good acoustic absorbers. It is imperative that the cells of the foam are interconnected to allow movement of air through the material. The thickness of the absorbing material determines the frequency at which useful absorption is obtained; if a sound wave is incident on a rigid wall, the maximum particle velocities will occur at distances 1/4 and 3/4 of the wavelength in front of the wall. Therefore if the foam is thinner than one quarter of the wavelength, the particle velocity through the foam will be low, producing little sound absorption. This normally results in porous absorbers only being efficient at absorbing higher frequencies (Marsh, Raines (-)). Higher material densities will produce greater acoustic absorption.

Figure 2.2: Scanning electron microscope view of an open cell foam porous absorber.³

³ Taken from D. Dooling (1998).
Experimental study has shown that there are three main properties that affect the absorption characteristics of porous materials; flow resistivity, porosity and tortuosity. The flow resistivity of a material refers to how easily air can propagate through a material, and relates the pressure of the oscillating air flow to the induced flow rate through the material. For a given material bulk density, the resistivity increases as fibre diameter decreases. The porosity or fraction open volume of the material affects the volume velocity within the material, and consequently the resistivity. The structural complexity or tortuosity of the interconnecting nature of the pores (encompassing abrupt changes in cross section, non parallel channels and the inclusion of discrete cavities), adds an inertial component to air flow, resisting the motion of air relative to its acceleration. This affects the apparent fluid density and compressibility of the air within the material (Fahy 2001, Zwikker, Kosten 1949).

Dual porosity and multi-scale porous materials incorporating meso-perforations throughout, or at different depths within a porous material, have shown significant enhancements of the absorption properties. Low frequency absorption can be significantly increased, and can be adjusted through modifications to the profile of the meso-perforations (Bécot, Jaouen & Gourdon 2007, Sgard et al. 2005).

### 2.2.2 Resonant Absorption

Resonant absorbers provide acoustic absorption through increased viscous frictional energy conversion due to the presence of induced high amplitude oscillations when the frequency of the incident sound matches the natural frequency of the absorber. One type of resonant absorber is a membrane absorber. It is essentially a diaphragm mounted a certain distance in front of a solid wall, creating an enclosed air space. Rapid flexing of the membrane occurs as it is excited by the incident sound wave, and heat is produced as the membrane resists this motion. Compression of the enclosed air space behind the membrane also occurs, and provides another mechanism of energy conversion into heat. The maximum energy loss occurs when the membrane vibrates with its greatest amplitude when it is at its resonant frequency. The resonant
frequency is determined by the surface density of the membrane, and the width of the enclosed air gap (Fry 1988):

\[ f_r = \frac{60}{\sqrt{M_s d}}, \]  

Eq 2.2

where \( f_r \) (Hz) is the resonant frequency, \( M_s \) (kg m\(^2\)) is the surface mass of the panel and \( d \) (m) is the depth of the air gap. Typical membrane absorbers are constructed of plywood or plasterboard and are often installed as suspended ceilings or stud partitions.

In building acoustics the most frequently used type of resonant absorber is the cavity absorber also known as a Helmholtz resonator after the German physicist Hermann von Helmholtz who first developed a set of resonators to study the auditory response of tones. It takes the form of an enclosed volume of air connected to the room where sound is to be absorbed by means of a small neck, depicted in Figure 2.3.

Figure 2.3: Cross section through a typical cavity resonator.
Assuming the incident sound wavelength is greater than any characteristic resonator dimension, a lumped element approach can be adopted whereby the behaviour of the different resonator elements can be approximated using simplified mechanical analogies. In this case, the cavity resonator acts as a mechanical mass-spring oscillator, where the air in the cavity acts as a spring with zero mass. The plug of air in the neck acts as an oscillating mass. When sound of a frequency matching the resonant frequency of the mass-spring system is incident on the resonator, large oscillations occur. The resonant frequency $f_r$ (Hz) can be calculated using (Beranek, Vér 1992),

$$f_r = \left( \frac{c}{2\pi} \right) \sqrt{\frac{S}{V(I + \Delta l)}}$$

Eq 2.3

where $S$ (m$^2$) is the cross sectional area of the neck, $l$ (m) is the length of the neck, $\Delta l$ (m) is the neck length end correction due air mass movements around each orifice of the neck and $V$ (m$^3$) is the volume of cavity.

A predominant peak of absorption is obtained when the frequency of an incident sound wave matches the resonant frequency of the absorber. The frequency of resonance can be tuned by changing the vibrating mass and the stiffness of the air-spring. During the oscillation of the air within the cavity, frictional energy conversion takes place within the viscous boundary layer near the walls of the absorber, producing heat and consequently absorbing sound energy. As the absorption of the resonator is only significant at the resonant and nearby frequencies, the range at which cavity absorbers are effective is very narrow. The effective frequency range is dependent on the resistance in the system. If damping is introduced in the form of a porous material over the mouth of the resonator, resistance to the movement of the air plug occurs. This consequently reduces the amplitude of the oscillations, but widens the effective frequency range of the absorber (Everest 2001). Using the correct combination of neck geometry and cavity volume, low frequency sounds can be absorbed using resonators of a much smaller size than the equivalent required thickness of porous absorber.
Helmholtz resonators do not necessarily have to take the form of a single orifice and enclosed volume. Often a more practical implementation comes in the form of a perforated plate mounted a distance \( d \) (m) from a solid wall. In this case the volume \( V \) (m\(^3\)) is represented by a portion of the air gap between the sheet and the wall, but is not actually segregated. This type of construction is depicted in Figure 2.4. Porous materials are often added in front or behind the perforations, to increase the effective bandwidth (Ingard 1954).

![Figure 2.4: Perforated plate resonator cross section.](image)

Maa (1998) described a perforated panel that does not require the addition of porous materials to achieve broadband absorption. Sub millimetre resonator neck dimensions, comparable to the thickness of the viscous boundary layer of air, achieve sufficient levels of viscous resistance to enable broadband absorption over 3 octaves (250Hz – 2000Hz).

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4 Taken from G. G. Sacerdote (1951).
2.2.3 Miscellaneous Absorption Methods

There are a number of other approaches that have also been shown to exhibit sound absorbing properties. The Schroeder pseudostochastic diffuser, shown in Figure 2.5, is commonly used to produce an even, diffuse sound field within a room. Research has shown however, that if properly designed they can provide high levels of absorption.

![One dimensional Schroeder diffuser](image)

Figure 2.5: One dimensional Schroeder diffuser.

Fujiwara and Miyajima (1992) measured remarkable levels of absorption from Schroeder diffusers which they later reported to be caused by poor construction. Gaps between the elements making up the various wells could act as openings to cavities behind the panel creating Helmholtz type, resonant absorbers. It was also anticipated that sound energy reduction could occur through resonant absorption at the quarter wave resonances of the wells. The levels of absorption achieved indicated that these effects alone could not account for the high absorption levels recorded. Kuttruff (1994) explained that the excessive absorption could be attributed to viscous energy dissipation of air flow between in-frequency wells and those wells out of frequency, shown in Figure 2.6.

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The design of a Schroeder-type surface for maximum absorption is significantly different to that of one optimised for diffusion. Some of the important design considerations are outlined by Cox and D’Antonio (2004): Two dimensional sequences have a greater number of well depths allowing the existence of more quarter wave resonances, and more wells for energy flow to occur between; the depth sequence should evenly distribute the well resonances through the design frequency bandwidth; the deepest well determines the lower limit of the frequency bandwidth. The resonant frequency of a well can be calculated using

$$f_r = \frac{(2m-1)c}{4d_n}, \quad m = 1, 2, 3\ldots,$$

Eq 2.4

where $d_n$ (m) is the depth of the $n$th well.

Another recent advent in sound reduction theory has been developed from the established phenomenon of electronic band gaps within semiconductor crystals. These crystals are often used within electronics to filter electrons in certain energy bands (Sanchez-Perez et al. 1998). The effect is attributable to the periodic array of atoms within the crystal (James et al. 1995). The theory behind this mechanism has been applied to electromagnetic waves to create ‘photonic’ crystals constituting a medium composed of synthetic periodic dielectric structures (Kushwaha, Djafari-Rouhani...
1998). The periodicity of the medium regulates the propagation of electromagnetic waves, creating a frequency window, or band gap that electromagnetic waves cannot pass through. The band gap is produced as the wavelength of the propagating waves approaches the period of the crystal (Shen, Cao 1999).

The mathematical analogy between electromagnetic waves and the elastic vibration of sound waves has led to the prediction of 'phononic' structures, with frequency band gaps in which the propagation of sound and phonons is forbidden (Vasseur et al. 1998). The crucial parameters that determine the band gaps are: the ratio between the wave velocities within the solid inclusions and the surrounding medium, the volume fraction occupied by the solid inclusions, and the density ratio between the two mediums (Martinez-Sala et al. 1995).

The majority of the work carried out in this area has been the theoretical modelling of two-dimensional crystals, composed of an array of cylindrical inclusions periodically placed in an elastic solid or fluid. However a sculpture exhibited at the Juan March Foundation in Madrid, shown in Figure 2.7, consisting of a large periodic array of hollow steel cylinders (considered to be a phononic structure) has been shown to exhibit prominent sound attenuation around 1.67 and 2.4 kHz (Martinez-Sala et al. 1995).

![Figure 2.7: Phononic sculpture at Juan March Foundation, Madrid.](Taken from F. Meseguer (1998).)
All the previous examples of sound energy reduction have been passive, relying on their specific geometries to manipulate sound energy. The advantage of these methods is that once implemented, they require no additional input or energy to operate. One approach that combines acoustics and signal processing is active noise control. In this case destructive interference is set up between the sound fields generated by the original sound source and that due to other sources (usually loudspeakers), whose acoustic outputs can be controlled (Elliott, Nelson 1993). The principle is based around the capture of the original sound signal and subsequent processing and real time manipulation, to produce an output in the form of a second sound field, such that the superposition of the two sound sources causes destructive interference. The signal processing element is crucial to the successful operation of active absorbers, and is difficult to achieve using an analogue system. Digital systems can successfully produce active adaptation of the signal, sufficiently accurate to achieve real time attenuation (Elliott, Nelson 1993). The classic application of this technology is in ducts where there is less complicated wave propagation. However more intelligent systems have been shown capable of minimising the total sound within a room or enclosure (Guicking, Karcher & Rollwage 1985).

Hybrid passive-active systems have been experimentally developed, consisting of a passive absorbing layer backed by an air space, terminated with an active surface instead of a solid wall. The passive layer may take the form of a porous absorbing layer (Beyene, Burdisso 1997, Smith, Johnson & Burdisso 1999) or a Helmholtz type resonant layer (Cobo et al. 2004). The active termination is used to modify the layer’s back impedance so as to match the characteristic impedance of air. This produces optimal boundary conditions in the cavity behind the passive layer, increasing the absorption of the system at the frequencies where the passive material alone is not effective (Smith, Johnson & Burdisso 1999). Systems like this have shown high absorption over a large frequency range, and are particularly effective at low frequencies. Active absorption systems have advantages over many passive solutions in terms of size and weight. This is offset, however, by their complexity and cost, making their use limited to specialised applications.

The measurement of acoustic absorption can be accomplished on a large scale within the diffuse field of a reverberation chamber. Large samples in the order of 10m² are
used to modify the time taken for sound within the chamber to decay, which can then be related to absorption. Alternatively a smaller scale direct measurement approach can be used whereby the amount of energy reflected from a test specimen is measured in a sealed impedance tube, using the superposition of standing waves. The subject of sound absorption testing is addressed within Appendix 1.

2.2.4 Traditional Absorber Manufacture

The manufacture of porous absorbing materials must encourage the formation of interconnections between pores. In the case of fibrous materials (e.g. mineral wool or glass fibre) the raw materials are melted at high temperatures and then spun or pulled together to form filaments. These are then bonded together to give the absorber its shape (Cox, D'Antonio 2004). Porous open celled foams are generally made from polymers (Polyurethane for example) and are formed through a process involving the nucleation and growth of gas bubbles within a polymer matrix. As the bubbles expand the foam density decreases. Open cellular structures are obtained if bubble expansion is allowed to continue, causing the cell walls to rupture (Eaves 2004). The random nature of how the microstructures of these porous materials are formed presents difficulties in predicting their acoustic performance. Calculations based on empirical trends tend to be the most effective and easy to apply (Cox, D'Antonio 2004, Delany, Bazley 1970); however complex semi-analytical calculation is possible using material characteristics such as pore shape, tortuosity and flow resistivity (Allard, Champoux 1992).

The material that low to mid frequency Helmholtz type resonator structures are made from is largely unimportant (providing it is a nonporous solid), and is generally dictated by the end application. Side branch resonators for exhausts or ducts will generally be constructed from sheet metal, whereas perforated panels intended for room acoustics are generally made from plywood, Medium Density Fibreboard (MDF) or fibreglass (Cox, D'Antonio 2004), but may mirror other common building materials such as metal or plaster. Acrylic can also be used allowing an absorbent panel to be produced from a visually transparent material. (D'Antonio, Cox 2005). Perforated panels offer a very simple resonator construction, only requiring an
accurate drilling process. The exception to this is the microperforated panel which introduces manufacturing difficulties due to the small scale and required accuracy of its perforations (Maa 1998). Methods of achieving these micro perforations include mechanical drilling, laser cutting or the use of hot needles (Fuchs 2000).

The limitations imposed by current manufacturing techniques place restrictions on the feasible resonant absorber designs, with the majority of existing designs based on simple regular orifice shapes and arbitrary cavity profiles. The manufacture of porous absorbers relies on irregular fabrication processes which can introduce variability in properties from one sample to the next. The application of advanced manufacturing processes capable of accurately reproducing small, complex features, to the fabrication of acoustic absorbers, introduces freedom and control to absorber design and manufacture. Such processes could be used to improve absorption performance, and tailor the response of a sound absorbing device.

2.3 Rapid Manufacturing

Rapid Manufacturing (RM) describes a collection of manufacturing technologies which were initially used for the fabrication of prototypes (also referred to as Rapid Prototyping). All techniques are similar in that they construct solid three dimensional parts in an additive fashion, by ‘growing’ slices of material, bonded together from the bottom to the top of the part, directly from computer-driven data (Cooper 2001). The evolution of these processes over the past two decades has seen many improvements in materials, process capabilities and build speed enabling them to produce end-use parts. Parts are produced directly from 3D Computer Aided Design (CAD) software with minimal human interaction offering new levels of design freedom. Traditionally the design of a component has been limited by the manufacturing process, for example:
• Re-entrant shapes are not feasible;
• tool clearance must be considered;
• draft angles are required for removal from a mould;
• split lines are produced where two mould halves meet;
• variable wall thicknesses produce sinks caused by uneven cooling.

The use of RM does not impose these restrictions and unlike conventional manufacturing there is no direct link to the cost of a component and the complexity of its design (Hague, Campbell & Dickens 2003). This effectively allows complicated designs to be fabricated just as easily as simple ones. This geometric freedom is exemplified in Figure 2.8.

Figure 2.8: Examples of RM geometric freedom\(^7\).

Aside to the geometrical design benefits there are other significant benefits available to the manufacturer and the engineer. These include:

• Complete product customisation whereby each individual part produced is tailored to the customer’s exact requirements (Wohlers 2004);
• multiple part production in a single build, each with a different geometry, traditionally requiring the production of a different mould for each geometry;

\(^7\) Taken from G. W. Hart (2005).
• no additional machine operator skill or intervention to be able to produce customised or complex geometries; they simply have to orient the parts within the build volume (Williams, Panchal & Rosen 2003);

• manufacturing location is no longer an important economic factor as the amount of hired labour is minimal and the cost of materials is fairly constant. Manufacturing of products could be carried out within the intended market, reducing shipping and transportation costs, and environmental impact.

Currently there are only a handful of companies that utilise RM technologies to produce mass customised products for the commercial market. RM has been used to produce custom fit hearing aids and dental aligners, shown in Figure 2.9. Hearing aid manufacturers Siemens and Phonak have taken advantage of the total customisation possibilities by producing bespoke, in-ear hearing aids that are tailored to the exact shape of the customer’s ear canal. This offers improved comfort, good retention in the ear and biocompatible, hypoallergenic material (Phonak Hearing Systems (-)). The custom shells are produced in Nylon using a Selective Laser Sintering (SLS) process and house all the necessary electronics. Reverse engineering is carried out on a clay impression of the customer’s ear and the scanned data used to create the CAD model of the shell (Williams, Panchal & Rosen 2003).

Figure 2.9: Rapid manufactured products: (a) Phonak eShell hearing aid (b) Invisalign dental aligner.

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8 Reverse engineering involves measuring an object using 3D scanning equipment, and then digitally reconstructing it as a CAD 3D model.

9 Taken from Phonak Hearing Systems (-).

10 Taken from Align Technology (2004).
Align Technologies laser scan a clay impression of a patient’s teeth to produce a CAD representation. From this the required dental aligner shape can be produced. A selective laser photo curing process, known as Stereolithography, is then used to produce a set of moulds over which a clear polymer is thermoformed to produce the finished aligner. Each patient requires a different aligner every two weeks to gradually correct the position of the teeth. This need for complete customisation and quick production makes it an ideal application of RM. Outside of the commercial market RM is also often used to create one-off highly customised parts. These include: Formula 1 car aerodynamic parts, air ducts for fighter jets, measuring equipment for space, tank gun sight camera mounts and submarine replacement parts (Wohlers 2004).

There are many different processes encompassed under RM. While the principle of additive, layer based fabrication is common between all processes, the different approaches each have advantages and limitations for different applications. Commonly available RM processes can be broadly classified by the pre-processed form of their bulk material (powder, liquid or solid).

Powder based processes sinter or bond a powdered build material to produce each solid layer of a part. The fabrication of highly complex inaccessible features is possible, as they are self supported during manufacture. The requirement for post-fabrication powder removal limits the scale to which fine complex features can be produced; also a level of accessibility is required to remove hidden powder.

Liquid based processes solidify a liquid build material, usually a photocurable resin, and do not suffer from the same build material removal issues as powder based processes. Excess liquid can drain away from within and around complex features. This leads to the ability to produce complex structures, with finer void sizes, or 'pores'. The drawback with liquid based processes is their requirement of separate support structures. This limits their ability to produce inaccessible features.
Solid based techniques do not selectively solidify areas of a bulk material, but deposit and bond together discrete areas of solid material. Therefore the problems associated with the removal of unconsolidated build materials within and around features are avoided. As with liquid based, solid based processes are not self supporting and therefore separate support structures are required for internal and overhanging features.

Below is a brief classification of common RM processes:

<table>
<thead>
<tr>
<th>Powder Based</th>
<th>Liquid Based</th>
<th>Solid Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selective Laser Sintering</td>
<td>Stereolithography</td>
<td>Fused Deposition Modelling</td>
</tr>
<tr>
<td>3D Printing</td>
<td>Perfactory</td>
<td>Jetting</td>
</tr>
<tr>
<td>Laser Engineered Net Shaping</td>
<td>Objet</td>
<td>Laminate Manufacturing</td>
</tr>
</tbody>
</table>

Each process is described below, including their advantages, disadvantages and the implications of their individual fabrication and material characteristics. The direct comparison of publicised process performance values can be unfair and unwise; the manufacturer’s specifications relating to processes characteristics such as build speed can be misleading, as they are often dependent on many different parameters (Grimm 2004). The aim of this review is to ascertain the potential of each process in producing acoustic absorbing structures: Porous topologies for porous absorption, cavity and orifice combinations for resonant cavity absorption, and limp membranes for resonant membrane absorption.

2.3.1 Powder Based Processes

Selective Laser Sintering (SLS) uses a scanning laser beam to selectively solidify a single layer of material. The build material is a polymer coated powder which is held just below the polymer’s glass transition temperature and melted using the additional energy supplied by the laser. Once a layer has been solidified the build platform is
lowered by the depth of one layer and recoated with powder using a counter rotating roller, depicted in Figure 2.10. In the RM family of processes, SLS has the largest range of materials available (Pham, Dimov & Lacan 1999). The range of materials and the excellent material properties that can be produced are the most attractive properties of SLS. Parts can be produced using nylon, elastomer, sand and even metal based powders, and can be made up to 380 x 330 x 455 mm (length x width x height (xyz)) (Wohlers 2004). As the process is self supporting there is no need for a separate support structure. This allows parts with internal features to be produced. It also reduces post processing, although the powder removal of large complicated parts can be very arduous. Build speed is dependent on: part volume, part height, layer thickness, build material and post process de-powdering time. The fabrication speed is similar to that of Stereolithography; however the careful control of the powder temperature and the long cool down period consequently increases part production time. Feature sizes down to 0.5mm can be fabricated (3D Systems Inc 2001b); although inaccuracy can be introduced through shrinkage during sintering which does not always occur in a uniform manner. Also the produced parts must be evenly cooled to room temperature to avoid warping. The material in which the parts are built, the part orientation, and the part size and geometry also have a significant effect on part accuracy. Often these dimensional errors can be anticipated and reduced by making modifications to the CAD model (Pham, Dimov & Lacan 1999). The suitability of using the SLS process to fabricate acoustic absorbing structures and topologies is summarised in Table 2.2.
Table 2.2: Suitability of SLS applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>Powder removal problems associated with small features and moderate accuracy may make it unsuitable for producing intricate voids required for porous absorbing structures.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>The ability to produce internal features without separate support structures could allow resonant absorber structures with complex cavities. The presence of residual powder and the rough micro surface finish may lead to increased viscous resistance as air passes over the material.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>The elastomer material may allow the fabrication of a flexible membrane; however the minimum thickness that could be feasibly fabricated may add excessive membrane weight, inhibiting its response to acoustic excitation.</td>
</tr>
</tbody>
</table>

![Figure 2.10: SLS process.](image-url)  

**3D Printing** uses well established inkjet technology to selectively deposit a liquid binder onto a base powder. The work platform is then lowered and recoated with powder, in the same way as the SLS process, before the next layer is consolidated. A process schematic is shown in Figure 2.11. Plaster, starch and sand/ceramic powder formulations are available. Commercially available machines have build sizes up to 400 x 500 x 600mm (xyz) (Wohlers 2004), and offer a binder deposition resolution of

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13 Taken from The University of Northern Iowa (-).
600 x 530 dpi (Z Corporation 2006). Colour parts can also be produced using coloured binders. Ranges up to 16,000,000 colours can be produced, allowing complicated colour schemes, textures, labels and mark ups to be added to parts (Dean 2005). The produced parts are generally very fragile and require infiltration with Cyanoacrylate, Epoxy, Elastomer or Wax to produce full strength parts. Infiltration can prove difficult for internal inaccessible features, and the relatively low strength parts may not be suitable for demanding environments. The major advantages of 3D printing are its use of off-the-shelf components, the high build speed, and the low cost of the machines and materials. The build speed is mainly dependent on layer thickness and part height, but is also affected by binder drying time, post process de-powdering and infiltration (Grimm 2004). The simplicity of the process allows it to be easily scaled up, exemplified by the 1500 x 750 x 750mm (xyz) build volume of the Generis GmbH 3D printer which is used to produce large sand casting patterns. The suitability of using 3D printing to fabricate acoustic absorbing structures and topologies is summarised in Table 2.3.

Table 2.3: Suitability of 3D printing applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The minimum feature size and problems with powder removal make this process unsuitable for producing fine porous structures. However, post process infiltration of the fabricated parts requires a level of material porosity which could be acoustically significant.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>As with SLS, the unbound powder acts as a support structure, allowing nested and overhanging features suited to the potential fabrication of complicated resonant absorber cavity designs.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>The elastomer infiltrant allows flexible parts to be produced, but like the SLS process, the minimum thickness and associated weight of a fabricated membrane may prevent significant acoustic excitation.</td>
</tr>
</tbody>
</table>
Laser Engineered Net Shaping (LENS) is a fabrication process that produces fully dense metal parts. The process uses a high power laser to create a small melt pool into which metal powder is injected by means of a carrier gas blown out of a series of nozzles surrounding the laser; the process schematic is depicted in Figure 2.12. The nozzles are directed such that the blown powder converges at the same point as the laser beam. The substrate onto which the material is deposited moves relative to the laser allowing selective deposition of thin discrete lines of material (Keicher, Miller 1998). These are built up layer by layer to produce the solid part. This makes the LENS process different to other powder based processes which rely on selective solidification. Deposition positional accuracy of $\pm 0.25\text{mm}$ and material deposition rates up to $0.5\ \text{kg h}^{-1}$ can be achieved, in a maximum build envelope of $900 \times 1500 \times 900\text{mm (xyz)}$ (Optomec 2007). Enclosed voids can be produced within solid structures which could enable the fabrication of internal resonant absorber features, without powder removal issues. The poor accuracy and rough surface finish produced often leads to the requirement of post process machining to achieve the intended geometry, reintroducing the need for tool clearance and limiting the design freedom. The method of powder delivery allows the material to be changed during the fabrication of a part. This introduces the possibility of functionally graded materials enabling the customisation of a part’s material properties. The localized heating properties of the laser produces a fine grain structure, which improves material strength and ductility (Keicher et al. 1998). This would allow any acoustic geometry produced to be used in harsh, high temperature environments such as exhaust systems.

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14 Taken from The University of Northern Iowa (-).
although the complexity of the process can lead to very high part costs. The suitability of using the LENS process to fabricate acoustic absorbing structures and topologies is summarised in Table 2.4.

Table 2.4: Suitability of LENS applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The requirement for post processing restricts the fabrication of intricate features required for porous absorption.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>The post process requirement also restricts the ability to fabricate enclosed resonator cavity geometries.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>The stiffness of produced parts makes it unsuitable for the fabrication of membrane absorbers.</td>
</tr>
</tbody>
</table>

![LENS process diagram](image)

Figure 2.12: LENS process.\(^{15}\)

2.3.2 Liquid Based Processes

**Stereolithography** (SLA) uses a scanning laser controlled by galvanometer mirrors to selectively cure a liquid photo-curable polymer resin (usually an epoxy) one layer at a time. The build platform is lowered by the depth of one layer, and then recoated with the photopolymer before the next layer is selectively cured; this is shown

\(^{15}\) Taken from The University of Northern Iowa (-).
schematically in Figure 2.13(a). Post curing is required to complete polymerisation. The diameter of the laser beam is typically 0.23 – 0.28mm (3D Systems Inc 2003), and parts can be made up 500 x 500 x 600mm (Wohlers 2004). The build speed is dependent on the part volume, build height, layer thickness, build style, build material, post curing time, and cleaning / support removal (Grimm 2004). The high throughput and accuracy of the Stereolithography process are its main advantages, potentially allowing fine features and voids to be produced. However the liquid based build material requires the fabrication of separate support structures for overhanging features. One development of the support structure is the build strategy known as QuickCast 2.0. This strategy was developed to produce collapsible parts suitable for use as a sacrificial pattern for the investment casting of metals (Hague, D’Costa & Dickens 2001). It consists of a solid outer shell and a hexagonal internal porous network which requires no supporting, and is shown in Figure 2.13(b).

The virgin build material is expensive and has a limited shelf life due to its photo reactive properties. It is also very susceptible to moisture ingress; therefore the machines and the resin must be kept in a controlled environment. During the recoating process, when the blade sweeps across the vat of resin, it is very difficult to make the blade remove the exact amount of resin from the part and leave exactly one layer thickness on it. This can result in layers which are either too thick or too thin, affecting the accuracy of the product. Also parts that have trapped volumes can cause problems when recoating if it is not performed in a proper way; inaccurate layer thickness can lead to adjacent layers not attaching to each other because the created layers are too thick, or if the parts are built too high, the blade will hit the part during the scraping operation (Renap, Kruth 1995). The suitability of using the Stereolithography process to fabricate acoustic absorbing structures and topologies is summarised in Table 2.5.
### Table 2.5: Suitability of Stereolithography applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The liquid based build material can easily be drained leaving air saturated inclusions; also the ability to produce fine features may allow the fabrication of porous topologies exemplified by the Quickcast build strategy. However, unlike powder based processes the solidified structure is not supported by the surrounding material and therefore supports would have to be constructed during the build to support overhanging features and removed in post-processing. This places restrictions on the type of pore geometry that could be produced.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>The requirement for support structures restricts the ability to fabricate enclosed cavity volumes; however a sparse support structure may be able to be considered acoustically insignificant. Also the recoating issues associated with trapped volumes may present complications when fabricating resonator cavities.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>Stereolithography allows the use of a soft-durometer flexible material with good post process strength; this coupled with the thin layer thickness introduces a possible application to membrane absorbers.</td>
</tr>
</tbody>
</table>
Perfactory uses a similar photo-curable resin to that used in the Stereolithography process. The major difference is that the light source is not a single point laser, but rather a projected image of the entire cross section of the layer being solidified. This is achieved using a digital micromirror based on the Digital Light Processing (DLP) chip from Texas Instruments. This consists of a rectangular array of digitally controllable micro-mirrors that can each project a single pixel of light, depending on their orientation (Dudley, Duncan & Slaughter 2003), schematically depicted in Figure 2.14. A voxel (volumetric pixel) size of 0.086 – 0.136mm is possible using this highly accurate cross section solidification method; also the time taken to define a single layer is less than the laser point scanning strategy of SLA. Parts can be build up to 20mm h\(^{-1}\) in the vertical z direction (for 0.1mm layer thickness), with a maximum build size of 190 x 142 x 230mm (xyz) (Envisiontec GmbH 2007). Another fundamental difference over SLA is that the layer being cured is at the bottom of the resin vat, and when solidified is lifted up by the build platform above. This allows accurate layer thickness to be maintained and also eliminates the recoating problems associated with Stereolithography. The straightforward layer increment method and whole layer exposure, leads to a fast process time and very accurate features. A requirement for support structures limits the types of features that can be produced. The relatively small build envelope, small machine size, ease of use, and the high

\[\text{Figure 2.13: (a) Stereolithography process}^{16}\ \text{(b) QuickCast 2.0 build strategy.}^{17}\]

\[\text{Perfactory uses a similar photo-curable resin to that used in the Stereolithography process. The major difference is that the light source is not a single point laser, but rather a projected image of the entire cross section of the layer being solidified. This is achieved using a digital micromirror based on the Digital Light Processing (DLP) chip from Texas Instruments. This consists of a rectangular array of digitally controllable micro-mirrors that can each project a single pixel of light, depending on their orientation (Dudley, Duncan & Slaughter 2003), schematically depicted in Figure 2.14. A voxel (volumetric pixel) size of 0.086 – 0.136mm is possible using this highly accurate cross section solidification method; also the time taken to define a single layer is less than the laser point scanning strategy of SLA. Parts can be build up to 20mm h\(^{-1}\) in the vertical z direction (for 0.1mm layer thickness), with a maximum build size of 190 x 142 x 230mm (xyz) (Envisiontec GmbH 2007). Another fundamental difference over SLA is that the layer being cured is at the bottom of the resin vat, and when solidified is lifted up by the build platform above. This allows accurate layer thickness to be maintained and also eliminates the recoating problems associated with Stereolithography. The straightforward layer increment method and whole layer exposure, leads to a fast process time and very accurate features. A requirement for support structures limits the types of features that can be produced. The relatively small build envelope, small machine size, ease of use, and the high}^\]

\[\text{Figure 2.13: (a) Stereolithography process}^{16}\ \text{(b) QuickCast 2.0 build strategy.}^{17}\]

\[\text{Perfactory uses a similar photo-curable resin to that used in the Stereolithography process. The major difference is that the light source is not a single point laser, but rather a projected image of the entire cross section of the layer being solidified. This is achieved using a digital micromirror based on the Digital Light Processing (DLP) chip from Texas Instruments. This consists of a rectangular array of digitally controllable micro-mirrors that can each project a single pixel of light, depending on their orientation (Dudley, Duncan & Slaughter 2003), schematically depicted in Figure 2.14. A voxel (volumetric pixel) size of 0.086 – 0.136mm is possible using this highly accurate cross section solidification method; also the time taken to define a single layer is less than the laser point scanning strategy of SLA. Parts can be build up to 20mm h\(^{-1}\) in the vertical z direction (for 0.1mm layer thickness), with a maximum build size of 190 x 142 x 230mm (xyz) (Envisiontec GmbH 2007). Another fundamental difference over SLA is that the layer being cured is at the bottom of the resin vat, and when solidified is lifted up by the build platform above. This allows accurate layer thickness to be maintained and also eliminates the recoating problems associated with Stereolithography. The straightforward layer increment method and whole layer exposure, leads to a fast process time and very accurate features. A requirement for support structures limits the types of features that can be produced. The relatively small build envelope, small machine size, ease of use, and the high}

\[\text{16} \text{ Taken from The University of Northern Iowa (-).}^{16}\]

\[\text{17} \text{ Taken from R. Hague (2001).}^{17}\]
detail that can be achieved have made this process very popular with jewellery manufacture, but this would restrict it to making small acoustic components. The suitability of using the Perfactory process to fabricate acoustic absorbing structures and topologies is summarised in Table 2.6.

Table 2.6: Suitability of the Perfactory process applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The high accuracy of the process and the small feature size that can be produced making it capable of fabricating the fine geometries and voids associated porous absorbers, although support structures are still required.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>The recoating strategy alleviates the problems associated with trapped volumes, therefore making the fabrication of enclosed resonant cavities more feasible. However the requirement for support structures may limit the fabrication of internal cavity features.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>The stiffness of produced parts makes it unsuitable for the fabrication of membrane absorbers.</td>
</tr>
</tbody>
</table>

Figure 2.14: Perfactory digital micromirror.\textsuperscript{18}

\textbf{Objet} is a type of jetting that selectively deposits uncured photopolymer using a specialist inkjet print head with 1536 nozzles, specifically designed to jet photopolymer materials (Wieneke-Toutaoui, Gerber 2003). The use of well

\textsuperscript{18} Taken from Dudley et al (2003).
established inkjet technology offers an accuracy of 0.1 – 0.3mm, allowing walls down to a thickness of 0.6mm to be fabricated (Objet Geometries Ltd 2007). The deposition head sweeps back and forth across the build area on a gantry, depositing the resin to form the desired layer. The deposited photopolymer is immediately solidified by a constant ultraviolet light source attached to the printer head. Once a single layer is completed the build platform drops by the thickness of one layer before fabricating the next layer. A process schematic is shown in Figure 2.15. Like the LENS process, Objet differs from other liquid based processes in that it can be considered a selective deposition method rather than a selective solidification method. This removes problems associated with material draining and trapped volumes. Support structures are required for overhanging features, removal of which can increase post processing time; however the process allows two different materials to be jetted during the build, allowing the deposition of a separate gel based support structure which can be easily washed away. Deposition rates up to 20mm h⁻¹ in the vertical z direction are possible in a maximum build volume of 490 x 390 x 200mm (xyz) (Objet Geometries Ltd 2007). The suitability of using the Objet process to fabricate acoustic absorbing structures and topologies is summarised in Table 2.7.

Table 2.7: Suitability of the Objet process applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The requirement for support materials limits the ability of this process to produce fine porous topologies. Gel based supports may alleviate some support issues, although removal from fine porous structures could prove difficult.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>The deposition based fabrication method alleviates problems associated with drainage and trapped volumes from within cavity absorbers, although the requirement for support structures may limit the fabrication of internal cavity features.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>The soft rubber-like Tango build material allows the fabrication of flexible parts. The thin layer thickness would allow the fabrication of thin membranes, although membrane strength may be an issue.</td>
</tr>
</tbody>
</table>
2.3.3 Solid Based Processes

**Fused Deposition Modelling (FDM)** is a small scale process that extrudes a continuous filament of material through a heated extrusion head. The head scans over the work area selectively depositing material where required as shown in Figure 2.16(a). The most commonly used materials are Acrylonitrile Butadiene Styrene (ABS) or Polycarbonate (PC), however any material that is capable of flowing through the head when hot and solidify when cooled can be used, including metal and ceramic slurries. The use of these common engineering materials results in highly resilient parts which can be used for functional testing and end use products. The deposition accuracy is ± 0.127mm and the maximum build size currently available is 914 x 610 x 914 mm (Stratasys Inc 2007). The process is relatively quick, laying filament tracks at a rate of 23m min\(^1\) (Steen 2003); although ultimately the overall production speed is dependent on the part volume, raster width, layer thickness and the time taken for support removal (Grimm 2004). The process requires a moderately high amount of post processing; as with other deposition based methods, a support structure is required for overhanging features. The extrusion head has a second nozzle that deposits the support material, which consequently has to be removed by hand; however water soluble support material is available. Also because of the rough

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19 Taken from AMT Korea (2004)
deposition of the filament, sanding is often required to produce a surface finish comparable with other RM processes. Material properties are very close to those of the parent material, making parts suitable for functional testing; however because of the fabrication method, material anisotropy is inevitable and can lead to delamination of adjacent layers (Ahn et al. 2002). The process software allows the spacing between adjacent filaments, and the filament thickness to be varied. This approach has previously been utilised for the development of biomedical tissue engineering, bone scaffold structures (Leong, Cheah & Chua 2003, Too 2002). The suitability of using FDM to fabricate acoustic absorbing structures and topologies is summarised in Table 2.8.

Table 2.8: Suitability of FDM applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The raster deposition method using fine extruded filaments could itself hold inherent porosity which could be exploited for porous absorption. Changes to the process parameters relating to the raster width (RW) and raster spacing (RS) (Figure 2.16(b)) may allow a porous absorbing acoustic topology to be produced.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>The accuracy, support requirement and finishing may limit the ability of FDM to fabricate fine details within enclosed resonant absorber cavities.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>The stiffness of produced parts makes it unsuitable for the fabrication of membrane absorbers.</td>
</tr>
</tbody>
</table>
Jetting is another process that utilises piezo electric deposition devices common to inkjet printer technology. There are some subtle differences between different jetting process manufacturers. One approach is the selective deposition of molten wax, thermoplastic or thermoset polymers followed by incremental lowering of the build platform. Vertical accuracy can be maintained by sweeping a heated roller across the platform after each layer is deposited. The deposition devices offer a volumetric resolution up to 300 x 400 x 600 dpi (3D Systems Inc 2001a), and parts produced using these methods can be made up to 900 x 300 x 300 mm (xyz) (Wohlers 2004), and are less accurate than Stereolithography or laser sintered parts. The processes require the construction of support structures, which have to be removed during post processing and often leave behind witness marks on the part. The removal of support structures coupled with low accuracy and poor part strength makes jetting only really suited to producing visual prototypes. Wax parts can be used as investment casting patterns for one off castings. The suitability of using Jetting to fabricate acoustic absorbing structures and topologies is summarised in Table 2.9.

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20 Taken from The University of Northern Iowa (-).
Table 2.9: Suitability of Jetting applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The poor fabricated part properties and accuracy, coupled with the requirement for support structures makes jetting unsuited to producing porous topologies.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>Simple resonant cavity shapes could feasibly be fabricated although the final part properties would limit its application and realistic use. The process could however, produce investment casting patterns for the production of highly resilient basic resonant absorber shapes.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>The fragility of fabricated parts makes them unsuitable for use as flexible membranes.</td>
</tr>
</tbody>
</table>

**Laminate Manufacturing** is a very basic layer based additive process which can be summarised as the stacking of cut sheets. Common materials used include paper, metal, polymers and ceramics. The Laminated Object Modelling (LOM) process uses paper backed with a polymer adhesive which is bonded to the build platform using a heated roller. The profile of the specific layer is cut using a scanning laser before the platform is lowered and the next layer bonded to the build platform, as depicted in Figure 2.17. This in an inherently slow process but is capable of cutting each paper layer at an accuracy of ±0.127mm (Chua, Leong & Lim 2003). Unlike the other solid based processes the build material surrounds the part being fabricated and is hatched to aid the removal of the final part. This prevents the fabrication of any inaccessible or enclosed features that inhibit the removal of the unwanted surrounding material. The largest laminate manufacture machine is the Kinergy Zippy II which has the largest build volume of any commercially available Rapid Prototyping / Manufacturing machine at 1180 x 730 x 550mm (xyz) (Wohlers 2004). The difference in the x,y build dimensions of this and other processes reflects the envelope of typical prototype geometries. Another similar laminate manufacturing system applies the adhesive layer as a photocopier toner and uses a knife to cut the layers. Paper parts are susceptible to damage by permeating moisture; therefore it is necessary to seal the part during post processing. This coupled with the removal of the unwanted material can lead to long post processing times. The paper based parts also have poor mechanical properties,
and are more suited as proof of concept models than for functional testing. The advantage of LOM parts is their insusceptibility to shrinkage and warping (Marais, Dominauskas 2003). Metal laminate systems use ultrasonic consolidation to bond thin layers of metal tape together, and contour milling to shape each layer. The suitability of using laminate manufacturing to fabricate acoustic absorbing structures and topologies is summarised in Table 2.10.

Table 2.10: Suitability of laminate manufacturing applied to acoustic absorption.

<table>
<thead>
<tr>
<th>Absorption Method</th>
<th>Process Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Absorption</td>
<td>The problems associated with removing support material from around features would inhibit the ability to produce a fine, open porous structure.</td>
</tr>
<tr>
<td>Resonant Cavity Absorption</td>
<td>Similarly the support material issues would restrict the fabrication of resonant cavity absorbers to very basic configurations.</td>
</tr>
<tr>
<td>Resonant Membrane Absorption</td>
<td>A single, unmodified sheet could be considered as a membrane, although removal of the unwanted material from any associated cavity would still be an issue.</td>
</tr>
</tbody>
</table>

![Figure 2.17: LOM Process.](image)

21 Taken from The University of Northern Iowa (-).
2.3.4 Rapid Manufacturing for Acoustics

Sound propagation within solid structures is largely dependent on the mass of the structure, therefore the added capabilities offered by RM may not be fully utilised in a structure borne propagation application. The frequency regions where structure borne propagation is controlled by coincidence and resonance effects are dependent on the damping within the structure, as well as the structure mass. Damping to vibrations within a solid structure could be added through geometric modifications that reduce resonant panel modes through the use of non homogenous constructions.

The employment of RM to airborne sound reduction offers broader application potential as geometry plays a more important role in acoustic absorber design and performance. The design freedom, and flexibility of rapid manufactured parts offers a method of introducing freedom and geometric control to the design of acoustic absorbers. Resonant cavity absorption relies on simple geometric shapes to achieve the resonant effect; however large absorption bandwidths can only be achieved through the incorporation of separate resistive materials or through the use of accurate sub-millimetre perforations. RM offers a method to produce acoustic resonant absorbers with levels of design freedom not previously viable, potentially allowing improved resonator design development, and alternate methods of adding acoustic resistance. The selective solidification/deposition of material and ability to produce internal, inaccessible features offers the potential to allow fabrication of porous absorbing structures. Similarly the exploitation of certain process fabrication characteristics, may present an alternative method of producing porous topologies. The minimum feature size of the majority of processes restricts the thickness of any fabricated membrane; this makes them an unsuited method of absorption for fabrication using RM. The potential for the application of RM to porous and resonant cavity absorption suggests that an investigation exploring the above aspects may lead to novel acoustic absorbers, with potential for performance benefits or added value.
2.4 Conclusions

The use of acoustic absorption to reduce nuisance noise and control the acoustic environment within an enclosure is a well studied area of research. However, the fundamental manufacturing technology behind the majority of current acoustic absorbing solutions has remained unchanged for decades. The exception to this is the microperforated panel, which has its own set of manufacturing complications.

Traditional porous absorbing materials offer a simple method of absorbing high frequency sound. Their fabrication methods produce non uniform pore sizes and shapes, leading to uncertainties in their acoustic performance prediction, and material characterisation. Bulk material properties can become predictable and repeatable after empirical measurements of a single sample, although prediction using material configuration characteristics alone is not possible.

The manufacture of resonant cavity absorbers used to address more problematic lower frequencies often relies on the drilling of holes in sheet material, and the basic fabrication of enclosures using traditional techniques. These simple designs usually require the addition of porous materials in order to operate efficiently and produce a wide bandwidth of absorption. The use of these material types is not desirable for many applications, leading to the requirement for single material, or fibreless absorbers.

The design of resonant cavity absorbers has been restricted by traditional manufacturing methods, and consequently research into their geometrical configuration has been limited. The microperforated panel is an example of how resonator construction can be modified to increase the acoustic resistance within the resonator neck, and produce a broadband absorber. However, its design is fundamentally the same as that of regular resonant cavity absorbers.

RM processes introduce a range of technologies capable of producing complicated geometries with ease, thus opening up considerable design freedom to the engineer or
designer. While limitations still exist, these technologies could be used to manufacture enable acoustic absorbers that exploit geometry.

The scale of the sub-millimetre interconnected features required for effective porous absorption (around 100 microns) is beyond the feature size limits for all but the finest of current RM processes (e.g. Micro Stereolithography (Bertsch et al. 2000)). Also the inaccessibility to the enclosed pores would make the removal of any support type difficult.

It may be possible to produce porous topologies through the exploitation of inherent material porosity within un-infiltrated parts produced using the 3D printing process. Alternatively the build characteristics of the FDM process can be modified to produce a porous structured weave pattern. This could lead to a method of producing a configurable porous absorber with predictable absorption characteristics.

The fabrication of the larger feature sizes of resonant cavity absorbers is feasible using most RM processes. However if resonator design is to be explored then processes that allow the easy removal of support material from internal cavities and between small features (powder based processes, or those with dissolvable supports), will be preferable over methods requiring more manual support removal methods, and extensive post processing.

This research will focus on the application of RM to resonant cavity, and porous absorption. The potential RM fabrication advantages identified, allow an investigation into resonant absorber geometry, and porous absorber topology.
Chapter 3

Absorber Theory and Modelling

Acoustic absorption of the lower frequency range presents a more challenging problem than higher frequencies due to the size of the wavelengths involved. There are issues relating to the size, material use and manufacturability of current low frequency absorbers. Helmholtz resonant absorbers offer compact low frequency absorption; however satisfactory performance levels can only be achieved through the addition of porous materials which may be undesirable, or by introducing highly accurate, small features which lead to manufacturing difficulties. These difficulties are often prohibitive and so the geometry of Helmholtz resonators is generally based around the traditional configurations described by Rayleigh (1945) and Ingard (1953). Rapid Manufacturing (RM) processes overcome traditional fabrication limitations and introduce the possibility of producing complex shapes and millimetre sized features. The geometry of the Helmholtz resonator is therefore an area of research with potential for improvement using the design freedom offered by RM.

Parts built using RM processes are often slightly porous due to the selective solidification / deposition, and layer based fabrication. Some fabricated materials are inherently porous to allow post fabrication infiltration with strengthening agents. The fabrication of specific porous topologies may be possible using highly accurate processes, or by modifying certain process parameters. An investigation into the possibility of porous absorption using porous properties produced using RM is therefore a further area of potential research.

To allow the development of an informed investigation this chapter expands on the background theory of resonant and porous absorbers from the previous chapter. The existing theory and research developments relating to each absorption method are discussed and the important characteristics and physical variables are determined.
3.1 Helmholtz Resonator Theory and Modelling

Helmholtz type resonant cavity absorbers are by no means a new method of absorbing sound energy. They have been the subject of mathematical and experimental study since the early part of the 20th century. It has even been claimed that they have been used in the form of vases in ancient Greek and Roman theatres, to improve sound quality. They are still used extensively to control room acoustics, and also as mufflers within Heating Ventilation and Air Conditioning (HVAC), vehicle exhaust and induction systems, (Munjal 1987) and even to improve the transmission loss of double glazed windows (Mason, Fahy 1988).

Regarding a Helmholtz resonant absorber using the lumped element approximation, the resonant system can be considered analogous to a one-degree-of-freedom mass attached to a spring. The air within the cavity of volume $V$ (m$^3$) acts as a spring (with no mass), and the plug of air in the neck acts as an oscillating mass. This basic configuration is shown in Figure 3.1. The equations that follow elaborate from the basic Helmholtz resonant frequency introduced in the previous chapter.
The equation giving the resonant frequency \( f_r \) (Hz), of a mass-spring oscillator is,

\[
f_r = \frac{1}{2\pi} \sqrt{\frac{s}{M}},
\]

Eq 3.1

where \( s \) (N m\(^{-1}\)) represents the spring stiffness and \( M \) (kg) is the mass. The equivalent stiffness of the air within the cavity of a Helmholtz resonator can be shown to be (Kinsler et al. 1982),

\[
s = \rho c^2 \frac{S^2}{V},
\]

where \( S \) (m\(^2\)) is the cross sectional area of the neck. The mass of the air within a simple cylindrical neck with neck length \( l \) (m), is given by,

\[
M = \rho Sl,
\]

Eq 3.3

then substitution gives the resonant frequency,
A correction factor is often added to \( I \) to account for air movement around the two orifices of the neck. If both inner and outer ends of the neck can be considered to be flanged then the neck end correction, \( \Delta l \) (m) is,

\[
\Delta l = 2(0.85a), \quad \text{Eq 3.5}
\]

where \( a \) (m) is the neck radius.

The open end of the neck can be considered to radiate sound into the surrounding as an open ended pipe does, so consequently has a related radiation resistance \( R_r \) (N s m\(^3\)) of,

\[
R_r = \frac{\rho c k^2 S^2}{2\pi}, \quad \text{Eq 3.6}
\]

where \( k \) (-) is the wave number equal to \( \omega/c \), and \( \omega \) (rad s\(^{-1}\)) is the angular frequency.

An incident sound wave of amplitude \( P \) (N m\(^{-2}\)) produces an instantaneous complex driving force \( F \) (N) on the resonator opening,

\[
F = SPe^{i\omega t}, \quad \text{Eq 3.7}
\]

which leads to a differential equation relating to the displacement \( \xi \) (m) of air in the resonator neck,

\[
M \frac{d^2 \xi}{dt^2} + R_r \frac{d\xi}{dt} + s\xi = SPe^{i\omega t}, \quad \text{Eq 3.8}
\]

\[
f_r = \frac{c}{2\pi \sqrt{\frac{S}{Vl}}}. \quad \text{Eq 3.4}
\]
representing this in terms of volume velocity \( U (m^3 s^{-1}) \), and volumetric displacement \( X (m^3) \) where,

\[
U = \frac{dX}{dt} = S \frac{d\xi}{dt}, \quad \text{Eq 3.9}
\]

yields,

\[
M \frac{d^2X}{dt^2} + R_r \frac{dX}{dt} + sX = S^2 Pe^{iat}. \quad \text{Eq 3.10}
\]

Assuming that \( X = X_0 e^{iat} \) and \( U = U_0 e^{iat} \) allows a simplification to,

\[
-\omega^2 MX_0 + i\omega R_r X_0 + sX_0 = S^2 P. \quad \text{Eq 3.11}
\]

and allows substitution to achieve an expression for acoustic impedance \( Z_{ac} (N s m^5) \),

\[
Z_{ac} = \frac{Pe^{iat}}{U} = \frac{R_r}{S^2} + i\omega M \frac{1}{S^2} - i \frac{s}{\omega S^2}. \quad \text{Eq 3.12}
\]

Simplifying and substituting the fundamental terms back in brings the final expression for acoustic impedance (including neck length corrections),

\[
Z_{ac} = \frac{pc^2}{2\pi} + i \left( \frac{\omega p(l + \Delta l)}{S} - \frac{pc^2}{\omega V} \right). \quad \text{Eq 3.13}
\]

The acoustic impedance exhibited by a surface of area \( S \) is the complex quotient of the acoustic pressure at the surface divided by the volume velocity at the surface (Kinsler et al. 1982). A complex value of impedance is used as the maximum air flow of the oscillating motion of a sound wave, may not occur at the same time (same phase) as maximum pressure. The first term is the real part of the equation and represents the acoustic resistance of the resonator. The second imaginary term represents the reactance.
The specific impedance \( Z (\text{N} \text{s} \text{m}^{-3}) \) can be calculated by multiplying through by \( S \),

\[
Z = \frac{\rho ck^2 S}{2\pi} + i \left[ \omega \rho (l + \Delta l) - \frac{\rho c^2 S}{\omega V} \right].
\]

Eq 3.14

The expression for impedance above is a simplistic lumped element approximation and ignores some additional physical effects including resistance attributable to viscous losses at the surfaces of the neck. Consequently the resistive term is generally an underestimation. An expression for the viscous resistance \( R_v (\text{N} \text{s} \text{m}^{-3}) \) was derived by Ingard (1953),

\[
R_v = \frac{2\pi}{a} (l + 2a),
\]

Eq 3.15

where \( \eta \) (kg m\(^{-1}\)s\(^{-1}\)) is the dynamic viscosity of air.

Ingard (1953) also presented a more complete expression for the mass end correction \( \Delta l \). The end correction associated with the inner orifice \( \Delta l_i \) differs from the external end correction \( \Delta l_e \) as it radiates into the confined cavity space and not into an infinite medium as previously considered. \( \Delta l_e \) can be simply defined as 0.85a, and

\[
\Delta l_i = 0.85a \left( 1 - 1.25 \frac{2a}{D} \right),
\]

Eq 3.16

where \( D \) (m) is the equivalent diameter of a cylindrical cavity of volume \( V \).

A more accurate description of the acoustic impedance, including viscous losses within the neck, and improved mass end correction factors then becomes:

\[
Z = \left[ \frac{\rho ck^2 S}{2\pi} + \sqrt{\frac{2\pi}{\eta \rho}} \frac{1}{a} (l + 2a) \right] + \left[ \omega \rho \left( l + \left( 0.85a + 0.85a \left( 1 - 1.25 \frac{2a}{D} \right) \right) \right) - \frac{\rho c^2 S}{\omega V} \right].
\]

Eq 3.17

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The left hand side of the real term represents radiation resistance, where the right hand term describes viscous internal resistance. The first term of the imaginary reactive part of the equation is equivalent to the acoustic inertia (mass reactance), and the last term represents the cavity stiffness.

It can be seen that by changing the relative dimensions of the neck and the volume of the cavity, the resonators can be tuned to different frequencies. The amount of resistance and reactance (impedance) is also affected by the neck dimensions and cavity volume.

When the resonator is excited by a sound wave whose frequency matches the natural frequency of the resonator, large oscillations of the plug of air within the neck occur. The movement of the air against the walls of the neck produces heat via viscous friction, providing a conversion of sound energy into heat, thus producing acoustic absorption. The absorption coefficient $\alpha$ at the opening of the resonator neck for normal incidence can be calculated from impedance using,

$$\alpha = 1 - \frac{\left| \frac{Z - \rho c}{Z + \rho c} \right|^2}{\frac{Z - \rho c}{Z + \rho c}}.$$  \hspace{1cm} \text{Eq 3.18}

The bandwidth over which the absorption curve spreads is determined by the amount of acoustic resistance present within the resonator. A small amount of resistance produces a sharp absorption curve only effective over a narrow frequency range, where a higher degree of resistance increases the effective bandwidth but can decrease the maximum absorption value. Figure 3.2 shows the effect of adding resistance to a simple single resonator test configuration. The curves were produced using Eq 3.17 and Eq 3.18 with environmental parameters relating to room temperature and one atmosphere, and resonator physical parameters: $l = 0.015\text{m}$, $a = 0.0075\text{m}$, $V = 0.000494486\text{m}^3$. The units of acoustic resistance are the pascal-second per meter (Pa s m$^{-1}$), but can equivalently be given in MKS Rayls or newton-seconds per cubic meter (N s m$^{-2}$). Resistance can be expressed as an absolute value or relative to the characteristic impedance of air $Z_0 = \rho c$ as is the case in Figure 3.2.
It can be seen that when the level of resistance is very low, the addition of further resistance will increase both the peak absorption and absorption bandwidth. When the resistance is comparable with the characteristic impedance of air ($Z_0$), absorption is complete. After this point only bandwidth increases occur, and the peak absorption value drops.

The amount of resistance governed by the radiation resistance and viscous losses within the neck are often less than the characteristic impedance of air, resulting in low absorption values and poor bandwidth. Resonator resistance can be increased by the addition of a porous material applied to the neck or cavity. This allows the total amount of resistance and hence the absorption to be tailored to suit the intended application. The addition of resistive material inside the neck, or within one neck diameter can be modelled as an additional resistance term in the impedance equation, however porous material situated further within the cavity usually requires a more complete solution using a transfer matrix (Cox, D'Antonio 2004). It is becoming more desirable to reduce the use of these separate resistive materials as they are generally hard to recycle and can cause health issues by releasing fibres into the air. Their inherent fragility restricts their use in physically or harsh surroundings, and they can be hard to clean (Fuchs 2001).
Many common applications of resonant absorbers come in the form of perforated panels backed by an air space as depicted in Figure 3.3. These configurations offer very simple construction and their response is similar to that of a single resonator.

![Perforated panel resonator cross section.](image)

For this design the equivalent cavity volume $V$ is the proportion volume of the air space that can be considered attributable to a single orifice $V = x^2 d$, where $d$ (m) is the depth of the air space and $x$ (m) is the perforation separation (the distance between adjacent perforations), for a square perforation configuration.

Theoretical modelling of perforated panel absorbers considers the impedance of the panel separately to the cavity air space, allowing the response of simple configurations to be easily calculated. The porosity or fraction open area, $\varepsilon$ (\%), of the perforated sheet is used for convenience where $\varepsilon = \frac{m'}{x'}$, this is sometimes also referred to as the perforation ratio (\%). The interaction of neighbouring perforations effects the movement of air as it exits each orifice; therefore the orifice length end correction value of 0.85 given in Eq 3.5 is no longer valid. A more accurate equivalent perforation length $l_p$ (m) including the effects of mutual interactions is (Ingard 1953),

$$l_p = l + 2a(0.8(1-1.4\varepsilon^{1/2})),$$

Eq 3.19

The impedance of the perforated layer alone $Z_p$ (N s m$^{-3}$) becomes,
\[ Z_p = \frac{\rho}{\varepsilon} \left( \frac{1}{2a} + 1 \right) \sqrt{8 \eta \rho \omega + \frac{i \omega \rho \varepsilon}{\varepsilon}}, \]  
\textbf{Eq 3.20}

and the impedance of the backing cavity space \( Z_s (\text{N s m}^{-3}), \)

\[ Z_s = -i \rho c \cot(\omega d / c). \]  
\textbf{Eq 3.21}

The impedance of the overall structure is,

\[ Z = Z_p + Z_s. \]  
\textbf{Eq 3.22}

Using this method, the resonant frequency becomes,

\[ f_r = \frac{c}{2\pi} \sqrt{\frac{\varepsilon}{l_p d}}. \]  
\textbf{Eq 3.23}

### 3.1.1 Developments in Helmholtz Resonator Design

The resonator performance theories discussed so far all consider the neck of the resonator to be cylindrical and they consider the cavity to be of arbitrary shape. Several authors have investigated the effect of changing resonator geometry. The cross sectional shape of the orifice has been shown to be insignificant by Chanaud (1994), but its position in relation to the axis of the cavity important. Changes to resonant frequency with varying cavity length-to-depth ratio are also demonstrated in this work. This effect was investigated further by Selamet (1997) who modelled the wave propagation within the cavity (normally considered to be planar) and showed that non-planar wave propagation in cavities with small length-to-depth ratios altered the resonant frequency, this propagation is demonstrated in Figure 3.4.
The previously described lumped parameter model produces satisfactorily accurate absorption predictions for concentric resonators with simple, axis-symmetric cavity shapes, without extreme length-to-depth ratio. Alster (1972) introduced a cavity form factor to more accurately predict the resonant frequency of fundamental, axis-symmetric cavity forms. Sapoval (1997) postulated that the use of an irregular, prefractal cavity shape would increase resonator damping by a factor that was dependent on the degree of irregularity of the cavity boundary, with a true mathematical fractal producing infinite damping.

Changes to the neck geometry have been a more widely investigated area as the air in and around the orifices is faster moving, and consequently holds more potential for energy dissipation. The effect of tapering the neck of resonators has been investigated by Vigran (2004) and Tang (2005). They reported significant improvements in absorption coefficient, with deeper tapering lengths producing better improvements in sound absorption. They also noted an increase in resonant frequency with increasing tapered section slope.

Selamet (2003) investigated extending the neck of the resonator into the cavity and found a lowering of resonant frequency was possible without increasing the size of the cavity. He also investigated expanding the neck portion within the cavity into a cone
shape, and the addition of perforations to the same section. The conical neck exhibited the same effects as reported by the previous two authors. As the perforation percentage of the neck increases, the damping decreases, resulting in a higher maximum absorption but sharper curve at resonance. The resonant frequency was also affected by the presence of neck perforations.

Arguably the most significant development in neck modification has been the introduction of the microperforated panel. This design addresses the problem of additional resistance required for broad absorption curves through the use of perforations with sub-millimetre dimensions. As the orifice diameter becomes comparable to the viscous boundary layer of air ($\approx 0.5\text{mm}$) large viscous resistance is achieved. This approach removes the need for additional undesirable resistive materials, allowing resonant absorbers to be produced from a single material, exemplified by the construction of transparent absorbing surfaces (D'Antonio, Cox 2005). Expressions for calculating the impedance for such constructions have been derived from standard resonant absorber theory, extending the applicability and accuracy of performance calculations to cases incorporating sub-millimetre features.

Maa (1998) developed theory for the calculation of impedance for a simple microperforated panel by considering the sound propagation within a short tube. An expression for the impedance of this geometry was taken from the work of Rayleigh (1945) considering an average particle velocity over the tube cross section,

$$Z_p = i\omega \rho \left[ 1 - \frac{2}{k_i \sqrt{-i}} \frac{J_0(k_i \sqrt{-i})}{J_0(k_i \sqrt{-i})} \right]^{-1},$$  \hspace{1cm} \text{Eq 3.24}$$

where $J_0$ and $J_1$ are the Bessel functions of the first kind, of orders 0 and 1, respectively, and $k_i$ (-) is the perforate constant (the ratio of orifice diameter to the thickness of the viscous boundary layer),

$$k_i = \frac{2a}{\sqrt{4\pi \omega \rho}},$$  \hspace{1cm} \text{Eq 3.25}$$
Due to the complicated nature of this equation, approximations were made by Crandall (1926), simplifying its application to porous materials ($k_r < 1$) and perforated plates ($k_r > 10$). Maa (1998) developed a further approximation from this work, for the intermediate region, applicable to perforated panels with sub-millimetre dimensions,

$$Z_p = \frac{32 \eta l}{\varepsilon (2a)^2} k_r + i \frac{\omega \rho l}{\varepsilon} k_m.$$  

Eq 3.26

$k_r (-)$ and $k_m (\cdot)$ are the resistance, and mass reactance coefficients which also contain end corrections accounting for viscous resistance over the panel surfaces, and additional mass reactance of the air movement around the perforations.

$$k_r = \left[ 1 + \frac{k_r^2}{32} \right]^{1/2} + \frac{\sqrt{2}}{32} k_t \frac{2a}{l},$$  

Eq 3.27

$$k_m = 1 + \left[ 1 + \frac{k_t^2}{2} \right]^{-1/2} + 0.85 \frac{2a}{l}.$$  

Eq 3.28

This expression for plate impedance can be combined with Eq 3.21 and Eq 3.22 to give the overall impedance of a microperforated panel absorber, including consideration of the significant aperture resistance achieved through the use of sub-millimetre perforations.

Several other authors have utilised micro resonator dimension principles to produce further high performing acoustic absorbers. Kang (1999) suggested that a microperforated panel produced from a limp membrane material could provide both cavity and membrane resonant absorption, and also that a double layer of microperforated panels each a different distance from a rigid wall, could substantially increase the bandwidth of absorption to produce a broadband absorber.

Mechel (1994) introduced a thin lateral slot between two plates containing concentric resonator orifices, which provided additional resistance. This becomes significant with the addition of a limp resistive foil covering the lower neck to make the neck impedance comparable to that of the slot, encouraging flow within the narrow slot,
thus increasing the viscous energy losses. A similar double orifice configuration is proposed by Randenberg (2000) including a narrow sub-millimetre gap between two perforated plates, but with the orifices offset. The effective neck path incorporates a portion of its length through the narrow slit where high viscous losses provide the increased resistance required for broadband absorption. The major problem encountered with these micro-dimensional designs is the accurate fabrication of sub-millimetre features (Cox, D’Antonio 2004, Maa 1998), which also restricts the material types that can be used (Fuchs 2000).

3.2 Porous Absorbing Material Properties

The important factors affecting porous absorption are explicitly described below and lead to a more informed description of how particular RM properties may influence the absorption of structures fabricated using RM processes.

The porosity, or fraction open volume of the material \( \varepsilon \) (\( \cdot \)) can be expressed in terms of the material bulk density \( \rho_m \) (kg m\(^{-3}\)), and the density of the fibre material \( \rho_f \) (kg m\(^{-3}\)) using the relationship,

\[
\rho_m \approx (1 - \varepsilon)\rho_f. \tag{3.29}
\]

Flow resistivity has already been identified as an important factor, affecting the porous absorption of a material. It is effectively a measure of how easily air can enter and flow through the material. The flow resistivity \( \sigma \) (Pa s m\(^{-2}\)) of a material varies greatly between different porous materials types such as fibres, foams, and granular materials, and is consequently difficult to predict theoretically. Therefore most analytical estimations of flow resistivity are empirically derived, and are specific to a particular material type or composition. Bies and Hansen (1980) developed an expression for the flow resistivity of fibreglass, following extensive empirical testing.

\[
\sigma = 27.3 \left( \frac{\rho_m}{\rho_f} \right)^{1.53} \left( \frac{\eta}{d_f^2} \right), \tag{3.30}
\]
where \( d_f (m) \) is the fibre diameter.

It can be seen that this can be expressed in terms of material porosity,

\[
\sigma = 27.3(1 - \varepsilon)^{1.53} \left( \frac{\eta}{d_f^2} \right).
\]

Similar empirical relationships have been reported by Mechel (2002) considering a consistent arrangement of parallel, equispaced, uniform fibres.

\[
\sigma = \frac{10.56\eta(1 - \varepsilon)^{1.531}}{(d_f/2)^2 \varepsilon^3}, \quad \text{for } 12 \leq d_f \leq 20 \mu m,
\]

and,

\[
\sigma = \frac{6.8\eta(1 - \varepsilon)^{1.296}}{(d_f/2)^2 \varepsilon^3}, \quad \text{for } 24 \leq d_f \leq 60 \mu m.
\]

The case where sound may propagate parallel to the fibres was also considered,

\[
\sigma = \frac{3.94\eta(1 - \varepsilon)^{1.413}[1 + 27(1 - \varepsilon)]}{(d_f/2)^2 \varepsilon}.
\]

The tortuosity (or structural complexity) \( k_s (\cdot) \) of the propagation path through the material is inherently difficult to define theoretically. By definition if the pores are cylindrical, and all aligned in the same direction the tortuosity is simply related to the angle of incident sound \( \theta_i (\text{deg}) \) (Zwikker, Kosten 1949),

\[
k_s = \frac{1}{\cos \theta_i^2}.
\]
For more complex examples the tortuosity can be directly measured by saturating the material with an electrically conducting material. The electrical resistance can then be related to tortuosity. Alternatively the time taken for ultrasonic frequencies to propagate through a material can be used to determine tortuosity.

These properties can be used to infer the acoustic characteristics of the material, namely the characteristic impedance \( Z_c \) (N s m\(^{-3}\)) and the wavenumber \( k \) (m\(^{-1}\)). Delany and Bazely (1970) used extensive empirical measurements on fibrous materials to relate these characteristics to material flow resistivity \( \sigma \).

\[
Z_c = \rho c \left[ 1 + 0.0497 \left( \frac{f}{\sigma} \right)^{-0.754} - i0.0758 \left( \frac{f}{\sigma} \right)^{-0.732} \right], \quad \text{Eq 3.36}
\]

\[
k = \frac{\omega}{c} \left[ 1 + 0.0858 \left( \frac{f}{\sigma} \right)^{-0.7} - i0.169 \left( \frac{f}{\sigma} \right)^{-0.595} \right]. \quad \text{Eq 3.37}
\]

These in turn, can be used to calculate the overall impedance of a finite thickness of material \( t \) (m). For the simple case of a single sample of material backed with a rigid termination, the impedance is,

\[
Z = -iZ_c \cot(kt). \quad \text{Eq 3.38}
\]

From which the absorption coefficient can be determined as previously described in Eq 3.18.

The Delany and Bazely approach is limited in applicability to materials with porosity close to 1, or those with high flow resistivity, and is only valid over a defined frequency range. Recognising these shortcomings, Miki (1990), introduced alternative empirically derived coefficients and degrees to the original power law relationships. While this model still possesses similar limitations, improved prediction of acoustical behaviour outside the range of validity of the Delany and Bazely model has been reported. The improved Miki model is described by:
Further improvement has been suggested by Komatsu (2008) through the use of expressions containing natural logarithms:

\[
Z_e = \rho c \left[ 1 + 0.07 \left( \frac{f}{\sigma} \right)^{-0.632} - i 0.107 \left( \frac{f}{\sigma} \right)^{-0.632} \right], \quad \text{Eq 3.39}
\]

\[
k = \frac{\omega}{c} \left[ 1 + 0.109 \left( \frac{f}{\sigma} \right)^{-0.618} - i 0.160 \left( \frac{f}{\sigma} \right)^{-0.618} \right]. \quad \text{Eq 3.40}
\]

The Komatsu model is more effective than the previous models, particularly outside of the previous limits when predicting the response of high-density fibrous materials where \( f / \sigma < 0.01 \text{ m}^3 \text{ kg}^{-1} \), and low-density ones where \( f / \sigma > 0.1 \text{ m}^3 \text{ kg}^{-1} \). This is accomplished through a reduction in the error margins associated with the prediction of samples with low or high flow resistivity.

The fact that these empirical models are based on the measurements of traditional fibrous materials, limits their application to prediction of those material types. Similar semi-empirical impedance modelling applied to loose granular material was proposed by Attenborough (1992). His model included an additional parameter relating to the change in porosity with depth, as the granular material becomes more compacted.

To ascertain the acoustic properties of more generic porous material configurations, an approach that considers how the material topology affects sound passing through it, including viscous and thermal effects, must be adopted. This approach has been addressed by modelling of the propagation within the pores of a material, through discretisation of the pore shape and structure on the microscopic level.
Biot (1956a, 1956b) initially highlighted that different flow regimes exist for low and high frequencies, and introduced a number of parameters relating to macroscopic pore properties, to describe low and high frequency behaviour. Attenborough (1983), using the assumption that porous materials can be modelled as a stack of parallel capillaries, described the influence of the visco-thermal effects within pores using complex functions relating to the effective changes in air density and compressibility (originally proposed by Zwikker and Kosten (1949)). Basic material characteristics relating to porosity, flow resistivity and tortuosity were used within the model to calculate acoustic impedance, although more complex, frequency dependent pore shape factors are also required.

Johnson, Koplik and Dashen (1987) introduced a characteristic length relating to the surface-to-pore-volume ratio of the pore-solid interface, which was consequently used in an expression to predict the dynamic tortuosity of porous media. The frequency-dependent effective density and bulk modulus of the saturating fluid within porous media were described by Stinson (1991) and Champoux and Allard (1991), through the use of dynamic tortuosity expressions. Allard and Champoux (1992) proposed an alternative generalised model for sound propagation, utilising expressions for effective density and bulk modulus. Characteristic lengths are used within correction functions to account for the viscous and thermal effects, and unlike the shape factors from the Attenborough model, are not frequency dependent, simplifying their derivation.

Stinson and Champoux (1992) produced exact theoretical expressions to describe specific pore cross section shapes. In most practical cases this approach is too complicated to implement; however it has been used to investigate and evaluate the assignment of pore shape factors in the Attenborough and Johnson-Allard-Champoux generalised models. Using models incorporating simple pore cross sections (e.g. circular, square, or triangular), it was found that the Johnson-Allard-Champoux model showed very good agreement with the exact solution.

The complex fluid functions from the Johnson-Allard-Champoux model are the effective density $\rho_{\text{eff}}$ (kg m$^{-3}$) and the effective bulk modulus $K_{\text{eff}}$ (N m$^{-2}$). These are
used to determine the characteristic impedance ($Z_c$) and wavenumber ($k$) (required for calculating $Z$ and consequently $\alpha$),

$$Z_c = \sqrt{K_{\text{eff}} \rho_{\text{eff}}} ,$$  \hspace{1cm} \text{Eq 3.43}

$$k = \omega \sqrt{\frac{\rho_{\text{eff}}}{K_{\text{eff}}}} .$$  \hspace{1cm} \text{Eq 3.44}

The effective density is,

$$\rho_{\text{eff}} = k_{\text{eff}} \rho ,$$  \hspace{1cm} \text{Eq 3.45}

where $k_{\text{eff}}$ is the dynamic tortuosity and is given by

$$k_{\text{eff}} = k_s \left(1 - i\frac{\sigma \varepsilon}{\omega \rho k_s} F(\omega)\right) ,$$  \hspace{1cm} \text{Eq 3.46}

and $F(\omega)$ is the frequency dependent viscosity correction function derived by Biot (1956a, 1956b), and Johnson, Koplik and Dashen (1987) to correct for discrepancies between low and high frequencies

$$F(\omega) = \sqrt{1 + i \frac{4k_s^2 \eta \rho \omega}{\sigma^2 \lambda^2 \varepsilon}} .$$  \hspace{1cm} \text{Eq 3.47}

$\Lambda$ (m) is a weighted characteristic length relating to the ratio of pore volume to surface area.

$$\Lambda = \frac{1}{s_p} \sqrt{\frac{8\eta k_s}{\varepsilon \sigma}} ,$$  \hspace{1cm} \text{Eq 3.48}
where $s_p$ is a constant considering the pore shape: 1 for circular, 1.07 for square, 1.14 for triangular, and 0.78 for slits (Stinson, Champoux 1992). The complementary effective bulk modulus can be calculated from,

$$K_{eff} = \frac{\gamma P_0}{\gamma - (\gamma - 1)\left[1 - i \frac{8\eta}{\Lambda^{12} N_p \rho \omega} F'(\omega)\right]^{-1}}, \quad \text{Eq 3.49}$$

where $P_0$ (N m$^{-2}$) is atmospheric pressure, and $\gamma$ is the ratio of the specific heat capacity at constant pressure $C_p$ (J kg$^{-1}$ K$^{-1}$), to that of constant volume $C_v$ (J kg$^{-1}$ K$^{-1}$). $F'(\omega)$ is a second frequency dependent function derived by Champoux and Allard (1991) relating to thermal interactions within the material:

$$F'(\omega) = \sqrt{1 + \frac{\rho \omega N_p \Lambda^{12}}{16\eta}}. \quad \text{Eq 3.50}$$

$\Lambda'$ is a second characteristic length required due to the fact that pores within materials generally do not have uniform cross sections but vary in diameter. This consequently means the effective density relating to the viscous effects, are more strongly affected by the narrower sections, while the thermal effects associated with the bulk modulus are exaggerated by the wider sections. For pores of uniform section $\Lambda = \Lambda'$ and for other cases, to a first approximation $\Lambda' = 2\Lambda$ (Allard, Champoux 1992). The value $N_p$ is the Prandtl number, relating the sizes of the viscous $\delta_v$ (m) and thermal $\delta_t$ (m) boundary layers,

$$N_p = \left(\frac{\delta_v}{\delta_t}\right)^2, \quad \text{Eq 3.51}$$

with,

$$\delta_v = \sqrt{\frac{2\eta}{\rho \omega}}, \quad \text{Eq 3.52}$$
\[ \delta_i = \frac{2\kappa}{\rho C_p \omega}, \]  
\text{Eq 3.53}

where \( \kappa \) (W m\(^{-1}\) K\(^{-1}\)) is the thermal conductivity for air at constant pressure.

The addition of characteristic length, (or shape factor) functions is required as porous materials are not in reality a series of uniform capillaries as the models assume. The inherent random nature of traditional porous materials (e.g. fibre size, fibre orientation, pore shape, pore size and pore distribution) is a consequence of their method of manufacture, and inhibits the ability to classify and predict the material characteristics by inspection. While the pore shape has been partially considered for simple pore geometries within the presented model, the distribution of different pore sizes is overlooked.

Yamamoto and Turgurt (1988) developed a viscosity correction function to allow for arbitrary distributions in pore size. Attenborough (1993) developed a further model to include effects relating to changes in pore size based on a statistical size distribution. These effects were found to be of more significance than those relating to pore shape. Developing the statistical modelling approach, Horoshenkov (1998) provided a more general explanation using a rational 2 point Padé approximation to predict acoustic properties of materials with log normally distributed pore sizes. Unlike many of the previously mentioned models which rely on empirically derived factors and incorporate complicated calculation methods, this model only requires values of porosity, flow resistivity, tortuosity, and the standard deviation of pore size. All of these variables can be easily determined using non-acoustic, laboratory test methods.

All of the discussed models for porous absorption predict the motion of the air through the material, considering the material to be infinitely stiff. They do not take into account the effect of elastic waves propagating within the solid material itself. Biot (1956a, 1956b) introduced expressions that consider both air-borne and frame-borne propagational waves of both low and high frequency, as well as the effect of dynamic coupling between the fluid and solid components. These effects do not significantly affect the material absorption characteristics in most practical situations.
(e.g. when the material is anchored to a rigid surface), and in most cases are partially compensated for by the empirical coefficients of the theories already described.

3.3 Conclusions

Review of the theories behind resonant and porous acoustic absorbers has identified the importance of geometry in their absorption mechanisms. The orifice and cavity dimensions of resonant absorbers determine the resonant frequency at which absorption occurs. Modification to the resonator orifice can produce acoustic resistance when its dimensions are reduced to sub-millimetre proportions, leading to broadband, fibreless absorbing devices. Cavity modifications however, have not yielded similar advantages, outside of theoretical speculation. The size and shape of the pores within porous absorbing materials influence the viscous and thermal loss mechanisms. Narrow restrictions within a material act to increase the viscous energy conversions into heat, while a large pore surface area encourages losses related to thermal conduction of energy into the material. The nature and distribution of pore size and shape within a material means these effects cannot be controlled or accurately predicted at a discrete level. Instead bulk material properties are used to predict an approximate acoustic response.

The presented absorber theories incorporate assumptions relating to the geometries they describe. Resonator modelling generally assumes arbitrary orifice and cavity shapes, while porous material theory often relies on empirical derivations and topological assumptions to calculate material properties. These assumptions are generally accepted due to the restrictions applied by the manufacturing methods employed: simplistic resonator fabrication techniques cannot viably produce complex geometries; therefore consideration of unconventional forms has been sparse, and predominantly theoretical. The orientation of fibres or the formation of bubbles, are characteristics that introduce indeterminate pore topologies during porous material manufacture and are responsible for the discrepancies in pore shape and size. This leads to complexity and inaccuracy in the prediction of their acoustic properties.
RM introduces the ability to explore resonator configuration and topology on a level not previously viable, potentially introducing an alternative method of broadband absorption without the use of separate porous materials or sub-millimetre dimensions. The measured absorption of RM fabricated resonant cavity absorbers can be compared to the theories presented within this chapter to derive the parameters affected by the changes made to configuration and topology. It has been suggested that RM may also offer a method of producing porous absorbing materials. Control of the material topology and of the pore size and shape would allow a uniform porous structure to be produced, without the uncertainty associated with traditional manufacturing methods. Comparison of measured absorption results with the porous absorbing theories will uncover how the absorption properties of RM porous absorbers differ from traditional materials.

The conformity between measured and predicted absorption results of both absorption methods will ascertain the suitability of the presented models in predicting the performance of novel RM enabled absorber types.
Chapter 4

Resistive Cavity Geometry

The use of RM removes design restrictions to resonant Helmholtz cavity absorbers so their form is no longer restricted to simple fundamental shapes; both the orifice and the cavity can take on arbitrary forms. Modifications to resonator geometry aimed at increasing acoustic resistance may allow absorption bandwidth to be improved, as exemplified by the micro-perforated panel absorber.

This chapter presents an investigation on how the application of RM to resonant cavity absorption can be exploited to improve absorption bandwidth. An analytical model is developed based on resonant cavity absorber theory and is used to develop the investigation. Different geometrical resonator design elements are analysed, and are used to identify areas which could offer absorption bandwidth improvements; from this three lines of investigation are proposed. For each line of investigation, background theory is presented to support the design of the test geometries. The level up to which each cavity modification can be explored is restricted by limitations in the RM fabrication process. In addition to the absorption results, these limitations are also presented. Modifications are only made to the cavity, (not to the orifice size or shape), and the design volume is also kept constant to maintain the same theoretical resonant frequency. Shifts in resonant frequency can then be attributed to the geometric modifications.

To determine the effect of each cavity modification, the absorption of each test sample is compared against the performance of a standard benchmark resonator configuration, which is evaluated in Appendix 2. An estimate of the amount of added resistance attributable to each modification is given, based on the resonator Q values determined through inspection of the recorded absorption data.
4.1 Resonator Geometry Investigation

It has been suggested that changes to the geometric design of a resonant cavity absorber could provide a source of added resistance. This has been exemplified by the use of microperforations and the theoretical exploration of prefractal cavity shapes by Sapoval (1997). With the exception of these examples, geometrical changes to the resonator cavity and neck have been simplistic, and not capable of achieving absorption bandwidth improvements. The principle aim of this work is to achieve sufficient resistance through the exploitation of the layer based fabrication benefits offered by RM, without the use of separate materials or the use of sub-millimetre features.

The resonator model proposed by Maa (1998) described in Eq 3.26 has been used to determine the sensitivity of varying certain resonator parameters in order to gain insight into the effect of changing different elements of a resonator structure. This model was chosen since it considers the additional viscous losses associated with micro orifice dimensions. To ascertain the effect of varying a single parameter, the characteristics of the absorption curves for different parameter values must be compared. The shape of an absorption curve can be described using two values, namely the frequency of resonance (frequency value at the peak absorption), and the frequency width at half the peak absorption value. These are depicted in Figure 4.1. Using these two values, the effect on the resonant frequency, and changes to the sharpness of the curve, caused by changing the resonator geometry, can be determined. Plotting these two values against the parameter being changed will show the effect of that parameter on the absorption curve.
To compare the effects of changing variables relating to the orifice and cavity design, a standard resonator configuration was used. This configuration has low inherent resistance and hence any changes in absorption attributable to physical variations can be identified. The orifices were designed with a 15mm diameter and 15mm length. A moderately low design frequency of 300 Hz was chosen to ensure that sensible cavity depth and perforation percentage values could be maintained.

The orifice diameter \((2a)\) and length \((l)\), along with the perforation separation \((x)\) and cavity depth \((d)\) were varied in isolation, 15mm either side of this standard configuration. The effects that these variances have on the resonant frequency and the half peak \(\alpha\) frequency width are depicted below in Figure 4.2, Figure 4.3 and Figure 4.4. The curves relating to the peak frequency are depicted as plain lines, while those relating to the frequency width at half peak \(\alpha\) are marked with asterisks.
Figure 4.2: Effect of varying orifice dimensions.

Figure 4.3: Effect of varying perforation separation.

Figure 4.2 and Figure 4.3 clearly demonstrate that varying the orifice dimensions above and below 15mm has a significant effect on both the resonant frequency and the absorption bandwidth. As orifice diameter is increased, the peak frequency increases, with the largest rate of change noticeable below 5mm. The frequency width
at half peak $\alpha$ also increases with orifice diameter. As the orifice length is increased the resonant frequency and frequency width at half peak $\alpha$, both decrease; again this is more significant at smaller dimensions.

The effect of varying the spacing of the perforations up to 15mm either side that of the spacing of the standard test geometry, also produces significant changes. It can be seen that both the peak absorption frequency and the half peak $\alpha$ frequency width increase as the separation decreases. As the separation decreases the rate of increase becomes greater.

Figure 4.4 shows that varying the cavity depth (and consequently the volume), has significantly less effect than similar dimensional changes to the orifice. There is a negligible change in half peak $\alpha$ frequency width and a slight trend towards higher peak absorption frequency as the cavity depth is decreased.

These plots indicate that the response of the resonator is more sensitive to dimensional changes to the orifice than to the cavity. The sensitivity increases as the dimensions are reduced. The performance of a resonator design that does not incorporate sub-millimetre dimensions, therefore, would be less susceptible to manufacturing
variances. In addition, geometrical changes to the cavity would be less likely to affect resonator response, allowing complex cavity shapes to be investigated and compared without manufacturing accuracy affecting the results.

The literature suggests that accurate sub-millimetre orifice dimensions are required to produce sufficient resistance to allow the realisation of a fibreless, single material, broadband absorber. However designs incorporating small features are more susceptible to manufacturing inaccuracies. Alternative methods of adding acoustic resistance through changes to resonator geometry using RM could alleviate these manufacturing issues. A single material absorber must rely on specific geometric features or inherent material porosity to achieve the resistance required to produce an absorption curve with a usefully broad profile. While there is research and related products concerning the incorporation specific geometric changes to the orifice, geometric changes to the cavity have not been explored as fully. There are few restrictions to the form that the cavity takes; also cavity changes are less susceptible to manufacturing accuracy. This makes them most suited to an investigation into their geometry.

A key issue is to establish what type of geometric changes to the cavity to make. It has already been suggested that the cavity shape may influence acoustic resistance, with sharp changes in section and greater surface area providing increased viscous losses at the cavity surfaces, the most extreme example of this being the proposed use of fractal cavity shapes. The use of RM to fabricate the resonator cavity offers an easy method to produce complex cavity shapes. An empirical investigation into the benefits of increasing the surface area of the cavity boundary, and the cross sectional irregularity associated with a fractal cavity shape will ascertain if the increases in resistance predicted by Sapoval (1997) are practically achievable.

The addition of certain cavity features aimed specifically at adding resistance is another area of consideration. To add acoustic resistance these features must interact with the air movement within the cavity. Therefore the nature of the air flow characteristics within the cavity must first be considered. If a sound wave of normal incidence strikes the surface of a Helmholtz resonator, the orifice distorts the flow of air in a small region around the perforation before returning to normal, planar flow.
The region of two dimensional complex flow around the orifice returns to normal planar flow after the depth approximately equal to the diameter of the perforation (Cox, D'Antonio 2004). This constriction of the air flow causes an increase in the kinetic energy present in the upper area of the cavity (Ingard 1954).

The flow behavior as it exits the orifice can be affected by the cavity shape. When the cavity is short with a large diameter, a one-dimensional radial wave propagates through the cavity. However for longer, narrower configurations an axial planar wave is produced. Therefore to ensure planar propagation (as many of the models presume), a length to depth ratio over 1 should be maintained. Any changes made to the cavity geometry should also encourage planar propagation.

The addition of resonator resistance using the cavity space is commonly accomplished through the addition of resistive materials to the cavity space, or lining the walls (Selamet et al. 2005). These provide damping to the movement of air within the cavity, slowing down the velocity of propagation. The porosity of the material represents a barrier to impede the motion of air which is further exaggerated by the tortuous nature of the air paths. Also the small pore sizes provide a large surface area, over which air flows as it propagates through the material, providing viscous
resistance. An investigation into the addition of resistance using internal cavity features should look to utilise methods employed within traditional resistive materials:

- Adding geometry that restricts and impedes the natural direction of air flow;
- adding geometry to the cavity that increases viscous resistance to the flow of air within the cavity.

The incorporation of features to impede the natural direction of air flow may take the form of a layer placed in the cavity orthogonal to the direction of air flow, with a low level of porosity achieved through the incorporation of perforations. Increased viscous resistance could be achieved through the incorporation of many additional surfaces in the form of concentric fins arranged in the axial direction.

In summary the three areas of investigation are:

- Use of fractal cavity shapes to increase viscous resistance at the cavity boundary through increased boundary surface area and cross sectional irregularity;
- addition of cavity restrictions in the form of a perforated layer to impede the motion of cavity air;
- incorporation of additional surfaces within the cavity using internal fins to provide a large surface area and increase viscous resistance.

4.2 Resistive Cavity Shape Changes

Existing work regarding the effect of the cavity shape on resonator performance has been largely focused on changes to the resonant frequency. This is most significant as the cavity length to depth ratio becomes extreme. Improved resonator design theory has been developed to include these effects (Alster 1972), allowing resonators to be designed to accurately address certain problematic frequencies. The influence of cavity shape on other resonator properties such as resistance is not as well reported, because the flow velocity within traditional, simple, axis-symmetric cavity shapes is
relatively low and only produces small frictional losses through viscous resistance at the cavity walls. Therefore the effect of cavity geometry is small compared to changes made to the neck, where the flow velocity is much higher. The simple lumped element resonator models reflect this behaviour by considering the enclosed cavity volume only as a compressible medium with known stiffness, and no mass. The effective mass of the air in and around the neck is considered attributable for the inertial reactance, while its interaction with the surrounding walls is responsible for the resistance to provide damping to the resonant effect. To achieve a broadband of absorption requires a high level of resistance, coupled with low reactance. Modifications to the resonator cavity aimed at adding resistance may promote this as they may not add to the mass of the neck air. Cavity modifications may however, change the effective compressibility of the cavity air.

The simplest form of cavity shape is a sphere. This form represents a configuration with no abrupt changes in geometry and with the minimum internal surface area for a given volume. Any deviation from a spherical cavity will increase the surface area of the boundary, increasing the losses arising from heat conduction and viscous dissipation at the cavity surfaces. These loss mechanisms are greater around sharp changes in cavity section where the boundary layers thickness is greater. Further acoustic dissipation may be possible using highly complex cavity shapes as the oscillating pressure in the cavity is diffused thorough complex geometric regions and thermal exchanges occur with the solid resonator material (Boutin, Royer & Auriault 1998). These effects serve to alter the effective compressibility of the cavity air, changing the imaginary reactive part of impedance, and modifying the resonant response.

While these effects may be small for simple shapes, an investigation into complex cavity shapes with large boundary surface area, enabled through the use of RM, has the potential to introduce higher levels of resistance, capable of adding useful damping to resonant absorption, or altering resonator reactance.

The level to which the complexity of the cavity shape and the associated cavity boundary surface area can be modified, is restricted by RM fabrication limitations.
These limitations will restrict the magnitude of the damping ultimately achievable using RM enabled cavity shape changes.

The total surface area of the cavity boundary $C_a$ (m$^2$) is related to the cavity volume $V$, using a parameter known as the hydraulic radius $HR$ (m).

$$HR = \frac{V}{C_a}.$$  \hspace{1cm} \text{Eq 4.1}

To encourage planar propagation within the resonator cavity (as many theoretical models assume), an axis-symmetric cavity shape should be used. In this case the hydraulic radius can be defined by the properties of the cavity cross section using the length of the cavity cross section perimeter $C_l$ (m), and the cavity cross sectional area $S_c$ (m$^2$),

$$HR = \frac{S_c}{C_l}.$$  \hspace{1cm} \text{Eq 4.2}

This parameter has been related to the resistance within porous materials (Fowler, Hertel 1940) and related by association to theoretical studies of fractal cavity shapes (Sapoval, Haeberlé & Russ 1997). In this work it was suggested that the resistance offered by fractal cavities is proportional to the length of the cavity perimeter. The losses at the cavity boundaries after $v$ fractal iterations were theorised as being $2^v$ greater than the original fractal initiator, with a true mathematical fractal producing infinite losses. This prediction challenges classical resonator theory which considers cavity shape to be resistively insignificant. RM introduces a method of empirically investigating the use of fractal cavity shapes, to ascertain if a realistically fabricated fractal cavity is capable of adding sufficient resistance to improve absorption bandwidth.
4.2.1 Design of Test Geometries

To encourage planar air propagation, and restrict the number of design variables an axis-symmetric two dimensional fractal cavity shape was used. The use of a fractal family based on the Minkowski curve offers a simple design method to double the cavity perimeter length whilst maintaining cavity volume, effectively halving the hydraulic radius after each iteration. It also allows comparison with the theoretical predictions proposed by Sapoval (1997).

The zeroth fractal iteration takes the shape of the fractal initiator which in this case is a simple square. The next iteration is produced by substituting each edge with the fractal generator which takes the form of an 8 segment stepped line (Figure 4.6).

Further fractal iterations were produced by substituting each edge of the previous iteration with the 8 segment generator. This produces the following family of geometries:

Figure 4.6: Fractal initiator and generator.
The stepped fractal generator produces fractal iterations with identical cavity cross section areas. This maintains a similar cavity volume throughout all the samples to promote resonance to at 300Hz.

The resonator geometries were produced using Selective Laser Sintering (SLS) following successful validation of the standard resonator geometry in Appendix 2. The 3rd iteration fractal with the most complex structure has segments 0.8mm long, which are approaching the minimum feature size that can be fabricated. Consequently for this process and this scale of cavity, an iteration limit of $\nu = 3$ is reached. Similarly to the standard benchmark resonator geometry, the base was not fabricated to allow the unsintered powder to be removed. An aluminium plate was used to terminate each cavity, sealed in place with silicone. The fabricated resonators are shown below in Figure 4.8.
4.2.2 Fabrication Issues and Measured Absorption

The fabrication of these complex cavity shapes exemplifies the geometric freedom possible through the application of RM. The removal of unsintered powder from the cavities was successfully achieved using compressed air to remove powder from the intricate areas. Despite the small feature size of the finest fractal, the detail of the features was well defined.

The measurement of the acoustic absorption properties of each test sample were carried out in accordance with BS EN ISO 10534-2 (British Standards Institute 2001b), using a two microphone transfer function method and a computer data acquisition unit as described in Appendix 1. All four resonators were measured using the same calibration minimising the uncertainty when comparing sample measurements.
The absorption results acquired from the test method provided results at a resolution of 3.125 Hz. The results for each sample were plotted against a logarithmic frequency scale from 125 Hz to 630Hz to focus on the area of low frequency resonance. The graphs for each fractal cavity are shown in Figure 4.9. To visualise the difference offered by the cavity modifications the absorption curve relating to the standard benchmark resonator (see Appendix 2) is also plotted (dotted line).

The values of hydraulic radius $HR$ (m) are depicted on each plot. To compare the resistive effects of each test sample, the bandwidth of absorption when $\alpha$ exceeds 0.4 $W$ (Hz), which is dependent on resistance, is also indicated. Similarly, to compare any reactive effects altering the frequency response, the resonant frequency $F_r$ (Hz) of the measured results, is also shown.

![Graphs showing absorption results](image)

Figure 4.9: Fractal cavity absorption results.

The results of the fractal cavity testing show that only a low level of resistance is achievable, resulting in an insignificant widening of the absorption curve (9.38 Hz)
over that of the standard benchmark resonator. It can be seen that the square cavity has a smaller absorption bandwidth than the cylindrical configuration of the standard benchmark cavity. The magnitude of this discrepancy may be deemed insignificant considering the 3.125 Hz resolution of the absorption measurements, and the uncertainty associated with microphone recalibration between the two tests. The bandwidth increases as the hydraulic radius is decreased but the resonant frequency does not shift more than 3 Hz, and there is no noticeable trend. These small shifts can be attributable to rounding errors as a result the frequency resolution of the absorption measurements.

4.3 Resistive Cavity Perforations

Additional resistance can be achieved through the incorporation of restrictions to the planar movement of air within the cavity, in a similar manner to the resistance provided by porous materials. While viscous effects also contribute towards their acoustic resistance, the importance of fraction open area, or porosity, is fundamental in reducing the flow of air through a porous material. The simplest method of geometric restriction is to introduce a section within the cavity, with significantly less cross section area than that of the cavity. This can be accomplished by using a layer of perforations.

The radiation resistance of an open ended pipe (Eq 3.6) is due to the final layer of fluid at the end of the pipe effectively acting as vibrating piston, radiating sound into a semi-infinite medium. For an orifice in a thin plate, the radiation resistance is twice that of a normal flanged pipe as it can be considered as a short pipe open at both ends (Blackstock 2000). The presence of a restriction within a given cross section gives rise to a concentration of flow through the restriction, with a subsequent increase in kinetic energy (Morse, Ingard 1968). This has the effect of increasing the viscous energy losses near the edges of the hole. These viscous effects have also previously been considered within the derivation of the resonator model (Eq 3.15).
The combination of these resistive effects, configured as a perforated layer is described within the model associated with the micro-perforated panel (Eq 3.26) which also includes consideration of sub-millimetre perforations. Using this model, Figure 4.10a shows the effect of changing perforation radius \( a \) (m) on resistance, and Figure 4.10b depicts the effect of fraction open area \( e \) (-). The standard variables used were: layer thickness \( l = 2\text{mm} \), perforation radius \( a = 1\text{mm} \) and perforation ratio \( e = 0.05 \).

![Figure 4.10: Perforated layer resistance: (a) changing radius (b) changing open area.](image)

The plots indicate that the resistance of a perforated layer increases as orifice radius decreases. This becomes particularly significant as the orifice radius becomes sub-millimetre and approaches the same order of size as the viscous boundary layer thickness. Also the resistance can be seen to increase as the open area decreases, particularly as the fraction open area becomes very low (<0.02). The predicted values of resistance from the model assume that the perforated plate is exposed to free field sound; this is not the case within the enclosed volume of a resonator. Therefore the calculated values cannot be used in the prediction of the inclusion of internal cavity resistance. The plots do, however, suggest that significant resistance could be achievable through the use of internal perforations. This leads to an investigation of incorporating plates with varying perforation configurations, within the cavity of the standard benchmark resonator (Appendix 2), aimed at increasing resistance and improving absorption bandwidth.
The longitudinal compression of the air within the cavity results in the velocity and displacement of the air movement at the top of the cavity being greater than that lower down. Applying restrictions to cavity areas where air velocity is higher may influence the amount of added resistance. Therefore the position of the internal cavity perforations within the cavity is further area of investigation.

To test the effect of this on the addition of internal restrictions it was decided to change the position of the restrictions within the cavity.

4.3.1 Design of Test Geometries

The incorporation of internal perforated layers represents the simplest topological configuration for adding cavity restrictions. While this simple configuration does not utilise the geometric freedom offered by RM, and could be fabricated using traditional manufacturing methods, it represents a logical initiation for an investigation into RM enabled, single material cavity resistance.

Two sets of perforated layers were produced. One set with varying perforation radius and the other with varying fraction open area. To minimise the effect on resonant frequency, the volume of each layer was minimised by restricting the layer thickness of the perforations to 2mm. To promote the natural propagation paths within the cavity, the restrictions were intended to only interact with the area of planar air movement. Each layer was mounted 15mm down from the top of the cavity (equal to 1 orifice diameter), to take advantage of the faster moving air towards the top of the cavity. This is shown in Figure 4.11
The perforation properties of each set of layers were chosen based on trends observed from the previous perforation resistance analysis; however the minimum feature size limits of the SLS process restricts the lowest perforation size to 1mm. To investigate the effect of perforation size four samples were produced with a fixed fraction open area of 0.05, and perforation radii of 0.5mm, 0.75mm, 1mm and 1.5mm. The effects of fraction open area were investigated using four perforated layers, each with a fixed perforation radius of 0.5mm (the smallest within feasible fabrication limits). The fraction open area was varied using values of 0.01, 0.02, 0.05 and 0.1. For each sample the spacing between adjacent perforations $D_p$ (m) was calculated using,

$$D_p = \sqrt{\frac{\pi r^2}{e}}.$$  

Eq 4.3

The fabricated perforated layers with varying perforation radius and fraction open area, are shown below in Figure 4.12(a) and Figure 4.12(b) respectively.
To investigate the effect of cavity position, one perforated layer was mounted at distances of 5mm, 15mm, 25mm, and 35mm from the top of the cavity. A perforation configuration with \( a = 0.75 \text{mm} \) and \( e = 0.05 \) was chosen as an intermediate sample, avoiding the extremes of fabrication feasibility or open area.

The configuration parameters of each internal perforated layer and the corresponding portion of cavity air space below the perforation were used with Eq 3.23 to check that any secondary resonances produced were higher than the primary resonant frequency of the main resonator, and therefore irrelevant within the cavity of the lower frequency resonator. This allows any noticed increases in absorption to be attributable to resistive effects only, and not affected by secondary resonances. The resonant frequencies for each internal perforated layer configuration are shown in Table 4.1.
### Table 4.1: Internal cavity perforated plate resonances.

<table>
<thead>
<tr>
<th>Fraction Open Area (-)</th>
<th>Perforation Radius (mm)</th>
<th>Perforation Depth (mm)</th>
<th>Cavity Depth (mm)</th>
<th>Resonant Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.5</td>
<td>2</td>
<td>58</td>
<td>839</td>
</tr>
<tr>
<td>0.05</td>
<td>0.75</td>
<td>2</td>
<td>58</td>
<td>954</td>
</tr>
<tr>
<td>0.05</td>
<td>0.5</td>
<td>2</td>
<td>58</td>
<td>1004</td>
</tr>
<tr>
<td>0.05</td>
<td>0.75</td>
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<td>881</td>
</tr>
<tr>
<td>0.05</td>
<td>0.75</td>
<td>2</td>
<td>48</td>
<td>1048</td>
</tr>
</tbody>
</table>

4.3.2 Fabrication Issues and Measured Absorption

The fabrication of the perforated layers using the SLS process was not as successful as that of other cavity geometries. While the shape of layer and the spacing between perforations was accurate, their size was not. Unconsolidated powder remained within the perforations even after significant de-powdering effort. To ensure the removal of all powder, and obtain perforation accuracy, each sample had to be reamed by hand. The comparison between reamed and un-reamed samples is shown in Figure 4.13.
Figure 4.13: Perforation fabrication issues: (a) directly fabricated sample and (b) reamed sample.

The absorption results were carried out as before at a resolution of 3.125 Hz and plotted against a logarithmic frequency scale from 125 to 630 Hz. A dotted curve relating to the standard benchmark resonator (with an empty cavity), is also plotted for comparison. The absorption bandwidth when $\alpha$ exceeds 0.4, $\omega$ (Hz), and resonant frequency, $F_r$ (Hz), are also depicted to indicate changes in resistance and reactance. The results relating to perforation radius are shown in Figure 4.14, while those relating to the fraction open area and perforation position are shown in Figure 4.15 and Figure 4.16 respectively.
It can be seen from Figure 4.14 that the inclusion of a perforated layer gives increased resonator resistance over that of an empty cavity. As the size of the perforations decreases, the resistance and the absorption bandwidth increases. The two samples incorporating perforations with sub-millimetre radii produce significantly higher bandwidths. The exponential curve depicted in Figure 4.10 predicted that large increases in resistance could be achieved as perforation radii become sub-millimetre. The absorption results presented here concur with this behaviour. The sample with 0.5mm radius perforations offers the most resistance increasing the bandwidth of absorption by 50 Hz over that of an empty cavity. The change in perforation size does not have a significant effect on the resonant frequency.
The results of changing the fraction open area of the perforated layer depicted in Figure 4.15, suggest that low values of open area (less than 0.05) give the most increase in absorption bandwidth over that of an empty cavity. The lowest fraction open area sample (0.01) provides the greatest increase of all the tested configurations, improving the bandwidth of absorption by 100Hz. This large increase is consistent with the trend noticeable in Figure 4.10(b), predicted by the theoretical resistance model. There is also a shift in resonant frequency as the fraction open area decreases, which becomes particularly noticeable with the two samples of lowest open area. This indicates that the fraction open area also controls an element of mass reactance.
Figure 4.16: Internal perforation position absorption results ($a = 0.75\text{mm}, c = 0.05$).

The effect of cavity position shown in Figure 4.16 indicates that the application of restrictions to the lower portion of the cavity produces less resistance, compared to those occupying the upper cavity area. The most resistance achieved is when the restrictions occupy the area of faster, two-dimensional airflow, 5mm below the cavity orifice. In this position the application of a perforated layer with 0.75mm radius perforations, and a fraction open area of 0.05, increases the bandwidth of absorption by 50Hz. This is 6Hz greater than the same sample situated at the start of planar air movement (15mm down). The resonant frequency decreases as the restrictions are situated higher up the cavity, with the most noticeable shifts produced by the two highest positions.

From the testing relating to the addition of cavity restrictions, the following assumptions can be made: smaller restrictions produce higher levels of resistance, particularly when the radius approaches sub-millimetre size. An increased resistive trend can also be achieved by lowering the fraction open area of the restrictions, and
by locating restrictions within the upper area of the cavity to interact with the faster moving air. A shift in resonant frequency occurs when the fraction open area is lowered, or the restrictions are moved closer to the resonator orifice, indicating these parameters effect mass reactance as well as resistance. The most significant bandwidth improvements were noticed by changing the fraction open area. The extreme of this test produced a large amount of resistance, and consequently led to an increase in the absorption bandwidth when $\alpha$ exceeds 0.4, almost four times that of a standard, empty cavity.

4.4 Resistive Cavity Fins

The investigation into increasing resonator resistance through the addition of cavity features indicates that adding surfaces within the cavity to increase the surface area that the oscillating air within the cavity passes over may lead to increased viscous resistance. The direction of air movement within the cavity is predominantly planar (with the exception of the air close to the orifice). To ensure that resonator flow characteristics are fundamentally similar to a standard resonator, and only viscous effects are considered, additions in surface area should encourage the natural direction of propagation. These requirements lead to an investigation of incorporating concentric cavity fins, occupying the planar flow section of the resonator cavity only.

The particle velocity through a pipe or channel is not constant throughout its cross section due to the viscous nature of air. The particles in the mainstream area will oscillate back and forth in response to an applied sound wave, however those adjacent to the channel walls will adhere to the surface and consequently have a velocity of zero. The motion of the air between these two extremes causes energy loss due to frictional shear viscosity, and thermal conduction. The minimum distance from a surface where thermal and viscous modes can be considered negligible are known as the acoustic viscous boundary layer ($\delta_v$), and the acoustic thermal boundary layer ($\delta_t$),
where \( N_p \) is the Prandtl number which relates viscosity to heat conduction. For air at 20°C and 1 atmosphere, \( N_p = 0.771 \) (Blackstock 2000).

The effective density \( \rho_{\text{eff}} \), of the oscillating cavity air describes the inertial and viscous interactions with the surrounding solid structure (Allard, Champoux 1992). At low frequencies viscous forces dominate, but become small compared to inertial forces at higher frequencies (Olny, Boutin 2003). The viscous forces increase as the distance between adjacent channel walls, through which air is oscillating, decreases.

The effective bulk modulus of the cavity air \( K_{\text{eff}} \), relates the divergence of molecular displacement in the air, to the variation in pressure, and is governed by thermal heat exchanges (Allard, Champoux 1992). These exchanges impart a more significant effect in areas with greater surface area, and also at higher frequencies when \( K_{\text{eff}} \) tends towards its adiabatic value (Olny, Boutin 2003).

The flow velocity of air oscillating in a Helmholtz resonator plays a more important part than the changes in pressure as far as dissipation is concerned. Therefore the thermal losses associated with pressure changes are often disregarded as they are negligible by comparison to viscous losses (Ingard 1953).

Figure 4.17 below shows that \( \delta_v \) is very small, but increases significantly (>0.2mm) towards the lower frequencies. This layer of slower moving air, while small, introduces resistance to the motion of air travelling over a surface.
The viscous resistance \( R_v \) (N s m\(^{-3}\)) of air moving over an infinite plane is given as:

\[
R_v = \frac{1}{2} \sqrt{2\eta \rho \omega}.
\]

Eq 4.6

This energy dissipation is predominant in the resistance associated with the neck of undamped Helmholtz resonators. It is used within the analytical description of Helmholtz resonator impedance (Eq 3.17) to calculate the total viscous resistance, \( R_v \), within the neck,

\[
R_v = \sqrt{2\eta \rho \omega \frac{1}{a}}(t + 2a).
\]

Eq 4.7

Figure 4.18(a) and Figure 4.18(b) show how viscous resistance changes with orifice radius and length respectively.
These plots show that as the neck length (and consequently the surface area) increases, the viscous resistance also increases. The same effect can be noticed as the neck radius decreases; however, a very large increase can be noticed when the neck radius starts to approach the viscous boundary layer thickness. Absorbers utilising micro perforations or dimensions utilise this effect to achieve single material broadband resonant absorption.

Applying viscous resistance to the cavity of a resonator should also aim to utilise these effects. The incorporation of concentric fins to the cavity effectively increases the surface area within the cavity and simultaneously provides narrow channels for the cavity air to propagate through. To maximise the surface area available, as much of the cavity volume as possible should be occupied; however, to ensure that interaction only occurs with the areas of planar propagation they should be absent from the upper cavity area. The fin thickness should also be minimal to minimise the volume occupied per fin, and maximise the number of fins that can fit within a given space. With the height and thickness of the fins constrained, the one free variable to
investigate is the spacing between adjacent fins. This basic dimensional change affects both the width of the propagation path and the amount of surface area present, thus addressing both variables associated with viscous resistance.

4.4.1 Design of Test Geometries

Four resonator test geometries were designed, each based around the standard benchmark resonator design (see Appendix 2). The neck shape and dimensions were identical to the standard design, however to maintain a volume of $2.198 \times 10^{-4} \text{ m}^3$ the volume occupied by the fins had to be taken into account and compensated for by increasing the diameter of the cavity. Radial enlargement was chosen to keep the overall sample depth constant. The volume analysis was carried out at the Computer Aided Design (CAD) modelling stage of each geometry, using solid modelling volumetric analysis tools.

A fin thickness and minimum fin spacing of 1mm were chosen to ensure feasible feature size, adequate fin strength and sufficient space for powder removal. These design parameters were chosen following consideration of process restrictions relating to minimum feature size, accuracy and the powder removal requirement of the Selective Laser Sintering process.

Based on these restrictions, fin spacings of 1mm, 1.5mm, 2mm and 3 mm were chosen and are shown in Figure 4.19. The fin height was set at 60mm, to ensure a gap of one orifice diameter (15mm), was left at the top of the cavity so the fins only interact with planar air propagation. The final cavity diameters are shown in Table 4.2, along with the diameter of the standard benchmark resonator for comparison.
Table 4.2: Cavity diameters.

<table>
<thead>
<tr>
<th>Fin Spacing (mm)</th>
<th>Cavity Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77.73</td>
</tr>
<tr>
<td>1.5</td>
<td>72.79</td>
</tr>
<tr>
<td>2</td>
<td>69.95</td>
</tr>
<tr>
<td>3</td>
<td>67.45</td>
</tr>
<tr>
<td>Standard Resonator</td>
<td>61.08</td>
</tr>
</tbody>
</table>

Each test piece was produced in two halves with the fins and the base of the resonator forming one half to allow easy powder removal from the cavity and between the fins.

![Figure 4.19: Internal cavity fins designs: (a) Assembled internal fins CAD sectional view (b) fabricated fins.](image)

4.4.2 Fabrication Issues and Measured Absorption

The fabrication of the internal fin test geometries was successfully achieved using the SLS process. Removal of unsintered powder from between the fins was relatively easy with the exception of the smallest 1mm spaced component. The fine spacing made access to the unsintered powder towards the bottom of the fins difficult, and complete removal of all powder could not be guaranteed. Resistive features of the
scale of 1mm or below are therefore beyond the level of feasible fabrication using current SLS based processes. Alternative deposition or liquid based processes may alleviate powder removal issues, although the requirement for separate support structures and problems associated with trapped volumes may introduce further fabrication issues.

The measurements of the acoustic absorption properties of each test sample were carried out using the same two microphone impedance tube method as the previous tests. The results for each sample are plotted against a logarithmic frequency scale from 125 Hz to 630Hz to focus on the area of the low frequency resonance. The curve relating to the standard benchmark resonator is once again plotted against each result for comparison, as a dotted line. The values of absorption bandwidth when $\alpha$ exceeds 0.4, $W$ (Hz), and resonant frequency $F_r$ (Hz), are also depicted to indicate resistive and reactive changes. The graphs for the four tests are shown in Figure 4.20.

Figure 4.20: Internal cavity fins absorption results.
The fin absorption results show that the addition of internal fins to the cavity introduces further acoustic resistance, increasing the absorption bandwidth of the resonator. The bandwidth increases as the spacing between the fins is decreased. The finest 1mm spaced fins improves the bandwidth of absorption by 50 Hz over the standard benchmark resonator. There is a trend towards a lowering in resonant frequency as the spacing is decreased. This indicates that the presence of the fins adds a component of mass reactance as well as resistance. However, the frequency shift of the 1mm spaced sample is not consistent with this trend. An explanation for this discrepancy can be related back to the powder removal issues encountered during fabrication. The presence of unwanted material within the cavity would have the effect of reducing cavity volume and consequently increasing resonant frequency. To confirm this theory the weight of each fin section was measured and its volume calculated using a density value\(^{22}\) of 970 kg m\(^{-3}\). These volumes were then compared to the design volume calculated from the CAD solid model. The results are shown in Table 4.3.

<table>
<thead>
<tr>
<th>Fin Spacing (mm)</th>
<th>Resonant Frequency Shift (Hz)</th>
<th>Fin Section Weight (g)</th>
<th>Volume (mm(^3))</th>
<th>Design Volume (mm(^3))</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-6</td>
<td>181.18</td>
<td>186784</td>
<td>174331</td>
<td>+7.1</td>
</tr>
<tr>
<td>1.5</td>
<td>-19</td>
<td>118.75</td>
<td>122423</td>
<td>130600</td>
<td>-6.3</td>
</tr>
<tr>
<td>2</td>
<td>-13</td>
<td>93.97</td>
<td>96876</td>
<td>106661</td>
<td>-9.2</td>
</tr>
<tr>
<td>3</td>
<td>-9</td>
<td>78.92</td>
<td>81361</td>
<td>86491</td>
<td>-5.9</td>
</tr>
</tbody>
</table>

While the three larger spaced fin configurations all possess similar negative volumetric discrepancies (within 3.3%), the 1mm spaced fin section has an average volumetric increase of 14.2% over the other parts. If this discrepancy is taken into account, the resonator open cavity volume decreases from the design volume of 219772mm\(^3\) to 188564mm\(^3\) which equates to a theoretical design frequency of 323Hz. Subtracting this frequency shift of 23Hz from the measured value, puts the resonant frequency of

\(^{22}\) SLS density values may be inaccurate as part density can vary between different build positions within the powder bed, and laser energy density (Tontowi, Childs 2001).
the 1mm sample at 271Hz, a shift of -29Hz. This represents an estimation of the resonant frequency had all powder been successfully removed, and is in line with the decreasing resonant frequency trend of the other internal fin test samples. To ensure that configurations such as these conform to expected trends, it is important that all excess powder is removed so the fabricated part accurately reflects the intended design.

4.4.3 Upper Cavity Fin Development

The investigation into cavity restrictions highlighted the greater bandwidth increases that could be achieved through the incorporation of resistive features in the upper cavity area. To test this hypothesis using cavity fins, a structure was developed with the aim of adding viscous resistance whilst encouraging the natural flow paths within the resonator. Like the concentric fin design, the development of an internal fin structure to act in the upper cavity area must also promote natural propagation paths, to encourage the process of resonance. The flow of air as it exits the orifice was previously depicted in Figure 4.5, and propagates both radially and axially up to a depth equivalent to the orifice diameter, after which only planar axial propagation occurs (Ingard 1954, Fig. 1). The design of a fin structure to follow this complex propagation behaviour must conform to these expected flow contours. Consequently to maintain constant fin spacing from the orifice to the entire cavity diameter, the number of fins must increase throughout the upper cavity area.

A conformal fin structure was designed to be retrofitted to the upper cavity area of the standard benchmark resonator described in Appendix 2. As the structure is to occupy only the upper 15mm, the change in cavity volume is relatively small. The associated increase in resonant frequency due to the reduction in cavity volume can be taken into consideration when evaluating any frequency shifts in the measured absorption curve. The spacing between the fins was set at 1.5mm following the previous internal fin results and the manufacturing complications encountered with smaller spacings. The thickness of the fins remained consistent with the other tests at 1mm. The 15mm orifice only allows enough space for three, 1.5mm circular openings. The three corresponding fin sections were then extended along expected flow paths whilst
maintaining a distance of 1.5mm from the cavity walls, and terminating equispaced at
the start of planar air propagation. The gaps between the three initial fins were then
filled with intermediate fins, which followed the contours of the existing fins and
were terminated when the spacing from adjacent fins decreased below 1.5mm. Five
ribs were added, intersecting the fins to hold them together and maintain their
location. They also extend beyond the outer fin section to locate the structure against
the cavity wall. The design is shown in Figure 4.21.

![Fabricated part and CAD cross section](image)

Figure 4.21: Conformal upper cavity fins: (a) fabricated part and CAD cross section
(b) CAD cross section, mounted.

SLS was used to fabricate the structure. Despite the narrow 1.5mm channels, the
removal of powder from the inaccessible areas following fabrication was
accomplished using flexible wire and compressed air. The absorption results of the
assembled structure are presented in Figure 4.22. A dotted curve representing the
'empty' standard benchmark resonator is shown for comparison. The values of
absorption bandwidth when \( a \) exceeds 0.4, \( W \) (Hz), and resonant frequency \( F_r \) (Hz),
are also depicted.
The absorption results show that the upper cavity fins offer a larger absorption bandwidth than the previously tested fin configurations occupying the lower portion of the cavity, despite having a spacing of only 1.5mm and only occupying 20% of the cavity volume. The increase in absorption bandwidth over that of the standard empty cavity is 55Hz. There is a significant decrease in resonant frequency (44Hz), which again suggests the fins contribute a mass reactance as well as providing resistance. The addition of the fins decreases the cavity volume by $0.1699 \times 10^{-4}$ m$^3$ which would theoretically increase the resonant frequency by 13Hz. Taking this into account the actual frequency shift attributable to the presence of the fins is 57 Hz.

4.5 Discussion

Three different approaches have been identified, all of which are aimed at increasing resonator resistance through modifications to the cavity geometry. These approaches have addressed the effect of cavity shape, cavity restrictions and increased surface area. All the samples were produced using the SLS process due to its suitability at producing complex internal features without separate support structures. The fabrication of the proposed geometries was achieved with varying success. The very complex, open structures offered by the fractal cavity shapes were highly successful,
with excellent feature definition and accuracy. Similarly the definition of the internal fin structures was generally good; however differences between the measured and calculated volumes indicates solid volume discrepancies, potentially suggesting inaccuracy in fin size. In addition the fine spacing of the largest surface area sample made powder removal difficult, reducing the open volume of the cavity. This results in a fin spacing of 1.5mm being identified as the minimum that can be feasibly fabricated. The fabrication of the perforated restrictions was not suited to this process. Every sample required extensive post processing to achieve accurate perforation size. Part of the problem was due to unconsolidated, or part consolidated powder blocking each perforation. This problem could be resolved through the use of an alternative process incorporating a low viscosity liquid based build material such as Stereolithography, or the use of a deposition based method without build material surrounding the part, such as Fused Deposition Modelling. The accuracy of very fine sub-millimetre perforations (providing the most resistance), may still prove problematic as they approach the limit of most currently available RM processes.

All the approaches demonstrate an ability to control the amount of added resistance through changes to simple geometric parameters. The magnitude of added resistance varied between the three approaches and is compared in Figure 4.23. The dotted line represents the absorption bandwidth of the standard empty cavity (37.5 Hz), determined in Appendix 2. The test references A to E relate to each test series, while the different bars within each group represent the specimens within each test. The details of these are summarised in Table 4.4.
Figure 4.23: Comparison of bandwidth improvements.

Table 4.4: Test specimen reference table.

<table>
<thead>
<tr>
<th>Test Reference Group</th>
<th>Related Cavity Geometry Test</th>
<th>Specimen Reference Within Group (left to right)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>Fractal Cavity Iteration, ( n ) (-)</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>Perforation Radius, ( P_r ) (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>Perforations - Fraction Open Area, ( P_f ) (-)</td>
<td>0.1</td>
</tr>
<tr>
<td>D</td>
<td>Perforation Position, ( P_p ) (mm)</td>
<td>35</td>
</tr>
<tr>
<td>E</td>
<td>Cavity Fin Spacing (mm)</td>
<td>3</td>
</tr>
</tbody>
</table>

Besides the absolute improvement in absorption bandwidth, the absorption curves for each test sample can also be used to estimate the quality factor, \( Q (\cdot) \),

\[
Q = \frac{\omega_q}{\Delta \omega}, \quad \text{Eq} \ 4.8
\]
where \( \omega_r \) (rad s\(^{-1}\)) is the resonant angular frequency, and \( \Delta\omega \) (rad s\(^{-1}\)) is the resonant frequency width between points where the response is \( 1/\sqrt{2} \) of the maximum (Moloney, Hatten 2001). The quality factor is a measure of how sharp the absorption curve is, and can be related to the amount of resistance using (Kinsler et al. 1982):

\[
Q = \frac{\omega_m}{R_x + R_v + R}, \tag{4.9}
\]

where the values of radiation and viscous resistance \((R_x \text{ and } R_v)\) take their specific values, and \( R \) (Pa s \(n\) m\(^{-1}\)) is the additional resistance attributable to the geometric changes. The \( Q \) values for each absorption curve were calculated from the recorded data and are given below in Table 4.5. The additional resistance, \( R \), is calculated by subtracting the total resistance of the standard benchmark resonator from each additional resistance value derived from the test absorption curves.
Table 4.5: Q values and additional resistance.

<table>
<thead>
<tr>
<th>Cavity Test specimen</th>
<th>$\omega_r$ (Rad s$^{-1}$)</th>
<th>$\Delta \omega$ (Rad s$^{-1}$)</th>
<th>$Q$ (-)</th>
<th>Additional Resistance, $R$ (Pa s m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard benchmark resonator</td>
<td>1884.96</td>
<td>235.62</td>
<td>8.00</td>
<td>0.00</td>
</tr>
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<td>Fractal Cavity Iteration, $\nu$ (-)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>0</td>
<td>1884.96</td>
<td>235.62</td>
<td>8.00</td>
<td>0.00</td>
</tr>
<tr>
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<td>1866.11</td>
<td>235.62</td>
<td>7.92</td>
<td>0.00</td>
</tr>
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<tr>
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<td>1884.96</td>
<td>255.25</td>
<td>7.38</td>
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<tr>
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<td></td>
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<td>6.72</td>
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<td>5.82</td>
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<td>141.43</td>
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<td>1652.48</td>
<td>471.24</td>
<td>3.51</td>
<td>339.43</td>
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<td>Perforation Position, $P_p$ (mm)</td>
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<td>Cavity Fin Spacing (mm)</td>
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<td>1847.26</td>
<td>314.16</td>
<td>5.88</td>
<td>113.14</td>
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<tr>
<td>Upper Cavity Fins</td>
<td>1608.50</td>
<td>274.89</td>
<td>5.85</td>
<td>56.57</td>
</tr>
</tbody>
</table>

The resolution of the recorded absorption data restricts the ability to accurately derive the Q values, and subsequently the added resistance. Furthermore the determination of the Q value through inspection alone can underestimate values (up to 30%) (Biwa et al. 2005, Moloney, Hatten 2001).
Comparing the resistances derived from the Q values, with those derived through comparison with analytical models in Section 6.1.1, it can be seen that Q derived added resistances are generally an underestimation. Also there is variability in the values for those samples where the cavity modifications cause a shift in resonant frequency. This may be attributable to the assumption of a simple resonator model, assumed in Eq 4.9, which does not take into account any unforeseen reactance changes.

It can be seen from the bandwidth and derived Q values that increasing the cavity hydraulic radius through the use of fractal shaped cavities provided the least amount of additional resistance of the three experiments. However an increasing bandwidth trend indicates that significant resistance could be achieved if higher fractal iterations were possible. This could be accomplished through the use of larger scale cavities, allowing a higher number of fractal iterations before the minimum feature size is reached.

The inclusion of cavity restrictions in the form of a perforated layer provided the greatest absorption bandwidth increases; also changes in the fraction open area produced the greatest variance in bandwidth values. The use of perforations allows simple tailoring of the amount of resistance through changes in perforation size, fraction open area, and layer position. The fabrication problems encountered could possibly be overcome through design changes. The use of alternative perforation shapes such as slits may be more suited to SLS fabrication. Also a study comparing intended and fabricated perforation sizes could be used to accurately predict fabricated dimensions, removing the need to ream each hole to size.

The inclusion of internal fins provided moderate bandwidth improvements, but produced less fabrication issues than encountered with the perforations. This makes the incorporation of fins the most successful approach overall.

The inclusion of resistive features to the upper cavity area provides greater resistance than similar features situated lower down, within the region of planar air movement. The resistance of both the upper cavity perforated layer sample, and the conformal fin
sample was increased by forcing their interaction with the faster two dimensional air flow, closer to the cavity orifice.

While the bandwidth of the upper cavity conformal fin test sample is greater than the other fin configurations, the overall performance is still less that that achieved by the incorporation of the two lowest fraction open area perforated layers. The increase in bandwidth at 0.4α is only half that achieved by the 0.5mm radius sample with 0.01 fraction open area. Another factor limiting the suitability of the conformal fin structure for broadband absorption is its reliance on a large orifice size. Introducing fin openings to the orifice, whilst maintaining minimum fin size and separation dimensions (1mm and 1.5mm), gives a minimum orifice diameter of 6.5mm if only a single fin is present. However this requires the fabrication of a 1.5mm central perforation, which as previously discovered would present complications regarding accuracy and powder removal.

From inspection of the changes in resonant frequency it can be seen that the most significant changes to reactance were achieved through the addition of internal perforations with low fraction open area, and when features were added to the upper cavity area. This suggests that the upper cavity fins and the perforations placed 5mm from the orifice interact with the hemispherical mass of air emanating from the orifice, and consequently influence the effective mass and inertia of the neck air.
Chapter 5

RM of Porous Structures

The layer based selective deposition or solidification methods of some RM processes may be capable of producing porous topologies. While this is undesirable in the fabrication of vessels or enclosed volumes, it may present a method of producing a structure with controlled porosity. Porosity incorporated within RM produced components could be used to add high frequency absorption to a fabricated part. Alternatively porosity could be utilised to add acoustic resistance, potentially introducing a method of improving resonant absorber bandwidth, leading to broadband, single material absorption.

The minimum feature size, achievable accuracy and support removal issues of the majority of currently available process, is not sufficient to be able to intentionally fabricate fine porous structures designed through CAD. However, discrete deposition / solidification, and layer based stacking of solid material, may allow porous topologies to be produced and controlled via the inherent method of the fabrication process itself.

To ascertain the feasibility of producing these acoustic properties from RM processes, the absorption properties of various RM material samples should be determined. Alternative build strategies should also be tested where possible to ascertain the potential of controlling porosity within the fabrication process itself. To determine the resistive potential of any porosity discovered, samples should be mounted over a basic resonator configuration to ascertain any added resistance to the resonant effect. This chapter presents an investigation ascertaining the feasibility of producing these acoustic properties through different RM approaches.
5.1 Absorption Using RM Porosity

To achieve porous absorption from parts produced using RM processes, an air saturated, open porous topology is required. Processes that solidify a bulk material can only achieve this if the excess material can be successfully removed from between pores, or if the bulk material possesses inherent porosity. Processes that deposit discrete areas of material are capable of creating air spaces between the regions of deposited material, potentially allowing a porous topology to be fabricated through alterations to the process parameters. These present three possible methods of introducing porosity using RM and form the basis of an investigation into porous absorption.

The proposed methods of producing porous topologies require the selection of suitable RM processes. From the review of RM in Section 2.3 three processes were chosen based on their fabrication characteristics: The liquid based Stereolithography (SLA) method is a selective solidification RM process capable of fabricating fine features. Excess build material can be drained out of unsolidified areas, revealing an air saturated structure. The Z Corp 3D printing process is a selective solidification RM approach which relies on inherent material porosity to add infiltrants during post processing. Fused Deposition Modelling (FDM) is a selective deposition method which lays fine extruded filaments of material. Increasing the spacing between adjacent filaments could lead to the fabrication of open porous topologies.

The production of an open porous topology using the fabrication accuracy of SLA can be achieved using the QuickCast 2.0 internal build strategy. This strategy was developed to produce collapsible parts suitable for use as a sacrificial pattern for the investment casting of metals (Hague, D'Costa & Dickens 2001). It consists of a solid outer shell and a hexagonal internal porous network, and relieves modelling issues and file size problems associated with fine intricate structures. The pore size is in the order of 1mm and the fabricated topology is shown in Figure 5.1a. To ensure any noticed absorptive effects are attributable to the fabricated porous topology, a set of non porous material samples were also produced for comparison, using the standard SLA build strategy.
The porous network was exposed by removing the top solid face using a lathe, although stopping the build before the top face was fabricated was also suggested as an alternative automatic solution. The fabricated parts needed support structures to be built on one side, which required subsequent removal. The solid, standard built sample was tested with the smooth face (which did not have supports) facing into the impedance tube.

Inherent RM material porosity was investigated through the fabrication of uninfiltrated Z Corp test samples. This is the state in which the parts emerge directly after fabrication. The porosity of these ‘green’ parts is caused by air voids between the particles of the build material. These voids are usually infiltrated with secondary low viscosity materials, which solidify to increase the strength of the part. For comparison infiltrated test samples were also produced with Z Bond and Paraplast infiltrants.

To investigate the acoustic absorption of porous topologies produced by increasing the spacing between selectively deposited filaments, the fraction open area, or porosity, of samples produced using FDM were varied through alterations to the raster parameters of each layer. The process software allows the spacing between adjacent

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23 Taken from R. Hague (2001).
rasters, and the filament thickness to be varied. This allows the fabrication of a non-
random 3D porous structure. This approach has previously been utilised for the
development of biomedical tissue engineering, including bone scaffold structures
(Leong, Cheah & Chua 2003, Too 2002). To gain a measure of the amount of porosity
through such a porous FDM structure, based on the process parameters alone, the
porosity was calculated using the raster width $RW$ (m), and raster spacing $RS$ (m),
depicted in Figure 5.2.

![Raster parameters](image)

Figure 5.2: FDM raster parameters.

Figure 5.2 shows two fabricated layers. For one single layer the fraction open area $\varepsilon$ (-),

$$\varepsilon = \left[ \frac{RS}{RS + RW} \right].$$  \hspace{1cm} Eq 5.1

The porosity percentage can be calculated by multiplying by 100. To obtain the
combined porosity of the entire hatch pattern, the open area of must be multiplied by
the fraction open area of the second, orthogonal layer. As the parameters are the same
the complete expression becomes,

$$\varepsilon = \left[ \frac{RS}{RS + RW} \right]^2.$$

Samples 20mm thick with 5%, 10%, 25% and 50% porosity were produced using
calculations based on this formula. Samples were also produced using the default
build process parameters with no raster spacing for comparison. The build parameters
used are detailed below in Table 5.1 and a measure of porosity is also given, based on the weight of each sample compared against the standard build strategy sample. The fabricated parts are shown in Figure 5.3.

Table 5.1: Porous FDM process parameters.

<table>
<thead>
<tr>
<th>FDM Porosity, $e$ (%)</th>
<th>Raster Width, $RW$ (mm)</th>
<th>Raster Spacing, $RS$ (mm)</th>
<th>Measured Porosity, $e$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Build</td>
<td>0.508</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.508</td>
<td>0.146</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>0.508</td>
<td>0.235</td>
<td>29</td>
</tr>
<tr>
<td>25</td>
<td>0.508</td>
<td>0.508</td>
<td>49</td>
</tr>
<tr>
<td>50</td>
<td>0.508</td>
<td>1.23</td>
<td>70</td>
</tr>
</tbody>
</table>

It can be seen that porosity value based on sample weight is much higher than the theoretical calculation. The simple porosity formula only considers the available process parameters and considers the hatch pattern to be two dimensional. In reality each layer is offset by a distance equal to the layer thickness of the process, thus producing voids under areas where the two layers of rasters do not cross. It also considers each filament to be of uniform section, whereas in reality the extruded section is more circular or elliptical. These simplifications are suitable for the purposes of providing a variable parameter for an empirical investigation, but would have to be revised for more detailed porous material characterisation.
Figure 5.3: FDM porous samples: (a) 5% (b) 10% (c) 25% (d) 50%.

A solid sample was also produced from SLS to ensure that porous absorption is minimal, and confirm that the absorption results from Chapter 4 are produced through resonant absorption alone. The RM porous configurations are summarised in Table 5.2.
Table 5.2: RM porous absorption test samples.

<table>
<thead>
<tr>
<th>Process</th>
<th>Material / Process Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selective Laser Sintering</td>
<td>DuraForm PA: ( (t = 20\text{mm}) )</td>
</tr>
<tr>
<td>Stereo Lithography</td>
<td>DSM Somos Watershed 11120: ( (t = 20\text{mm}) )</td>
</tr>
<tr>
<td></td>
<td>QuickCast 2.0 Build Strategy: ( (t = 20\text{mm}) )</td>
</tr>
<tr>
<td>Z Corp 3D Printing</td>
<td>Virgin ZP130 Material: ( (t = 20\text{mm}) )</td>
</tr>
<tr>
<td></td>
<td>Paraplast X-TRA Wax Infiltrant: ( (t = 20\text{mm}) )</td>
</tr>
<tr>
<td></td>
<td>Z-Bond 101 Infiltrant: ( (t = 20\text{mm}) )</td>
</tr>
<tr>
<td>Fused Deposition Modelling</td>
<td>Polycarbonate Standard Build: ( (t = 20\text{mm}) )</td>
</tr>
<tr>
<td></td>
<td>5% Open Area: ( (e = 0.05, t = 20\text{mm}, d_f = 0.508\text{mm}, k_s = 1, s_p = 1.07) )</td>
</tr>
<tr>
<td></td>
<td>10% Open Area: ( (e = 0.1, t = 20\text{mm}, d_f = 0.508\text{mm}, k_s = 1, s_p = 1.07) )</td>
</tr>
<tr>
<td></td>
<td>25% Open Area: ( (e = 0.25, t = 20\text{mm}, d_f = 0.508\text{mm}, k_s = 1, s_p = 1.07) )</td>
</tr>
<tr>
<td></td>
<td>50% Open Area: ( (e = 0.5, t = 20\text{mm}, d_f = 0.508\text{mm}, k_s = 1, s_p = 1.07) )</td>
</tr>
</tbody>
</table>

The absorption properties of each RM produced, porous structure was obtained using the impedance tube test method described in Appendix 1. To include higher frequency absorption, the smaller diameter impedance tube also had to be used. Consequently two samples for each test were produced, 100mm and 28mm in diameter. The thickness of all the samples was kept constant at 20mm for ease of fabrication and handling, although this thickness limits the lower frequency absorption.

The absorption results from the impedance tube are shown in the plots below. As before, the results were acquired at a resolution of 3.125Hz and plotted on a logarithmic scale. The frequency range covers 250 – 3000 Hz, focusing on the area of mid to high frequency. For each sample the results from the two different sized impedance tubes were combined and averaged to give a single absorption curve within the dB Alpha Test acquisition software. Figure 5.4 depicts the absorption for the fabricated porous topology created using SLA, along with solid SLA and SLS material samples. Figure 5.5 shows the absorption of inherent material porosity using
different Z Corp samples, while Figure 5.6 shows the absorption results of producing porous topologies through modified FDM deposition parameters.

Figure 5.4: SLA Quickcast porous topology, standard SLA and SLS absorption.

Figure 5.5: Material absorption of Z Corp samples.
The combination of absorption data from the two different sized samples can result in discrepancies in the absorption curves at the points where the overlap in readings ceases, and a single data set takes over. This is most noticeable around 500 and 1600Hz and is likely to be due to differences in calibration between the two tubes.

The results show that the highly dense samples (SLA, SLS, Infiltrated Z Corp and FDM standard build) all exhibit minimal absorptive properties. The Quickcast SLA sample possesses a fabricated structured porous topology, produced using selective solidification of a bulk material. The pore size of this topology was too large to provide significant resistance to air movement through the structure; consequently the measured porous absorption effects were negligible. The inherent material porosity of the uninfiltreted Z Corp sample possesses slightly higher absorption than the infiltrated parts, due to its higher porosity; however the overall level of absorption is still largely insignificant. The porous FDM parts, produced through the modification of the deposition process parameters, produced a fine porous structure, and bear a much closer resemblance to traditional porous absorptive materials, such as mineral wool. There are however, noticeable differences: The level of porosity is much lower (most fibrous porous absorbers are over 90% porous), the fibre diameter is much higher (around 500 µm), and the uniformity of the structure is much higher. These material configurations provided the most absorption. As the raster spacing was decreased the
porosity and pore size were decreased, producing a higher flow resistivity, and consequently increasing the porous absorption.

Following these results two further FDM samples were produced using a reduced fibre diameter $d_f = 0.305\text{mm}$, the minimum size possible by varying the FDM process parameters. Two porosity values were fabricated, 10% and 50% allowing comparison with two of the existing $d_f = 0.508\text{mm}$ samples. The raster spacing values used were 0.141 and 0.737 mm respectively. The use of a thinner fibre diameter increases the surface area within the structure, and also decreases the effective pore size. The results of absorption of these thinner fibre diameter samples are presented below in Figure 5.7, along with the corresponding previous results of the same porosity, but incorporating a 0.508mm raster width.

![Figure 5.7: Absorption of FDM variable deposition samples with 0.305mm raster width.](image)

It can be seen that the samples with the lower raster width give improved absorption results over the larger width samples of the same porosity. This can be attributed to the increased surface area within the material topology. The absorption of the 10% porosity sample with the thin raster width even gives improved absorption over the previous 5% porosity sample.
Of the three approaches aimed at achieving porous absorption through RM, varying
the spacing between the depositions of material extruded using the FDM process was
by far the most successful. The low resistance of the porous topology created using
SLA was unsuited to porous absorption, while the material porosity inherent within
uninfiltrated Z Corp samples was too low to achieve acoustic absorption. The use of
the FDM process has proven its ability not only to produce porous absorbing
topologies, but also to modify the absorptive properties through modifications to the
process parameters.

5.2 Resistance Using RM Porosity

The porous absorbing topologies fabricated using the FDM process produced low
tortuosity due to the highly structured nature of the material fibres. Modification of
the material porosity influenced the flow resistivity through the sample, which was
consequently the major contributing factor to the level of porous absorption achieved.
The ability to produce a material with a variable flow resistivity could be used to,
cover the orifice of a Helmholtz resonator, providing a tailored amount of acoustic
resistance to improve absorption bandwidth. The control of pore geometry achievable
through the use of the FDM process offers the possibility to produce porous resonator
coverings with high flow resistivity. This may offer a method of providing a suitably
large amount of resistance to achieve significant absorption bandwidth improvements.
It may also allow the fabrication of a high resistance – low reactance covering, ideal
for promoting broadband resonant absorption.

Conventional resonant absorbers use porous materials to either slow the motion of air
around the orifice, or within the cavity. This is accomplished by either placing the
porous material directly above or below the orifice, or by filling the entire cavity with
the material. The application of the resistive material close to the orifice, takes
advantage of the faster moving air to increase the resistive effects. The results relating
to the absorption properties of the FDM samples produced using variable deposition,
suggest that topologies can also be produced with different acoustically resistive
properties. The application of resistive FDM porous topologies to improve resonant
absorption bandwidth is investigated by mounting the existing FDM material samples
directly over the orifice of the standard benchmark resonator (see Appendix 2). This configuration is depicted in Figure 5.8. While this configuration is suited to the mounting conditions of the impedance tube, and makes use of the existing porous test samples, the resistive effect is only influential in the hemispherical area of air movement surrounding the orifice entrance.

![Figure 5.8: Resistive FDM covering.](image)

The FDM porous coverings were mounted in turn over the standard benchmark resonator and sealed in place within the impedance tube sample holder. The absorption was measured at resolution of 3.125 Hz and plotted against a logarithmic frequency scale from 125 to 630 Hz; the same manner as the geometric cavity resistance results in Chapter 4. The three most porous samples (25%, 50%, and 50% with thin, 0.305mm raster width) all improved the resonant absorption bandwidth; these are depicted below in Figure 5.9. The other FDM material samples with lower porosity values provided a level of acoustic resistance too great, preventing any resonant absorption effect. This is demonstrated in the absorption results relating to the 10% porosity covering, also depicted in Figure 5.9. A dotted curve relating to the standard benchmark resonator alone is also plotted for comparison. The values of absorption bandwidth when $\alpha$ exceeds 0.4, $W$ (Hz), and resonant frequency $F_r$ (Hz), are also depicted to indicate changes in resistance and reactance.
Figure 5.9: Absorption results of resistive FDM covering.

The Q values of the three covering configurations with highest porosity, and their associated additional resistance values were derived from inspection of the absorption curves are given below in Table 5.3. The Q value for curve relating to the 10% porous covering could not be determined due to its level profile.

<table>
<thead>
<tr>
<th>Porous FDM Covering Sample</th>
<th>$\omega_r$ (Rad s$^{-1}$)</th>
<th>$\Delta \omega$ (Rad s$^{-1}$)</th>
<th>$Q$ ($)</th>
<th>Additional Resistance, R (Pa s m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1709.03</td>
<td>471.24</td>
<td>3.63</td>
<td>339.43</td>
</tr>
<tr>
<td>50 ($d_f = 0.305mm$)</td>
<td>1746.73</td>
<td>510.10</td>
<td>3.42</td>
<td>396.00</td>
</tr>
<tr>
<td>25</td>
<td>1495.40</td>
<td>1001.38</td>
<td>1.49</td>
<td>1103.14</td>
</tr>
</tbody>
</table>

It can be see from the absorption bandwidth and Q value results, that a large amount of resistance can be added through the addition of a layer of porous FDM material. The two coverings with 50% porosity provide a large amount of resistance, resulting
in large bandwidth increases. The 50% porous FDM covering, offers an improvement in bandwidth when \( \alpha \) exceeds 0.4, of 103Hz. The 50% porous sample with thinner 0.305mm fibre diameters, increases bandwidth by 119Hz. The 25% porous covering, introduced an amount of resistance large enough to over damp the resonator, resulting in a severe lowering of the peak absorption. The bandwidth improvement was less than the 50% porous sample with thin raster width, but still offered a substantial bandwidth improvement (113 Hz). The spike noticeable around 500Hz on each graph can be attributed to a calibration error. As in the previous chapter, the values of resistance derived from the Q values are an underestimation compared to the analytical models in Section 6.1.1, reflecting the inaccuracy the Q derived method of resistance estimation.

5.3 Discussion

The investigation into porous absorption through RM has highlighted that the direct fabrication of designed features fine enough for porous absorption is beyond the capabilities of the current SLA process. Processes offering the ability to produce finer features, such as Micro Stereolithography, may offer the required feature size capability, although the limited scale of which parts can be produced would reduce their practical applicability. Porous absorption obtained through the inherent material porosity of RM parts produced using Z Corp 3D printing is also unsuccessful, due to the level of porosity being too low to allow air propagation through the material. Modification of the deposition process parameters relating to Fused Deposition Modelling, allowed tailoring of the deposited topology on a scale fine enough to produce significant porous absorption. This approach enabled customisable levels of porosity to be incorporated during fabrication. Modification of the process parameters has demonstrated the ability to alter the acoustic properties, producing topologies suitable for adding significant acoustic resistance to increase the absorption bandwidth of resonant absorbers, or capable of high frequency porous absorption.

The added resistance to resonant absorption achievable using FDM porous topologies, derived from the deduced Q values, and from the analytical model in Section 6.1.1 is far greater than any of the RM examples based on cavity geometry. The higher
porosity samples with 50% porosity, in this example, provided a suitable amount of resistance to dampen the resonant effect of the standard benchmark resonator, and significantly increase the bandwidth of resonant absorption (an improvement up to 119Hz). The 25% porosity, and the other lower porosity samples provided too much resistance to the air movement around the orifice, resulting in an over-damping of the resonant effect, and a decrease in overall absorption coefficient. These coverings could be modified to provide less resistance by decreasing the thickness of the material used, and would allow a high amount of resistance to be provided by a very thin layer of material. Additional resonator resistance using FDM could be achieved by adding a covering either side of resonator orifice, or by filling the cavity space. This approach to adding resistance is more flexible than the methods based on modifying cavity geometry, as the orifice size and cavity geometry do not restrict the addition of resistance. This, coupled with the ability to easily tailor the required amount and provide much higher levels of resistance, makes the use of the FDM process more suited to the development of a broadband RM enabled acoustic absorber.
Chapter 6

Evaluation of RM Enabled Absorption

The ability to modify cavity geometry and produce porous topologies using RM have both been exploited to provide damping to a simple resonant device, without the use of traditional fibrous materials or sub-millimetre orifice dimensions. The configuration of the simple, standard benchmark resonator was designed to have low inherent resistance allowing improvements in absorption bandwidth to be easily implemented. The resistance methods investigated have the potential to offer greater absorption bandwidth if incorporated within resonator configurations with greater inherent resistance, or perforated panel absorbers. The results of each resistive method have been compared using the improvement in absorption bandwidth they offer. However, the resistance derived from the Q values only gives an approximate indication of the resistive effect, and is limited by the 3.125 Hz resolution of the acquired absorption results. The porous absorptive properties of the topologies produced using the FDM process have also only been analysed and compared experimentally.

This chapter compares and evaluates the resonant and porous absorption results against the theories presented in Chapter 3 to derive predictions relating to the theoretical characteristics and performance parameters of each method. These parameters can then facilitate the incorporation of the investigated RM absorption methods in the design of broadband absorbing devices.

By comparing the measured absorption of the RM fabricated resonant cavity absorber configurations to theoretical predictions, parameters relating to added resistance can be derived and a more accurate and informed evaluation of the various resistive additions can be achieved. This then allows the development of improved resonant absorber designs, incorporating tailored amounts of added resistance.
The application of high frequency FDM porous absorption also requires further evaluation in order to accurately predict the absorption and enable the development of improved absorber designs. Comparison of the measured absorption results to the porous absorbing theories will uncover how the absorption properties of RM porous absorbers differ from traditional materials.

The conformity between the measured and predicted absorption results of both absorption methods will ascertain the suitability of the presented theoretical models in predicting the performance of novel RM enabled absorber types.

6.1 Evaluation of RM Resonant Absorber Resistance

The evaluation of the resonant absorption bandwidth improvements in Section 4.5 and Section 5.2, allowed the effects resulting from the added resistance to be compared. At low levels of resistance, changes in bandwidth are small, and susceptible to rounding errors associated with the frequency resolution of 3.125 Hz. The subsequent error in the determination of the Q value through inspection alone, leads to inaccuracies in the derived resistance. Evaluating the measured absorption curves' characteristics in more detail will lead to a more accurate and informed measure of the performance of each resistive method. An improved measure of acoustic resistance will also allow the incorporation of the resistive methods within resonant absorber design formulae, leading to further, improved RM enabled, resonant absorber designs.

Once the added resistance values of each method have been accurately established, the differences can be more reliably compared and the most suitable method for adding resistance determined. The amount of resistance achieved and ease of fabrication must both be considered when comparing the different resistive methods.
6.1.1 Evaluation of Acoustic Resistance

The amount of acoustic resistance added by each method can be estimated by comparing the measured absorption to that predicted using the theoretical models. The value of added resistance can then be inferred from the model parameters. These parameters can then be used to compare the performance of different resistive configurations. To produce absorption predictions for each of the RM resistive methods a theoretical impedance model based on Eq 3.17 from the work of Ingard (1953) was used. This includes a coefficient \( R \) (Pa s m\(^{-1}\)) which represents the amount resistance over that predicted by the model, attributable to the added resistive features. The resulting impedance equation is given by,

\[
Z = \frac{\rho c^2 S}{2\pi} + \sqrt{2\eta\rho\omega \frac{1}{a}(l + 2a) + R} + i\left[ \omega\rho\left( l + 0.85a + 0.85a\left( 1 - 1.25 \frac{2a}{D} \right) \right) \right] - \frac{\rho c^2 S}{\omega V}
\]

Eq 6.1

The corresponding absorption curve is then produced using Eq 3.18. This impedance model is based on the prediction of the resonant response of a single resonator configuration with added resistance provided by simple resistive measures. Therefore the assumption is made that the resonant response of the RM fabricated single resonant absorber, with alternative resistive measures will be equivalent to the more traditional configurations that the model was derived from. While efforts have been made to avoid additional absorptive effects, including second resonant modes, the complex nature of the cavity additions may introduce absorption discrepancies.

To ensure that the model parameters accurately reflect the characteristics of the measured absorption, the curve created from the model must be fitted to the curve of the measured results. Firstly the peak frequencies of the measured and theoretical absorption curves are matched; this can be accomplished by altering the cavity volume parameter, \( V \) within in the model. Since cavity volume only affects the imaginary reactive part of impedance, the curve shape defined by the resistive, real part of the equation is not affected. Secondly the shape of the curve is altered by
changing the value of the added resistance \( R \), until reasonable agreement between the measured and predicted absorption is achieved.

A measure of the agreement between the two curves can be obtained by calculating the mean squared difference between the two curves at each data point. The value obtained is known as mean squared error (MSE),

\[
MSE = \frac{1}{n} \sum_{i=0}^{n} (x'_i - x_i)^2,
\]

where \( x'_i \) is the theoretical value, \( x_i \) is the measured value and \( n \) is the number of data points. The MSE value of curves with different amounts of added resistance \( R \), can then be compared to determine the added resistance value that best fits the measured results. A reasonable estimation of the amount of resistance provided by each method can be obtained by varying the resistance coefficient \( R \) of the model, to 3 decimal places, until a minimum MSE value is reached.

This method of estimating added resistance is exemplified below using the standard benchmark resonator described in Appendix 2. The absorption values measured at each 3.125Hz interval were compared with the same frequency points from the theoretical model, over the frequency range where the resonant curve predominates (125Hz - 630Hz). The peak resonant frequencies of the two curves did not require matching as they were already coincident. The added resistance of the model was varied at a resolution of 3 decimal places, until a minimum MSE value was achieved. Normalised resistance values (\( R/pc \)) were used within the analysis to allow sensible increments in resistance to be made. The analysis is show in Table 6.1.
Table 6.1: MSE analysis.

<table>
<thead>
<tr>
<th>Added Resistance R/pc (-)</th>
<th>MSE (x10⁻⁴) (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.187</td>
</tr>
<tr>
<td>0.1</td>
<td>10.386</td>
</tr>
<tr>
<td>0.05</td>
<td>3.994</td>
</tr>
<tr>
<td>0.04</td>
<td>4.715</td>
</tr>
<tr>
<td>0.06</td>
<td>4.010</td>
</tr>
<tr>
<td>0.055</td>
<td>3.914</td>
</tr>
<tr>
<td>0.056</td>
<td>3.919</td>
</tr>
<tr>
<td>0.054</td>
<td>3.916</td>
</tr>
</tbody>
</table>

It can be seen that a minimum MSE value is obtained at a resistance value of 0.055, which corresponds to 22.03 Pa s m⁻¹. Analysing normalised resistance to 3 decimal places, ensures the corresponding resistance estimate is optimal within 0.4 Pa s m⁻¹.

Figure 6.1 shows the measured absorption curve (solid), and the curve of best fit based on the theoretical model (dashed). The annotated values give an indication of the resonant frequency $F_r$ (Hz), the amount of additional resistance $R$ (Pa s m⁻¹), and the MSE agreement value of the fitted curves.
The small amount of additional resistance that is present in the standard resonator (22 Pa s m\(^{-1}\)) can be attributed to the surface finish produced as a result of using the SLS process. The derived value of \( R \) is dependent on the accuracy of the theoretical model as well as the quality of the measured results. Therefore without a direct measure, the value of \( R \) will be a best estimate.

The resistance of the geometric cavity modifications and the porous FDM coverings were also derived using this method. These are shown in Table 6.2 along with the MSE agreement values, indicating the closeness of fit of theoretical absorption curve. The derived resistive trends relating to each test group are depicted graphically in Figure 6.2.
Table 6.2: Absorption properties and derived resistance reference table.

<table>
<thead>
<tr>
<th>Resistive test specimen</th>
<th>Max $a$ (-)</th>
<th>Bandwidth @ $a &gt; 0.4, \text{ (Hz)}$</th>
<th>Added resistance, $R$ (Pa s m$^{-1}$)</th>
<th>MSE (x10$^{-3}$) (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractal iteration, $v$ (-)</td>
<td>Cavity shape / hydraulic radius (Section 4.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.52</td>
<td>31.25</td>
<td>10.82</td>
<td>3.33</td>
</tr>
<tr>
<td>1</td>
<td>0.56</td>
<td>34.38</td>
<td>19.63</td>
<td>2.27</td>
</tr>
<tr>
<td>2</td>
<td>0.59</td>
<td>40.63</td>
<td>27.27</td>
<td>3.57</td>
</tr>
<tr>
<td>3</td>
<td>0.67</td>
<td>46.88</td>
<td>43.27</td>
<td>2.45</td>
</tr>
<tr>
<td>Perforation radius, $P_p$ (mm)</td>
<td>Internal cavity perforations (Section 4.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>0.78</td>
<td>59.38</td>
<td>79.32</td>
<td>4.27</td>
</tr>
<tr>
<td>1</td>
<td>0.82</td>
<td>65.63</td>
<td>96.15</td>
<td>7.26</td>
</tr>
<tr>
<td>0.75</td>
<td>0.91</td>
<td>81.25</td>
<td>155.84</td>
<td>5.75</td>
</tr>
<tr>
<td>0.5</td>
<td>0.95</td>
<td>87.50</td>
<td>191.50</td>
<td>12.54</td>
</tr>
<tr>
<td>Fraction open area, $\varepsilon$ (-)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.84</td>
<td>75.00</td>
<td>110.97</td>
<td>5.97</td>
</tr>
<tr>
<td>0.05</td>
<td>0.95</td>
<td>87.50</td>
<td>191.50</td>
<td>12.54</td>
</tr>
<tr>
<td>0.02</td>
<td>0.99</td>
<td>103.13</td>
<td>279.64</td>
<td>16.42</td>
</tr>
<tr>
<td>0.01</td>
<td>0.96</td>
<td>137.50</td>
<td>556.47</td>
<td>10.28</td>
</tr>
<tr>
<td>Perforation Position, $P_p$ (mm)</td>
<td>((\varepsilon = 0.05, a=0.75) perforations)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>0.79</td>
<td>65.63</td>
<td>89.34</td>
<td>12.66</td>
</tr>
<tr>
<td>25</td>
<td>0.83</td>
<td>71.88</td>
<td>106.97</td>
<td>12.67</td>
</tr>
<tr>
<td>15</td>
<td>0.91</td>
<td>81.25</td>
<td>155.84</td>
<td>5.75</td>
</tr>
<tr>
<td>5</td>
<td>0.97</td>
<td>87.50</td>
<td>185.09</td>
<td>13.95</td>
</tr>
<tr>
<td>Fin spacing, $x_f$ (mm)</td>
<td>Internal cavity fins (Section 4.4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.81</td>
<td>71.88</td>
<td>104.56</td>
<td>4.32</td>
</tr>
<tr>
<td>2</td>
<td>0.86</td>
<td>78.13</td>
<td>134.61</td>
<td>5.46</td>
</tr>
<tr>
<td>1.5</td>
<td>0.87</td>
<td>78.13</td>
<td>142.62</td>
<td>5.27</td>
</tr>
<tr>
<td>1</td>
<td>0.92</td>
<td>87.50</td>
<td>177.47</td>
<td>4.21</td>
</tr>
<tr>
<td>Upper cavity fins</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.99</td>
<td>92.50</td>
<td>194.70</td>
<td>8.89</td>
<td></td>
</tr>
<tr>
<td>Porosity, $\varepsilon$ (%)</td>
<td>FDM porous covering (Section 5.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.94</td>
<td>140.63</td>
<td>661.03</td>
<td>14.46</td>
</tr>
<tr>
<td>50, (thin track width)</td>
<td>0.91</td>
<td>156.25</td>
<td>836.10</td>
<td>12.43</td>
</tr>
<tr>
<td>25</td>
<td>0.55</td>
<td>150</td>
<td>2271.94</td>
<td>17.97</td>
</tr>
<tr>
<td>Standard Benchmark resonator</td>
<td>0.57</td>
<td>37.50</td>
<td>22.03</td>
<td>3.91</td>
</tr>
</tbody>
</table>
Figure 6.2: Derived resistance trends.
From the resistance plots and the reference table, it can be seen that the level of resistance offered by the porous FDM materials is higher in all cases than any of the resistive geometric cavity modifications. The range of resistance demonstrated is also greater than any of the other methods (1611 Pa s m\(^{-1}\)). Of the geometric resistive approaches the greatest amount of added resistance (556 Pa s m\(^{-1}\)), and the broadest range of resistance (445 Pa s m\(^{-1}\)), is achieved through variation of the fraction open area of internal perforations. The success of these two methods highlights that modifications or additions which restrict the motion of air by reducing the open area of sections where air oscillates, are the most effective; reducing the open area results in increased resistance. The plot depicting the resistance associated with the position of the perforated layer indicates that these restrictions are more influential when they interact with the faster moving air adjacent to the resonator neck. The increasing resistance trends associated with a decrease in perforation size or a decrease in the porous FDM raster width, highlight that narrower flow paths serve to increase viscous resistance.

Although small, the resistance associated with the decreasing hydraulic radius of fractal cavity shapes increases with each fractal iteration, v. Sapoval (1997) theorised that this increase is exponential following a 2\(^{\text{nd}}\) relationship. The resistance value from the \(v = 0\) sample represents the amount of additional resistance, over that predicted, attributable to increased viscous losses caused by the rough material surface. To determine the resistance caused by decreasing the hydraulic radius (HR), this value must be removed from the other derived resistance values. The details of this analysis are shown in Table 6.3.

<table>
<thead>
<tr>
<th>Fractal iteration, (v) (-)</th>
<th>Inferred resistance (Pa s m(^{-1}))</th>
<th>Resistance attributable to decreasing HR (Pa s m(^{-1}))</th>
<th>Percentage increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10.82</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>19.63</td>
<td>8.81</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>27.24</td>
<td>16.42</td>
<td>186</td>
</tr>
<tr>
<td>3</td>
<td>43.27</td>
<td>32.45</td>
<td>198</td>
</tr>
</tbody>
</table>
The increase in cavity resistance of the $v = 2$ and $v = 3$ samples, approximately doubles from that of the previous sample. This pattern is reasonably consistent with the exponential $2^v$ relationship theorised by Sapoval (1997). The $v = 0$ results cannot be included in validating this relationship as the value of resistance includes additional components of both cavity and neck resistance.

Assuming the use the $2^v$ relationship, the amount of additional cavity resistance offered by the square $v = 0$ sample, above that predicted, can be estimated at 4.4 Pa s m$^{-1}$. Subsequently the additional resistance attributable to the neck becomes $10.82 - 4.4 = 6.42$ Pa s m$^{-1}$. It can also be predicted that an iteration level of $v = 7$ would be necessary in order to achieve a significant level of resistance, in the same order of magnitude as the characteristic impedance of air ($\approx 415$ Pa s m$^{-1}$). This is well beyond the capability of current RM processes for a fractal of this scale, but could be achievable using larger cavity sizes.

The plot depicting the resistance associated with the addition of internal cavity fins shows a trend of increasing resistance as fin spacing is reduced. This can be attributed to improved viscous resistance due to an increase in the number of fins (and consequently surface area), and a reduction in the size of the flow paths. Further resistive improvements were achieved through the application of internal fins to the area of faster moving, two-dimensional airflow at the top of the cavity. This was demonstrated using a conformal, fin design, aimed at increasing losses within the upper cavity area, inspired from the success of the application of perforations to the upper cavity area. This design aimed at combining the most significant effects from the study of resistive cavity geometry, whilst also considering material and process restrictions. The amount of resistance achieved by the upper cavity fin design (195 Pa s m$^{-1}$) was sufficient to maximise the absorption coefficient at resonance, but was not sufficient to provide substantial improvements in absorption bandwidth.

Control over the amount of added resistance was shown to be possible through changes to internal feature configuration (fin spacing, perforation size, perforation fraction open area), as well as changes to the cavity hydraulic radius. It may be possible to predict the amount of added resistance of each of these simple resistive
geometries using their design variables, but is beyond the scope of this work. The upper cavity fin design incorporates more geometric variables, and interacts with more complicated 2-dimensional airflow. Factors such as the complexity of the air channels, orifice size and expansion ratio (orifice to cavity size ratio), may affect the amount of resistance achievable. Prediction of resistance from these more complex design variables would become an impossible task to calculate by hand, and would require a more discretised computational analysis to predict its acoustic influence.

As suggested by the derived resistance trends, as well as the theoretical curves relating to perforated layer resistance and viscous resistance (previously depicted in Figure 4.10 and Figure 4.18), high levels of resistance using internal cavity features can only be achieved using features in the order of the thickness of the viscous boundary layer (<1mm). The developed internal cavity features indicate that only a finite amount of resistance can be achieved without introducing sub-millimetre features. This limits the applicability of RM fabricated, resistive internal features, to resonant configurations only requiring a low amount of added resistance.

The use of porous FDM material to provide acoustic resistance has been shown to achieve large amounts of acoustic resistance. Samples incorporating 50% porosity, covering the resonator orifice, provided a suited amount of resistance for the resonator configuration tested, significantly increasing the bandwidth of absorption. Decreasing the porosity and the fibre diameter resulted in an increase the added resistance. When lower porosity samples were tested, the magnitude of resistance achieved was too high, and decreased the resonant absorption effect. Unlike the addition of internal cavity features, the use of a porous FDM resistive covering is capable of providing more resistance than is required. The reliance on a configurable topology to achieve resistance allows flexibility in the application of resistance to an acoustic resonator. Unlike the conformal fin design, and other internal features that require uniform cavity configurations, FDM porous resistance can be applied as a covering or within the cavity, irrespective of cavity or orifice shape.

Control over the amount of added resistance can be achieved through varying the process parameters relating to track spacing and track width, which directly affect the material porosity, and the fibre diameter. Further material characterisation is
necessary to determine the exact relationships, and allow resistance prediction directly from process parameters but is beyond the scope of this work.

The derived resistance trends for each test sample reflect the measured absorption bandwidth increases in most cases. The exception is the case when the resonant effect is over-damped with the 25% porous FDM covering. Resistance analysis indicates that the very high level of resistance offered (2272 Pa s m⁻¹), is too great for the resonant configuration, decreasing the overall absorption.

The MSE values for each fitted absorption curve are generally low, particularly in the fractal cavity shape, and internal fin tests. The higher resistance internal perforation tests and the very high resistance FDM coverings produce greater error between the experimental and analytical curves. This indicates that the model used is not as accurate at predicting the response of high resistance configurations. Alternatively, the unconventional nature of the methods of adding resistance may affect the ability of the theoretical model in predicting the absorption. The maximum MSE noticed was 17.97 x10⁻⁴ (25% porous FDM covering) which equates to a mean deviation of $\pm \sqrt{17.97 \times 10^{-4}} = \pm 0.04\alpha$. This is comparable to the level of measurement uncertainty (0.02\alpha) as determined in Appendix 2, and is acceptably low.

6.1.2 Fabrication Evaluation

The use of the SLS process to fabricate cavity features highlighted accuracy issues relating to small perforations, and powder removal problems from deep, narrow channels. These issues became particularly problematic when the dimensions involved were in the order of 1mm or less. The use of a more accurate RM process may enable finer features to be more successfully fabricated, although process limitations would still exist, ultimately restricting the amount of resistance possible. A liquid based selective solidification method (such as Stereolithography), or a deposition based process would alleviate the powder removal issues. Both approaches would require separate support structures for overhanging features, introducing new fabrication limitations to the internal features.
The majority of the cavity features produced required separate fabrication, and subsequent assembly into the body of a resonator. This was only a minor inconvenience for the purposes of producing test samples. However, the ability to incorporate acoustic absorbing structures within RM parts during fabrication is a key advantage of the RM approach, and has potential to add value to any part produced. A requirement for post fabrication assembly restricts the possible design complexity as compound, nested or convoluted features cannot be easily assembled by hand.

The fabrication of a highly resistive FDM porous material can be produced through modifications to the process build parameters. The fabrication of a simple material sample requires the removal of a thin layer of support material from the bottom face. This can be easily achieved as the support material is different from the build material, and can be peeled away from the main part. More complicated geometries with overhanging features may require the removal of internal support structures. If the area being supported is inaccessible a water soluble support material can be used. The process software only allows the modification of the raster properties of individual layers. Therefore the porous properties within a single layer can not varied; however a produced FDM part can possess different porous configurations on different layers, introducing the possibility of a graded porosity structure.

The testing in Chapter 5 showed that the FDM standard build parameters produce a non porous structure. This makes it suited to the fabrication of a sealed acoustic resonator structures, and introduces the possibility to fabricate a resonant cavity absorber incorporating a porous resistive layer, as a single build. In this way resistance can be designed into the structure of the resonator itself, fully incorporated after fabrication, requiring no separate assembly.

6.1.3 RM Resistance Conclusions

While the fabrication method of deposition based processes such as FDM is not as flexible as that of SLS, precise control of the deposition parameters allows a topology with highly resistive properties to be produced. Process restrictions, such as the requirement for separate support structures, imply that FDM cannot produce complex
features with the same level of freedom as SLS. However the resistance provided by the topological configuration alone is far greater than that achieved using the incorporation of complex internal cavity features produced using SLS. For internal cavity features to be able to offer the same level of resistance, features fabricated on a sub-millimetre scale must be used. This is currently beyond feasible fabrication capabilities of the majority of RM processes. These observations indicate that the use of porous FDM topological configurations is the most successful method of adding acoustic resistance to RM fabricated resonant absorbers.

6.2 Evaluation of RM Porous Absorption

Of the different RM approaches aimed at providing porous absorption, the most successful was the use of porous FDM topologies, created through modifications to the process deposition parameters. The measured absorption characteristics in Section 5.1 indicated that different absorptive properties could be produced by varying the porosity and filament thickness. This investigation highlighted the effect of changing these parameters, and identified highly absorbing configurations. This empirical information allows comparison between the different test specimens, but a further analytical description is required to predict the absorption of these topological configurations when incorporated in alternative absorber designs.

The porous topologies produced using the FDM process possess unconventional porous absorber characteristics. Low porosity, large fibre size and a highly structured fibre orientation, may restrict the applicability of traditional porous absorber theoretical models. To determine the suitability of applying existing theoretical models to predict the porous absorption of the FDM topologies, the physical characteristics were applied to both empirically derived, and theoretical porous absorption models.

The empirically derived model described in Section 3.2, based on the work of Delany and Bazely (1970), is only accurate over a limited frequency range, and for a limited range of material flow resistivity, \( \sigma \) (Pa s m\(^{-2}\)). The improved empirical model proposed by Komatsu (2008) is more suited to the low porosity, high density
configuration of the porous FDM topologies. The theoretical model based on the work of Johnson, Allard and Champoux, described in Section 3.2 describes the acoustic response using characteristic lengths based on the porous microstructure, and unlike the Komatsu model is more generic in its applicability. To compare the predictions of these two different modelling approaches each was used to predict the absorption of FDM samples with two different porosities (10% and 50%), and also of the samples with the same porosity but reduced 0.305mm raster width.

The Bies and Hansen model for flow resistivity (Eq 3.30), was used to predict the resistivity of each of the porous samples. The calculated values are given in Table 6.4.

<table>
<thead>
<tr>
<th>Porosity, $\varepsilon$</th>
<th>Raster / Fibre Width, $d_f$ (mm)</th>
<th>Resistivity, $\sigma$ (Pa s m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.508</td>
<td>1657</td>
</tr>
<tr>
<td>0.1</td>
<td>0.305</td>
<td>4596</td>
</tr>
<tr>
<td>0.5</td>
<td>0.508</td>
<td>674</td>
</tr>
<tr>
<td>0.5</td>
<td>0.305</td>
<td>1870</td>
</tr>
</tbody>
</table>

The empirically based Komatsu approach for characteristic impedance (Eq 3.41), and wavenumber (Eq 3.42), were applied to the various FDM absorber configurations, and the absorption results were obtained. Figure 6.3 compares the absorption relating to changes in porosity, while Figure 6.4 compares the absorption relating to changes in raster width. Equation constants relating to air at 20°C and one atmosphere were used; $\rho = 1.2041$ kg m$^{-3}$, $\eta = 1.84 \times 10^{-5}$ kg s$^{-1}$ m$^{-1}$. Material constants relating to fraction open area $\varepsilon = 0.1$, $\varepsilon = 0.5$ were used for the two different porosities, while values of $d_f = 0.508$mm and $d_f = 0.305$mm were used for the different fibre diameters. A constant sample thickness of $t = 20$mm was used throughout; the sample was assumed to be mounted on a rigid termination.
Figure 6.3: Absorption prediction of FDM samples (Komatsu model(K)).

The predicted results of the Komatsu model do not fit those of the experimental data, but the trends noticed are similar. Decreasing porosity and raster width (effective fibre size) give improved absorption characteristics, as noticed in the experimental testing. The results relating to the higher porosity 50% sample are a closer match to the model.
than the 10% porosity sample; this may be because the porosity levels are closer to traditional porous materials, on which the empirical measurements used to derive the model are based. For this reason, the highly unconventional porous FDM structure is unlikely to fall within the applicability of the model, particularly at low levels of porosity.

The application of the theoretically based Johnson-Allard-Champoux model, described from Eq 3.43 to Eq 3.53 in place of the Komatsu approach, involves less empirical correction coefficients, and depends more heavily on the topology of the porous structure. The unconventional nature of the FDM porous material is more suited to this approach; however assumptions still have to be made when characterising the pore structure. Also the predicted flow resistivity values are still reliant on the empirical Bies and Hanson relationship.

Classifying the material as a uniform structure with parallel square pores allows relatively simple prediction of some of characteristic dimensions and properties. The tortuosity \( k_2 \) can be set at 1 as the sound is at normal incidence. For pores that have a uniform cross section throughout their length, the air velocity can be considered constant, and for this case the shape factor \( \Lambda \) is equal to the hydraulic radius, that is, twice the pore cross-sectional area divided by the pore perimeter (Allard, Champoux 1992). This arrangement also yields \( \Lambda' = \Lambda \),

\[
\Lambda = \frac{2RS^2}{4RS}.
\]

Eq 6.3

The shape factors for each porous FDM configuration calculated using Eq 6.3 are given in Table 6.5.
Table 6.5: Porous FDM shape factors

<table>
<thead>
<tr>
<th>Porosity, ε (−)</th>
<th>Raster / Fibre Width, d_f (mm)</th>
<th>Raster Spacing, RS (mm)</th>
<th>Shape Factors, A / A’ (x10^-4) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.508</td>
<td>0.235</td>
<td>1.175</td>
</tr>
<tr>
<td>0.1</td>
<td>0.305</td>
<td>0.141</td>
<td>0.705</td>
</tr>
<tr>
<td>0.5</td>
<td>0.508</td>
<td>1.230</td>
<td>6.150</td>
</tr>
<tr>
<td>0.5</td>
<td>0.305</td>
<td>0.737</td>
<td>3.685</td>
</tr>
</tbody>
</table>

Figure 6.5 shows the results of applying this theoretical model to the two different porosity FDM samples, while Figure 6.6 compares the samples with thinner 0.305mm raster spacing as before. The values of flow resistivity calculated in Table 6.4 are used, as well as environmental constants relating to air at 20°C and one atmosphere; \( \rho = 1.2041 \, \text{kg m}^{-3}, \eta = 1.84 \times 10^{-5} \, \text{kg s}^{-1} \, \text{m}^{-1}, \gamma = 1.4, P_0 = 101,320 \, \text{N m}^{-2}, N_{pr} = 0.702. \)

Figure 6.5: Absorption prediction of FDM samples (theoretical Johnson-Allard-Champoux model).
The magnitude of the absorption coefficients resulting from the theoretical model provide a much closer approximation to the measured values than the simple empirical Komatsu model. For frequencies where absorption effects become significant (>800Hz), the trends for both changing porosity and fibre diameter are consistent with the measured samples, and the magnitude of change is closer to the measured trends. Despite these improved predictions the unconventional nature of the material still results in the theoretical predictions being an underestimation of the measured absorption. Assumptions relating to the material configuration and fibre geometry may be sources of prediction error, as may the empirically derived Bies and Hansen calculation of flow resistivity used in both models. This resistivity calculation is more suited to porous materials with high porosity, and therefore may not provide accurate predictions for the low porosity FDM topologies. Despite the inaccuracies of the theoretical predictions, estimates of absorption trends and an approximate response are possible using existing theory. Further material characterisation and the use of more elaborate, theoretically derived, flow resistivity calculations, is necessary for accurate prediction of these new FDM type porous materials, but is beyond the scope of this investigative work.

Figure 6.6: Absorption prediction of FDM samples with reduced (0.305mm) raster width (theoretical Johnson-Allard-Champoux model).
6.3 Development of RM Broadband Absorption

The FDM process has been shown to be capable of depositing material in a controlled way such that a porous topology can be fabricated which possesses good acoustic resistance or porous absorption. The previous investigations have highlighted these capabilities, but have not explored the potential they introduce. Having derived theoretical values for the amount of acoustic resistance, and a reasonable prediction of porous absorption, an improved resonant absorber can be designed aimed at providing broadband absorption comparable with that achievable using existing methods.

The microperforated panel absorber proposed by Maa (1998) offers broadband absorption over 3 octaves (250Hz – 2000Hz), and achieves large acoustic resistance without the use of separate resistive materials. Single material broadband absorption is a common objective of the proposed FDM broadband absorber; therefore it provides an existing method to compare absorption performance against.

6.3.1 Broadband Absorber Design

The use of a perforated panel resonator configuration over that of a single orifice resonator, increases the absorption cross section, and is a more commonly employed absorber configuration. Absorption coefficient and bandwidth increases are achieved through additional resistance, commonly added in the form of a cloth, screen or other porous covering (Ingard 1953). When the covering is directly behind or in front of the perforations it behaves as if it were actually in the openings (Cox, D'Antonio 2004). Resistance can also be applied by filling the cavity with porous material, or provided by micro-perforations as previously discussed. Further bandwidth improvements can be achieved by incorporating two resonant layers, tuned to different frequencies. Placing a perforated panel construction tuned to a high frequency, above that of one tuned to a lower frequency, can be used to produce a wider band of absorption if the response curves are designed to overlap (Jinkyo, George & Swenson 1992, Kang, Fuchs 1999).
The design of a dual layer perforated panel resonant absorber incorporating porous FDM topologies to achieve the required acoustic resistance, demonstrates the potential of RM enabled, single material, broadband absorption. Furthermore, porous absorptive properties could also be added using alternative FDM topological configurations.

Freedom of design is a common advantage of all RM processes and for this application allows any perforated panel configuration to be realised. Orifice dimensions, orifice spacing, cavity depth and the thickness of resistive material, can all take on arbitrary values and are not constrained by generic tool sizes or stock material size conventions. More complex configurations including dual layer absorbers can also easily be produced. The acoustic resistance that can be provided by modifying FDM process parameters can be used to add the correct amount of tailored resistance to the perforated panel, or panels, improving their bandwidth of absorption. Similar changes to the process parameters can be utilised to make the area surrounding the perforations absorb higher frequencies through porous absorption. The low porosity (5% and 10%), samples tested in Section 5.1 exhibited significant porous absorption over 1600Hz. However these low porosity configurations were not suited to providing added resistance to resonant absorption. When placed over the standard benchmark resonator in Section 5.2 they provided too much resistance, and changed the effective density of the oscillating air emanating from the neck, adding mass reactance. This served to almost completely diminish any resonant absorption. The use of variable porosity configurations in the production of a perforated panel absorber offers potential to add high frequency porous absorption on top of the low frequency resonant absorption. A combined dual layer perforated panel structure incorporating tailored acoustic resistance and high frequency porous absorption has the potential to produce a large range of absorption, if the effects of the two resonances and that of the porous absorption can be made to overlap.

The preceding pages describe the design, fabrication and testing of a dual layer resonant absorber, incorporating acoustic resistance and additional high frequency porous absorption provided by porous FDM topologies. Reference can be made to Figure 6.8 which schematically depicts the absorber’s configuration.
The use of the FDM process in the fabrication of this proposed absorber introduces design constraints, restricting the extent to which all of the aforementioned features can be incorporated. The perforation radius should be above 2mm to ensure fabrication success and accuracy; this in turn affects the perforation fraction open area and cavity depth options. The impedance tube test method limits the total sample depth to ≈100mm to ensure compatibility with the test piece holder, and also makes the absorber comparable with the other samples previously tested. This restricts the thickness of the resistive coverings and the perforated plates, affecting the amount of resistance that can be applied and the low frequency limit of porous absorption.

The required configuration of the resonant geometries of the dual layer perforated panel construction, are established by considering the lower frequency limit of the upper porous absorption effect. From the porous absorption trends revealed in the testing within Section 5.1, a configuration combining 5% porosity and 0.305mm fibre diameter promotes low frequency response. Using the theoretical, Johnson-Allard-Champoux model of absorption (Eq 3.43 to Eq 3.53), the absorption curves shown in Figure 6.7 were produced for different thicknesses of this FDM configuration,

![Figure 6.7: Effect of varying material thickness on porous absorption.](image)

Section 6.2 highlighted that the accuracy of these predictions is restricted by the use of topological assumptions and the use of the Bies and Hansen expression for flow
The resonant response of a complementary dual layer perforated panel absorber, must consider the combined impedance of both perforated panels and their associated cavity spaces. This has been previously accomplished by considering the resistive and reactive impedance components to be analogous to electrical impedance (Kang, Fuchs 1999, Maa 1975). The components of impedance relating to orifice resistance, orifice mass reactance, and cavity reactance, are treated as series elements within a circuit. The addition of a second layer of perforations can then be simply modelled as a second series circuit connected in parallel with the first. This theory can be extended to include an arbitrary number of perforated panels, allowing further increases in the resonant absorption bandwidth (Asdrubali, Pispola 2007). The accuracy of impedance prediction has been improved through the use of alternative impedance transfer modelling (Zou et al. 2006). Similar multiple layer resonant structures have been proposed for use as sound barriers without the inclusion of a rigid backing; the second layer of perforations partially acting as the backing wall. Their performance can be estimated through the consideration of both acoustic absorption and transmission analysis (Asdrubali, Pispola 2007, Sakagami, Morimoto & Koike 2006).

The impedance of a single perforated layer, derived from Eq 3.20, includes added resistance, \( R \) (Pa s m\(^{-1}\)),

\[
Z_r = \frac{\rho}{\varepsilon} \left( \frac{1}{2a} + 1 \right) \sqrt{8 \mu \omega} + R + \frac{i \omega \rho l_p}{\varepsilon},
\]

Eq 6.4

where the added resistance \( R \) (Pa s m\(^{-1}\)) provided by a resistive coverings of thickness \( t \) (m) is calculated from,
\[ R = \frac{\alpha}{\epsilon} \]  

Eq 6.5

The impedance of each associated cavity space is,

\[ Z_s = -i\rho c \cot(\omega d/c). \]  

Eq 6.6

The impedance of a dual layer perforated panel configuration must combine the impedances of the individual layers. This is accomplished using the impedance transfer method (Zou et al. 2006), derived from the work presented by Maa (1975) and Kang (1999).

\[ Z = Z_{p1} - i\rho c \cot(\omega d_1/c) + \frac{1 + \rho c \cot^2(\omega d_1/c)}{Z_{p2} - i\rho c \cot(\omega d_1/c) - i\rho c \cot(\omega d_2/c)}, \]  

Eq 6.7

where the subscripts 1 and 2 represent the values associated with the top and bottom resonant absorber configurations respectively.

This theoretical model was used to design the resonant response of a dual layer perforated panel configuration. To complement the previously determined porous absorption, the design must provide resonant absorption below 3000Hz, and extend as low as possible given the dimensional constraints. To maximise the viscous neck losses, the perforation radius should be as low as possible, but to ensure accurate FDM fabrication should not be less than 2mm, therefore \( a_1 = a_2 = 2 \text{mm} \). In order to incorporate the 10mm porous absorbing layer within the resonant structure, the thickness of the top perforated panel is \( l_1 = 10 \text{mm} \). To keep the overall depth of the combined composition to a minimum, the cavity depths \( d_1 \) and \( d_2 \) as well as the thickness of the bottom perforated panel \( l_2 \), should be kept as low as possible.

Observing all these design constraints, a dual layer perforated panel absorber was modelled using Eq 6.7 with the following variables: Top perforated panel: \( a_1 = 2 \text{mm}, \epsilon_1 = 0.28, l_1 = 10 \text{mm} \) and \( d_1 = 40 \text{mm} \). Bottom perforated panel: \( a_2 = 2 \text{mm}, \epsilon_2 = 0.12, l_2 = 5 \text{mm} \) and \( d_2 = 45 \text{mm} \). This configuration was chosen to provide resonant peaks
around 1600 and 700 Hz, and with the incorporation of additional resistance, provide continuous absorption above $0.4\alpha$ between the two resonant peaks and the point where porous absorption takes over (3000Hz). This additional resistance can be provided through the use of porous FDM layers covering each perforated panel. The thickness of these resistive coverings was limited to 8mm to keep the overall sample depth to a minimum, therefore a highly resistive porous configuration must be used. Following the acoustic resistance evaluation of porous FDM topologies (Section 6.1.1), a configuration with $\varepsilon = 0.25$ was shown to provide high resistance when used as a covering over the standard benchmark resonator. Resistance can be further increased through the use of a reduced (0.305mm) fibre diameter, allowing a high level of resistance from an 8mm thick covering. The broadband, dual perforated panel, test sample is shown schematically in Figure 6.8.

Once the two sections are assembled the 8mm low porosity resistive covering, fabricated over the bottom perforated panel, constitutes 8mm of the 40mm cavity depth associated with the top perforated panel.
6.3.2 Broadband Absorber Fabrication

Due to restrictions imposed by simultaneous research involving the available FDM machinery, the build material used for the dual layer absorber was PC-ABS, different from the Polycarbonate parts previously produced. The FDM material used to fabricate the parts is not an issue as the microscopic material properties are acoustically irrelevant; the resistive and absorptive properties are produced by topologies created via changes to the material deposition configuration, which are dependent on the process parameters only.

The two layers were fabricated separately, orientated with the resistive layer face down to produce no overhanging features and alleviate the need for any support structures. The amount of post processing required was minimal; a thin layer of support material on the base of each section was easily peeled off, leaving behind the unrestricted open porous resistive coverings. The fabricated top and bottom layers are shown in Figure 6.9. The two layers were fixed together using M4 bolts running through specifically designed sealed channels within each section, so as to not protrude inside each resonator cavity. The bottom layer was sealed with a 2mm aluminium sheet, providing an acoustically reflective termination. The junctions between the two layers and the aluminium base plate were sealed with silicone.
6.3.3 Broadband Absorption Predictions

To predict the absorption of the FDM dual layer broadband absorber, the resistivity $\sigma$ (Pa s m$^{-2}$) of the resistive covering layers must be determined. The Bies and Hansen expression for porous material flow resistivity (Eq 3.30) can be used, and yields an estimation of 3477 Pa s m$^{-2}$. However, the inaccuracies of the previous porous absorption predictions in Section 6.2 have been partly attributed to this simple approximation of flow resistivity. To ascertain a more accurate value of flow resistivity, the absorption of the two perforated layers were tested individually and compared against the theoretical model based on a single perforated panel (Eq 6.4). The resonant frequency of each theoretical curve was matched to the measured peak absorption frequency, and the amount of added resistance $R$ (Pa s m$^{-1}$) was estimated using the minimisation of the mean squared error between the two curves, as described in Section 6.1.1. From this the flow resistivity, $\sigma$ (Pa s m$^{-2}$), of the FDM topology covering each perforated layer, can be easily derived using Eq 6.5.
Figure 6.10 shows the absorption results of the individual perforated layers. The solid line represents the measured values, while the dotted curves are the fitted theoretical predictions. The derived values of flow resistivity \( \sigma \) (Pa s m\(^{-2}\)), and the MSE agreement value (-) are also depicted on each plot.

The normal incidence limit of the large impedance tube restricts the measured values to below 1600Hz; only allowing comparison between the measured and predicted curves up to this point. Averaging the two obtained values of flow resistivity yields \( \sigma = 5796 \) Pa s m\(^{-2}\) for the 25% porous FDM topology, incorporating 0.305mm raster width. This is considerably greater than the prediction obtained from the use of the Bies and Hansen expression for resistivity, highlighting its inadequacy in predicting the characteristics of the FDM porous configurations. The discrepancies between the values of resistivity inferred from the two measured absorption curves may be a result of the frequency limit of the impedance tube, or could indicate that there are influences affecting the resonant response other than the resistivity of the covering material. The use of a low porosity, acoustically absorbing FDM topology to fabricate each perforated layer is not accounted for within the theoretical model and is a likely source of error.

Using the average inferred value of resistivity, environmental constants relating to air at 20°C and 1 atmosphere and the previously defined design dimensions, the theoretical response of the FDM dual layer broadband absorber can be determined. The resonant response is calculated using Eq 6.4 – Eq 6.7, and the porous response
using Eq 3.43 to Eq 3.53. The design variables used in these calculations are reiterated in Table 6.6 and the resulting absorption curves are depicted in Figure 6.11. The solid line represents the predicted resonant absorption while the dashed line represents porous absorption.

Table 6.6: Dual layer broadband absorber design parameters.

<table>
<thead>
<tr>
<th>Design Value</th>
<th>Top Layer</th>
<th>Bottom Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resonant perforated panel parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture radius $a$ (mm)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Fraction open area $\varepsilon$ (-)</td>
<td>0.28</td>
<td>0.12</td>
</tr>
<tr>
<td>Aperture length $l$ (mm)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td><strong>Resistive covering parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity $\varepsilon$ (-)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Raster width / fibre diameter $d_f$ (mm)</td>
<td>0.305</td>
<td>0.305</td>
</tr>
<tr>
<td>Material thickness $t$ (mm)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Inferred resistivity $\sigma$ (Pa s m$^{-2}$)</td>
<td>5796</td>
<td>5796</td>
</tr>
<tr>
<td><strong>Porous absorptive parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity $\varepsilon$ (-)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Raster width / fibre diameter $d_f$ (mm)</td>
<td>0.305</td>
<td>0.305</td>
</tr>
<tr>
<td>Material thickness $t$ (mm)</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 6.11: Predicted dual layer broadband resonant and porous absorption.
The bandwidth of the predicted resonant absorption at $0.4\alpha$ is over 3 octaves (2234Hz), and is comparable to the range of the microperforated panel presented by Maa (1998). The high frequency porous absorbing properties of the perforated panel's FDM topology, allow absorption to continue into the higher frequency range. The dotted curve predicting the porous absorption of the dual layer construction is based on the theoretical model of porous absorption from Section 6.2. This model produced underestimates of the measured porous absorption, suggesting that the material configuration used within the dual layer absorber construction would provide similar or superior absorption to the predictions shown above. This would allow the bandwidth of absorption to continue uninterrupted, past the limit of resonant absorption, and into the higher frequency range.

6.3.4 Measured Broadband Absorption

To ascertain the physical absorption properties, and the level of agreement with the theoretical predictions, the complete fabricated dual layer sample was mounted in the impedance tube and tested using the two microphone impedance tube method described in Appendix 1. The measured results are shown in Figure 6.12 as a solid line. The upper frequency limit of the large impedance tube again restricts the measured response to below 1600Hz. Therefore the porous absorption predictions cannot be compared. The predicted resonant response from Figure 6.11 is plotted as a dotted line for comparison.
The measured results offer reasonable agreement with the predicted curve. There is however a measurable discrepancy in the lower resonant peaks of 110Hz. The predicted peak absorption value is also 0.03α greater than the measured curve. The upper frequency limit of absorption measurement restricts the comparison of the upper resonant absorption curve. As the curve reaches the 1600Hz limit of measurement the absorption coefficient begins to level after a steady increase. This trend follows that of the predicted curve, but appears lower in magnitude. Assuming the absorption continues to follow the trends of the predicted curve, absorption bandwidth when α exceeds 0.4 will be over 3 octaves as the model suggests, and comparable to the microperforated panel absorber. The differences in the maximum absorption values of the two resonant peaks, and the depth of the trough between the two peaks, indicates that the amount of acoustic resistance is less than that predicted. This could be due to the average resistivity value used, or the low porosity properties of each perforated layer. Further discrepancies may be attributable to inaccuracies in the models used in predicting the absorption of the dual layer absorber. The porous FDM topologies used to provide acoustic resistance and porous absorption are unlike the configurations of traditional porous materials, which the current theoretical models are based on. Therefore the measured response of these porous topologies may differ from traditional predictions. A more accurate prediction of acoustic response
requires the characterisation of the porous topologies fabricated using the FDM process.

6.3.5 RM Broadband Absorption Conclusions

The developed method of producing flexible, high level acoustic resistance from the FDM process has been used to produce a broadband acoustic absorber. By utilising freedom of geometry, and the ability to 'build in' porous material properties a dual layer, single material broadband acoustic absorber was produced comparable in performance to a microperforated absorber. This absorber configuration exemplifies the potential benefits of using RM, by combining porous and resonant acoustic absorption. The combination of these acoustic characteristics introduces the ability to produce a single material absorber capable of addressing both low and high frequencies.

The scale of possible fabrication limited testing of the absorption properties to the impedance tube. The production of a narrow section of the dual layer resonator, suitable for the small 28mm impedance tube is not feasible due to design requirements such as cavity wall thickness and connecting bolts. Consequently testing could only be carried out in the large 100mm tube, restricting the frequencies that could be measured to less than 1600Hz. The resonant and porous absorption above this frequency can therefore only be predicted based on theoretical models and previous high frequency testing results. Reasonable agreement between the results and the predictions of the resonant effect at lower frequencies indicates that similar correlation would continue. To confirm the high frequency absorption effects an alternative test method would have to be used. The use of a reverberation chamber to measure random incidence absorption would allow higher frequency measurements. However the sample sizes required are in the order of 10m², and are not feasible for fabrication using currently available FDM processes.

The absorption predictions underestimated the amount of resistance provided by the material covering each layer of perforations. This can be attributed to the inability of the theoretical models to predict accurately the performance of the porous FDM
topologies used. A more detailed characterisation of porosity would be required to
derive accurately the acoustic properties from the topologies produced using FDM, or
from the process parameters. This could lead to the ability to fabricate a structure with
predictable, customisable acoustic properties, directly, without the need for post
fabrication characterisation of acoustic behaviour.

Differences in the measured and predicted resonant frequencies were also
encountered. The empirically derived resistivity was also different between the top
and bottom sections. The transfer function matrix method of determining the dual
layer impedance is based on a microperforated panel. This configuration has no
separate resistive material covering the perforations. The configuration presented here
includes a thickness of resistive material covering the bottom layer, which can also be
considered to partially fill the cavity of the upper layer. This may introduce an added
damping effect by adding cavity resistance that is not accounted for within the model.
Its presence also reduces the cavity volume, which may affect the resonant frequency.

Discrepancies between the measured and predicted results may also be attributable to
the configuration of the material surrounding the perforations. By making one of the
cavity boundaries slightly porous, the air contained in the cavity becomes less
resistive to volumetric changes, effectively reducing the stiffness of the air within the
cavity. This would have the effect of decreasing the resonant response and could
potentially be utilised to reduce the volume required for low frequency resonant
absorbers.

The use of alternative theoretical models capable of combining the effects of different
porous / resonant configurations, might well improve absorption predictions.
Combining the impedance of multiple layers (Asdrubali, Pispola 2007) or including
the effects of sound transmission through the combined structure (Sakagami,
Morimoto & Koike 2006), should both be investigated as part of future work.

The fabrication of a single material broadband acoustic absorber using RM has been
demonstrated, without the use of additional fibrous materials or sub millimetre
features. Furthermore the ability to vary porosity, using the FDM process, adds the
possibility to produce a combined resonant / porous absorber addressing both low and high frequency absorption. This addresses the principal aim of this research.
Chapter 7

Conclusions

7.1 The Application of RM to Acoustic Absorption

The reduction of unwanted noise and the tailoring of the acoustic environment are possible through the use of acoustic absorbers. Traditional absorbers are based on simplistic manufacturing methods which restrict their design and discourage investigative research into their geometry. The use of RM technologies in the fabrication of acoustic absorbers offers considerably more freedom of design than traditional manufacturing processes. The ability to produce easily, small (∼1mm), intricate features enables the production of more complex shapes, allowing an empirical investigation into absorber geometry. In addition, RM processes utilising the selective deposition of discrete areas of solid material introduce the ability to fabricate porous topologies with acoustic relevance.

Low frequency Helmholtz type resonant absorbers rely on specific geometric configurations. Without adding acoustic resistance, their bandwidth of absorption is limited. Most practical resonant absorbers attain acoustic resistance through the inclusion of separate, undesirable materials or through the use of highly accurate, sub-millimetre features, which introduce manufacturing difficulties. RM offers a method of fabrication to address these issues through changes to the geometric resonator configuration, or by introducing porosity during fabrication.
7.2 Geometric Resonant Absorber Bandwidth Improvements

Analysis of the existing theories and research relating to acoustic resonators highlighted the resonator cavity as an area with potential to provide the acoustic resistance required for broadband absorption. Resonator response is less susceptible to dimensional changes, and therefore manufacturing inaccuracies in the cavity, compared to similar changes made to the orifice. Therefore resistive cavity modifications do not require the same accuracy constraints as resistive orifice solutions (e.g. microperforated panels). The modification or addition of internal cavity geometry aimed at increasing resonator resistance was instigated by:

- Increasing the cavity hydraulic radius;
- adding internal cavity restrictions;
- including additional surfaces within the cavity volume.

Viscous resistance at the cavity boundaries is dependent on the hydraulic radius of the cavity. The cavity hydraulic radius was modified through the use of fractal cavity shapes based on the Minkowski curve, with each fractal iteration decreasing the hydraulic radius by half. After 3 fractal iterations only a slight increase in resonator resistance was achieved (43 Pa s m\(^{-1}\)), resulting in an absorption bandwidth improvement of 9Hz. Only 3 fractal iterations were possible given the scale of the resonator cavity. The low resistance increase resulted in a negligible improvement in absorption bandwidth. The increase in resistance between different fractal iterations was consistent with the theoretical predictions suggested by Sapoval (1997). Using the measured results and observed trends it was concluded that 7 fractal iterations would be required to provide sufficient resistance for broadband absorption.

Internal cavity restrictions in the form of a perforated layer were added to resist the movement of air within the cavity. It was found that smaller perforations, lower fraction open area, and a higher position within the cavity all resulted in greater levels of resistance. The highest resistance demonstrated was 556 Pa s m\(^{-1}\), increasing absorption bandwidth by 100Hz. The highly variable configuration of the perforated plate easily allows a tailored amount of resistance to be added. Significant fabrication
issues were encountered whereby fabrication perforation sizes were not accurate. Consolidation of unsintered powder within the finest samples with 0.5 and 0.75mm radii prevented the formation of any perforations. To achieve the desired diameter each sample required reaming.

The addition of internal surfaces was achieved through the incorporation of cavity fins. Concentric fins occupying the region of planar air propagation were aimed at increasing viscous resistance; the concentric fins with 1mm spacing provided an additional 177 Pa s m⁻¹ of resistance, increasing the bandwidth of absorption by 49Hz. However fabrication issues were experienced relating to the removal of unsintered powder between the finest 1mm spaced fins, this caused a decrease in cavity volume of 3.12 x10⁻⁵ m³ (14 %), increasing the resonant frequency by 23Hz A conformal fin structure was developed to utilise the fabrication benefits of the fin structures and the faster moving upper cavity air, utilised in the internal perforation investigation. The developed solution added 195 Pa s m⁻¹ of resistance, providing an absorption bandwidth increase of 55Hz. This design represents a successful trade off between performance and fabrication.

The results of the investigation into geometric cavity changes indicated that high levels of resistance could only be achieved through the incorporation of features in the order of 1mm or less. Fabrication of these feature sizes was unsuccessful using Selective Laser Sintering. The use of a more accurate process could present a method of producing highly resistive internal geometries.

7.3 Fabrication of Porous Topologies Using RM

An evaluation of the acoustic properties of various RM materials revealed that materials produced using standard build strategies were highly dense, and exhibited predominantly reflective acoustic properties. The ability to vary the raster width and raster spacing of the FDM process has been shown to allow the fabrication of topologies with various levels of porosity. Control of these parameters has enabled the fabrication of a porous absorber, 25mm thick, which exhibited significant absorption over 1600Hz. Alternative parameter configurations have been used to produce
topologies more suited to providing acoustic resistance. The inclusion of these composition types as a resonator covering provided up to 2272 Pa s m⁻¹ of resistance, and in one example increased absorption bandwidth by 119 Hz. The resistive and absorptive properties of these topologies can be tailored through alterations to the FDM process parameters. The performance of these porous FDM topologies did not correlate with theoretical predictions. The unconventional pore structure is unlike traditional porous materials in terms of regularity, porosity and fibre size. Consequently theoretical models based on empirical derivations, such as the Bies and Hansen flow resistivity model and the Komatsu model for characteristic impedance and wavenumber, are not applicable. Theoretically derived models, such as the Johnson-Allard-Champoux model utilise shape factors relating to pore geometry and provide a more suitable method for predicting the acoustic properties of unconventional porous topologies. These theoretical approaches are limited by a requirement to accurately characterise the pore structure of the fabricated porous topology.

7.4 RM Enabled Single Material Broadband Absorption

The level of resistance achievable, configurability and ease of fabrication of the resistive FDM material makes it the most successful method of improving the absorption bandwidth of acoustic resonators using RM. The ability to produce structures offering porous absorption, acoustic resistance and fully reflective solid properties, from the same material, and in a single build, introduces potential to produce high performance, single material, broadband absorbers. This potential has been exemplified in the fabrication of a FDM, dual layer resonant absorber, damped using resistive material configurations, and also incorporating porous absorbing elements. Performance predictions of this structure indicate resonant absorption over a broad frequency range of 2234 Hz (>3 octaves) which is complemented by higher porous absorption over 3000 Hz.

This example demonstrates how the highly configurable topology offered by FDM can be used to produce a broadband, single material absorber. It draws on the initial acoustic findings uncovered by this research but does not represent a final solution.
Further investigation into the acoustic properties of the FDM configurations, and into the types of absorber constructions it can facilitate, may lead to solutions offering higher absorption, over a larger range, from a smaller sized absorber.

The main contributions offered by this work have been the introduction of new RM technologies to the application of acoustic absorption. Investigation of resonant absorber design, enabled through the use of these technologies, has highlighted how different approaches to modifying the cavity geometry can be implemented to achieve the acoustic resistance required to increase the bandwidth of resonant absorption. The use of the FDM process to selectively deposit material filaments has been proven to be significant to the application of acoustic absorption. Control of the size and orientation of the filaments introduces a method of producing configurable porous topologies, allowing control of the acoustic response through changes to the process parameters.

7.5 Future Research and Practical Implications

The investigation into the addition of cavity geometry focused on addressing the effects of cavity shape separately to adding cavity features in the form of concentric fins and perforations. Consequently the effects of each modification could be determined. Development of these initial simple configurations based on the results obtained, has already proven to be successful in the conformal upper cavity fin design. Using this initial research as inspiration, there is much potential to be uncovered through the development of further internal cavity geometries.

The practical application of the fractal cavity shape limits how far the hydraulic radius can be changed. The scale of most resonant absorbers restricts the number of fractal iterations that can be applied before the fractal segments become too small to fabricate. The presented investigation of cavity shape was limited to two dimensional changes of the cavity cross section. Extending the application to 3 dimensions may present a method of further decreasing the hydraulic radius and increasing the amount of resistance.
The concentric fins and the upper cavity conformal fin designs are both cavity additions, rather than cavity modifications. Therefore they could be retrofitted into existing resonators, or allow resonator resistance to be varied using interchangeable fin configurations. The spacing between fins ultimately defines the maximum amount of resistance that can be achieved from the presented configurations; therefore their practical application can only extend to resonator configurations which require light damping. The concentric fins design represents a simple design with few design variables. The use of RM processes offers much higher levels of possible fin complexity. Higher levels of resistance may be achievable through the incorporation of more tortuous propagation paths, or by adding interconnections between adjacent fins to encourage more complex air flow. The fin spacing and associated powder removal issues could possibly be reduced through improved fin design: interconnected fins with no solid base would allow powder removal access from both ends, and a clear path through the part to facilitate powder removal using compressed air. Alternatively producing a fin configuration in two sections, and assembling them after fabrication could potentially alleviate fabrication issues.

As with the fins, the internal perforations offer the potential to be retrofitted or swapped within the cavities of existing resonators. The major issues relating to the use of perforated layers produced using RM, were the fabrication problems encountered regarding powder removal and dimensional accuracy. The measurement of different fabricated perforation sizes, and comparison with their intended design dimensions could lead to a method of accurately predicting their final dimensions, allowing samples to be produced which match the intended design without significant post processing. Further study of the perforated plate parameters and their cavity position may lead to a model capable of predicting resistance based on the fraction open area, perforation radius and position within the cavity. The use of perforations was chosen as it represents the simplest method of adding restrictions. Alternative restrictions, such as slits, fractals, or more three dimensional geometries may be equally as effective at restricting the motion of cavity air, and may prove easier to fabricate. The influence of adding more than one layer of perforations could also be investigated.

The fin and perforation investigation has focused on forcing air through constrictions of ever decreasing size, in an effort to increase resistance. The strength in using the
geometric freedom offered by RM is not in the size of features that can be fabricated, but in the feature complexity that can be achieved. It has been shown that there are limits to the amount of complexity that can be achieved for a given scale of fabrication; however both the concentric fin and perforation designs are geometrically simple. Further research into the acoustic resistance possible through geometric modifications should focus on complexity rather than feature size.

The inclusion of cavity fins and perforations to the upper cavity area highlighted that adding features to interact with faster moving air can result in increased resistance. Further investigation into the nature of oscillatory air movement in and around the resonator using finite element, computational fluid dynamics would allow a more informed understanding of the areas of high flow velocity. This could then be used to optimise resonator design, or the design of resistive cavity geometries to interact with areas of faster moving air more effectively and produce higher levels of resistance.

The use of FDM to produce variable topological configurations has shown great potential in the fabrication of both porous absorptive and acoustically resistive topologies. The samples produced for this investigation have demonstrated an ability to control the porous absorptive properties and the amount of resistance achieved. The inaccuracies encountered in the application of existing theoretical models to predict the response of these new porous topologies indicates that a more in-depth investigation is required. One major source of error was the use of empirically derived flow resistivity predictions. The use of a more theoretical flow resistivity model such as the one given by Stinson and Champoux (1992) which considers the pore shape and hydraulic radius, may lead to improved absorption predictions. The suitability of different models could be validated through comparison with empirical flow resistivity measurement of the FDM porous samples. Further error may be attributable to assumptions made regarding the structure of the fabricated porous structure.

The use of more suitable theoretical models and an improved classification of the pore configuration, could lead to a better prediction of the acoustic behaviour of these homogenous configurations using existing theories. Once the structure and acoustic properties are accurately modelled they can be related to the process parameters, allowing an easily configurable porous absorber to be realised. The design of
structures incorporating traditional porous absorbers is restricted by the fixed acoustic properties of the material used. The use of a configurable porous topology allows the acoustic properties to be tailored to the intended application, offering more design freedom to acoustic absorbing structures.

The samples produced represented very simple configurations with only two variables; raster width and raster spacing. The porous configurations produced possessed simple square pore shapes, homogenous porosity levels and straight propagation paths through the structure. The modification of the FDM process parameters offers the potential to incorporate more diverse fibre arrangements. The angle offset between adjacent layers can be varied, producing different pore cross sections, and more complex propagation paths. The parameters of each layer deposited can be varied independently of the other layers; this opens the possibility of producing parts with variable porosity throughout their depth. This would allow a controlled level of tortuosity to be designed into the material. The existing FDM process software only allows modifications to be made to entire layers, restricting changes to the Z-direction only. The ability to vary the material configuration throughout a single layer is only restricted by the current software and not the fabrication method. Software improvements could lead to the ability to tailor the porous topology in three dimensions, allowing 'volumes' within a part to exhibit different acoustic properties to that of the surrounding material.

The use of the FDM process to produce porous acoustic topologies offers configuration flexibility - an ability not previously possible with traditional porous materials. Most theory relating to the response of porous materials has an element of empirical derivation. This is due to the random nature of traditional porous materials; e.g. random fibre orientation, or pore size. The ability to control the porous parameters, and repeatedly produce more uniform configurations offers an opportunity to investigate the factors influencing the acoustic properties in more depth. This has the potential to add further non-empirical derivations to porous material theory.

The ability to fabricate parts incorporating different acoustic properties introduces the opportunity to design absorber structures combining different methods of absorption.
from a single material. The combination of resonant and porous absorber types allows both low and high frequencies to be addressed, without the need to introduce large thicknesses of undesirable porous materials. Further investigation into the design of combined effect absorbers, may lead to absorption bandwidths greater than previously produced using single material absorbers. The developed dual layer resonant / porous absorber indicated that the incorporation of different absorption methods within the same structure, affects the absorption of the individual elements. Therefore the use of improved theoretical models, capable of combining the impedance of all the different porous and resonant elements, is required to accurately predict the absorption of structures such as these.

The scale of parts that can currently be fabricated using the commercially available FDM processes, limits the immediate application of these absorber types to noise suppression treatment rather than room acoustics. The materials that can be fabricated using FDM are mainly plastics, restricting their use to low temperature applications. However a recently introduced material (Polyphenylsulphone) can produce parts with a glass transition temperature of 230°C (Bak 2003), potentially permitting engine exhaust noise suppression as a possible acoustic application. Process and material developments may eventually allow the use of this technology on a larger scale, and in harsher environments.

This investigative research into the potential of using RM in the fabrication of acoustic absorbers, has uncovered benefits relating to performance, fabrication and materials. While these advantages have been demonstrated, their full potential has not been uncovered. The conclusions relating to the different objectives of the investigation have instigated questions of much interest, and have highlighted significant areas for future research.

To date this work has been published within the Rapid Prototyping Journal and has been disseminated at the 19th International Conference on Acoustics. Further publications are being prepared for both acoustics and RM audiences.

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Appendix 1

Sound Absorption Testing

To ascertain the absorption properties of acoustic absorbing structures there exist consistent test methods described by British Standards. Large samples can be tested in a diffuse sound field, indicative of their application, using a reverberation chamber, while detailed absorption characteristics can be measured using the small scale impedance tube method.

The reverberation room method is described in BS EN ISO 354:2003 (British Standards Institute 2003). The test method described is intended to simulate the real conditions in which acoustic absorbers will be practically used, where the sound field will be of random incidence and the real effects of acoustic absorption (reverberation time) are measured to calculate the absorption. The basic test method involves producing a constant sound and measuring the time decay time once the sound has been stopped, the reverberation time can then be calculated. By comparing the reverberation time of the room with and without the specimen present, the equivalent sound absorption area can be calculated. This can then be divided by the surface area of the specimen to give the absorption coefficient. The problem with this method is its reliance on large specimen sizes (in the order of 10m²) making it unsuitable for the measurement of samples produced using currently available RM processes.

The measurement of acoustic absorption using the impedance tube method is considered a reliable, repeatable test method. This is exemplified by its adoption as a British Standard (British Standards Institute 2001b). The test method uses an enclosed tube with totally reflective internal surfaces to set up a standing planar wave using sound energy provided by a loudspeaker attached to a pure tone generator. The material whose absorption and impedance properties are to be measured is placed in front of a metal termination plate at the end of the tube. As it can be assumed that the
only absorption within the tube is that provided by the sample, measurement of the standing wave set up in the tube can be used to determine the absorption and impedance of the sample. The measurement of the standing wave can be undertaken by hand using a movable microphone (British Standards Institute 2001a), or using an automated acquisition method incorporating fixed microphones (British Standards Institute 2001b). The automated method BS EN ISO 10534-2, utilises two fixed microphones and randomly generated Gaussian white noise to allow a complete frequency absorption test to be automatically carried out in a matter of seconds, removing the need for tedious measurements of standing wave pressure peaks at separate frequency intervals (Figure 8.1). The outputs of the two microphones are fed into a Fast Fourier Transform (FFT) signal analyser that is capable of measuring the sound pressure at each microphone and can calculate the transfer function \( H(\omega) \) between them (British Standards Institute 2001b, Seybert, Ross 1977).

![Figure 8.1: Two microphone impedance tube schematic.](image)

The fraction of sound energy reflected is given by the reflection coefficient, \( r(\omega) \), and can be calculated from,

\[
    r = \frac{H e^{jkz_1} - e^{-jkz_2}}{e^{-jkz_2} - H e^{-jkz_1}},
\]

Eq 8.1

where \( z_1 \) (m) and \( z_2 \) (m) are the distance to Mic 1 and Mic 2 respectively (Cox, D'Antonio 2004).
and subsequently the absorption coefficient $\alpha$ ($\cdot$) is:

$$\alpha = 1 - r^2.$$  \hspace{1cm} \text{Eq 8.2}

The absorption coefficient only gives an overall measure of energy loss, however the surface impedance can also be calculated to give more insight into the absorbent properties of the test material. The acoustic impedance $Z$ (N s m$^{-3}$) is often calculated as a relative value to the impedance of the surrounding air $Z_0$ (N s m$^{-3}$).

$$\frac{Z}{Z_0} = \frac{1 + re^{i\theta}}{1 - re^{i\theta}},$$  \hspace{1cm} \text{Eq 8.3}

where $\theta$ (deg) represents the phase change at reflection. Using Euler’s Equation, $ZZ_0$ can be represented as:

$$\frac{Z}{Z_0} = \frac{1 + r(\cos \theta + isin \theta)}{1 - r(\cos \theta + isin \theta)},$$  \hspace{1cm} \text{Eq 8.4}

which can be multiplied by its complex conjugate in order to reduce the equation to have a single imaginary part,

$$\frac{Z}{Z_0} = \frac{(1 + r \cos \theta)(1 - r \cos \theta) + (1 + r \cos \theta)ir \sin \theta + (1 - r \cos \theta)ir \sin \theta + i^2 r^2 \sin^2 \theta}{(1 - r \cos \theta)(1 - r \cos \theta) + (1 - r \cos \theta)ir \sin \theta - (1 - r \cos \theta)ir \sin \theta - i^2 r^2 \sin^2 \theta}$$

$$= \frac{1 + 2ir \sin \theta - r^2}{1 - 2r \cos \theta + r^2}.$$  \hspace{1cm} \text{Eq 8.5}

The real part of this equation is:

$$\frac{Z_{\text{real}}}{Z_0} = \frac{1 - r^2}{1 - 2r \cos \theta + r^2},$$  \hspace{1cm} \text{Eq 8.6}
and the imaginary part is:

\[
\frac{Z_{\text{imaginary}}}{Z_0} = \frac{2ir \sin \theta}{1 - 2r \cos \theta + r^2}.
\]

Eq 8.7

To obtain the normalised acoustic impedance values, each of these expressions must be divided by the impedance of air,

\[
Z_0 = \rho c,
\]

Eq 8.8

where \( \rho \) (kg m\(^{-3}\)) is the density of air and \( c \) (m s\(^{-1}\)) the speed of sound in air.

The real part of acoustic impedance is known as the resistance and is associated with the energy losses that occur, while the imaginary part is known as the reactance and is associated with phase changes.

To measure frequencies up to 1600Hz, a tube with 100mm diameter is used. After this frequency the wavelength is too short to ensure planar wave propagation. For higher frequencies a smaller 28mm diameter impedance tube is used. The scale of the samples required for the impedance tube is more suited to fabrication using RM. Unlike the reverberation room the impedance tube only measures absorption of normal incidence sound waves and therefore is not entirely indicative of the properties of a material when installed within a room.
Appendix 2

Standard Resonator Performance

While the simple geometric features associated with traditional Helmholtz resonator forms are well within the capabilities of the majority of commercially available RM processes, any affects on resonator performance characteristics need to be determined. The feasibility of resonator fabrication has been proven through the fabrication of standard benchmark resonator geometry, following the selection of a suitable process. To determine the performance characteristics the measured absorption of this standard test geometry was compared against that predicted by the analytical model (Eq 3.17). To ensure any observed effects are attributable to the resonator characteristics and not to uncertainties in the experimental configuration, a sensitivity analysis was carried out to establish the confidence in the measured results.

9.1 Fabrication

The configuration of the standard benchmark resonator mirrors the design of the theoretical model used as the base model in resonator parameter study in Section 0. The 15mm neck diameter and length are large enough to allow easy fabrication and also have low inherent resistance. A design resonant frequency of 300Hz avoids the frequency limits of the test apparatus, whilst still demonstrating low frequency absorption. This allows for a sensible cavity volume of $2.198 \times 10^{-4}$ m$^3$ (calculated using Eq 2.3), suitable for testing within a 100mm diameter impedance tube. This configuration forms the basic design of all test resonators; accordingly the cavity volume also has scope for expansion as the addition of internal features may require. The standard resonator configuration is shown in Figure 9.1.
Factors affecting the selection of an appropriate RM process for the proposed testing are the ability to fabricate internal features in enclosed cavities, and to create complex internal features. The removal of support material from complex inaccessible features can be problematic and can be assisted by the use of a dissolvable or powder based support system. Even surface finish is required to promote consistent air flow over all surfaces in order to ensure consistent viscous resistance between samples. The availability / access to the process will affect the number of samples that can ultimately be produced, and the time taken to produce them. For the purposes of evaluating cavity geometry the properties of the RM material must be non porous to ensure air flow is restricted to the cavity and neck area. The strength of the samples must be adequate to withstand rough handling and multiple mounting and removal from the test apparatus.

The process that satisfies these criteria most fully is Selective Laser Sintering (SLS) (Section 2.3.1), particularly in its ability to produce full strength nylon parts, with complex internal features being self-supported by the surrounding powder during fabrication. The standard resonator configuration was fabricated using SLS and is shown in Figure 9.1(a). The base of the cavity was left off the model to simplify fabrication and reduce problems with the removal of support material. Instead it takes the form of a separate aluminium sheet fixed in place with four M4 bolts and sealed with silicone sealant.

Figure 9.1: Standard resonator: (a) Fabricated part (b) CAD cross section (c) CAD cavity positive with dimensions.
9.2 Absorption

To determine the improvement in acoustic absorption of the proposed resonant absorber modifications, the response of the standard benchmark resonator must first be established. The absorption properties were measured using an impedance tube in accordance with BS EN ISO 10534-2 (British Standards Institute 2001b). A two microphone transfer function method was employed with the use of a computer data acquisition unit as described in Appendix 1. This method was used as it allows relatively small, 100mm diameter samples to be tested, and can accurately determine small variances in absorption characteristics. The impedance tube used was an SCS 9020 Kundt device. The test sample was mounted in the sample holder; however, manufacturing inaccuracies in the sample resulted in small air gaps around the sample perimeter, these were subsequently sealed prior to measurement. A 01dB Symphonie PC data acquisition unit was used to record the microphone responses and output the test signal to the impedance tube speaker via an amplifier. The microphones used were GRAS 40AI ½” condenser microphones. 01dB Metravib dBAalphaTest software was used to collect and interpret the data which was subsequently exported into Matlab to produce the absorption plots. The test equipment setup is shown in Figure 9.2.

![Figure 9.2: Impedance tube test equipment.](image)

The absorption coefficient values were acquired at a resolution of 3.125 Hz and plotted on a logarithmic 1/3 octave frequency scale from 125Hz to 630Hz, to focus on the resonance curve. The measured results are shown as a solid line in Figure 9.3 below. A theoretical absorption curve was produced from the model of impedance
derived from the work of Ingard (1953) (Eq 3.17), using the same cavity and orifice dimensions as the fabricated sample. This is plotted as a dotted line, so the responses can be compared.

The resonant frequency of the measured resonator matches that of the prediction. The bandwidth of absorption when \( \alpha \) exceeds 0.4 covers 37.5Hz. An \( \alpha \) value of 0.4 was chosen as the level at which to measure bandwidth as it can be considered a significant level of absorption for room acoustics applications, and has previously been used in the measurement of resonant absorber bandwidth (Kang, Fuchs 1999). A discrepancy between the measured and predicted absorption curves can be noticed. Referring to Figure 3.2, the addition of a small amount of resistance to a lightly damped resonator has the effect of increasing the peak absorption frequency as well as broadening the bandwidth of absorption. This behaviour can also be noticed in Figure 9.3, indicating a slight increase in resistance over that predicted by the model. This is likely to be caused by an increase in viscous resistance caused by the surface finish resulting from the SLS process. The results of this standard benchmark resonator, provides a base model against which to compare the performance of resonator developments.
9.3 Experimental Uncertainty

Without some estimation of confidence, observed differences due to uncertainties in the measurement method or instrument calibration may be incorrectly interpreted as a significant effect of the sample being tested.

To ascertain the level of confidence in the measured absorption results, a study was conducted to test the repeatability of the absorption results. The differences in consecutively measured results were compared in statistical analysis to obtain a band of values representing a 95% confidence level for each frequency point.

The sources of uncertainty may be inherent in the testing method, or in the calibration of the test equipment. There may also be uncertainty with the physical setup of the test part. Therefore three comparison schemes were devised to measure each source of uncertainty:

- Consecutive measurements without any recalibration or remounting of the sample to ascertain uncertainty inherent in the test method;
- Consecutive measurements with recalibration of the test equipment between each test, but without remounting of the sample, to test calibration uncertainty;
- Consecutive measurements without recalibration, but removing and remounting the test sample to ascertain uncertainty in the physical setup.

Each scheme consisted of a sample size (N) of 6 sets of absorption curves.

The mean absorption curve of the six sets of data is calculated by averaging the absorption value at each frequency point. The mean value is calculated using,

$$\bar{\alpha} = \frac{1}{N} \sum_{i=1}^{N} \alpha_i$$  \hspace{1cm} Eq 9.1

The corresponding standard deviation ($S_\alpha$) at each frequency point is given by,
To obtain values of uncertainty for each source, the random uncertainty can be calculated within a given confidence level. This allows the magnitude of uncertainty to be expressed absolutely, in terms of the absorption coefficient, $\alpha$. The random uncertainty ($P_\alpha$) at each frequency point is,

$$P_\alpha = \frac{t' S_\alpha}{\sqrt{N}},$$

Eq 9.3

where $t'$ is the value given by a t-distribution table for $N-1$ degrees of freedom and the required confidence level. A t-distribution is used rather than a Gaussian distribution, as $S_\alpha$ is only an estimation of the true standard deviation based on a finite number of readings $N$ (Coleman, Steele 1999). For the purpose of this analysis a confidence level of 95% is used with 5 degrees of freedom ($N=6$), which corresponds to $t' = 2.015$.

The confidence plots for each of the three comparison schemes are shown in the figures below. The dotted curves represent the mean absorption ($\overline{\alpha}$), while the solid lines are the 95% confidence intervals ($\overline{\alpha} \pm P_\alpha$). Figure 9.4 to Figure 9.6 show the confidence levels for each of the three schemes and Figure 9.7 compares the absolute uncertainty values of each scheme.
Figure 9.4: Measurement uncertainty – consecutive retests.

Figure 9.5: Measurement uncertainty – recalibrated equipment.
From the plots it can be seen that the uncertainty between consecutive tests, without recalibration or remounting of the sample is very low (<0.005\(\alpha\)). The uncertainty following remounting of the sample, but maintaining the same calibration is higher but under 0.02\(\alpha\) for the frequencies of interest. The uncertainty following recalibration of the test equipment is higher than the other two schemes, particularly at frequencies below 200Hz.
It can therefore be concluded that in order to minimise the uncertainty within a group of samples whose results are to be directly compared, they should be tested in the same session without recalibration of the test equipment. If this is observed, any changes above 0.02\(\alpha\), can be considered significant.