Diffuse field measurements of Locally resonant partitions

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ABSTRACT

Noise control at lower frequencies is becoming increasingly important with housing densification, as this frequency range is where the threshhold of the human ear is at its highest and sound insulation is the most challenging and expensive. Meta-materials offer a novel approach to achieving sound and vibration management through the use of panels with internal resonant structures with geometries sub-wavelength. These structures can yield significantly greater transmission loss than conventional insulation systems. Numerical models based on networks of single-degree of freedom oscillators were used to understand how the components of the locally resonant structure (LRS) can be manipulated to generate desirable sound transmission loss (TL) performance spectrums. Designs with the targeted TL characteristics were then examined in detail under FEA and plane wave impedance tube testing and samples were fabricated using industry-standard materials and processes. This paper focuses on the acoustic testing of large scale LRS samples at low frequencies under diffuse field conditions. Locally resonant partition wall systems were designed to target frequency regions where poor TL is expected such as the mass air mass region (MAM) and the coincidence frequency region (CF). Samples from between $2m^2$ to $10m^2$ were tested with variations in system arrangements such as mass and geometry. Results are presented here for $2.4m^2$ samples which showed significant TL improvements with approximately $20dB$ improvement above that of a conventional panel over bandwidths in the order of $300Hz$. Comparisons were made between, numerical predictions and plane wave experimental results. The resulting systems have the potential to provide significantly higher transmission loss at low frequencies than conventional wall systems of similar size and weight.

1 INTRODUCTION

As traffic density increases, domestic home entertainment systems grow and automation proliferates, so does noise pollution. There is increasing concern in New Zealand Rudman 2006 and overseas (Wright, Skinner, and Grimwood 2001; Sounds 2008), about inadequate sound insulation in buildings and the consequent implications for occupants' health and well-being both in the public and private sector. Indications from recent studies (Nivison and Endresen 1993; Patterson and Bowen 2004) show growing dissatisfaction from residents regarding the acoustic performance of their accommodation. The problem is particularly evident in medium-high density housing situations, which are projected to become 30 percent of Auckland's housing by 2050 (Lyne and Moore 2004).

Irritating acoustic intrusion frequently occurs at low frequencies, below $1kHz$ (eg; the bass beat from music systems). Sound within this frequency range is often found in the work-place, and can cause loss of concentration and thus reduced productivity. Achieving effective isolation in this range is both challenging and expensive with conventional solutions, which require significantly increasing the density, mass or thickness of the partition through which the sound is transmitted. This introduces additional weight and costs as well as a reduction in usable floor space. The mass law is a commonly used approximation for predicting the ability of a single panel to reflect sound at frequencies below coincidence. It assumes that the partition element is infinite, that the panel has negligible bending and shear stiffness, that the partition element has no damping forces and that the incidence waves are plane waves at any angle of incidence (Beranek and Ver 1992). The mass law may be expressed as a magnitude of sound transmission loss (TL) by the equation:

$$TL = 10log\left[1+\left(\frac{\pi f M cos\theta}{\rho_a c_a}\right)^2\right] \tag{1}$$

where M is the mass, ρ_a is the density of air, c_a speed of sound in air, f is the frequency and θ is the angle of incidence. It can be seen from equation 1 that there is an increase in the TL of about $6dB$ for every doubling of the mass per unit area (Santos and Tadeu 2002) and poor performance at low frequencies below $1000Hz$.

Over the past few years novel approaches to sound and vibration isolation and absorption have been developed, based on the unique characteristics of an expanding field of materials known as metamaterials. Metamaterials, defined by S., Weiglhofer, and Lakhtakia 2003 as being man-made materials with three-dimensional periodic cellular structures, are designed to produce an optimised combination of two or more responses to specific excitation. Metamaterials can also be considered as generalized composite materials, with properties that are determined as much by their internal structure as by their chemical composition. Because of this, metamaterials can be engineered to have unique macroscopic properties not available in naturally found materials, such as negative density and stiffness.

By exploiting mechanical and acoustic resonances in the internal structure of a metamaterial their dynamic response can be designed to strongly interact with propagating waves around certain frequencies, potentially creating band gaps. Ho et al. 2005 introduced a new elastic metamaterial concept known as a locally resonant sonic material (LRSM), which relied on mechanical resonances created by metal spheres coated in soft silicone and embedded in a polymer resin matrix. LRSM panels have been shown to reduce sound transmission at low frequencies by over $50dB$ (Liu et al. 2000). This was significantly more than conventional panels of similar mass and thickness. They attributed the observed behaviour to negative effective density in the LRSM around resonance. More recently it has been shown that the attenuation band corresponds quite closely to the frequency region where the absolute value of the effective or dynamic mass is significantly increased by resonance motion.

The ultimate goal of this research is to design and demonstrate an acoustic insulation system that provides improved sound insulation performance over a system with an equivalent mass density within this frequency range. Research has focused on developing new knowledge and implementations of elastic meta-materials with locally resonant structures (LRS) with the ultimate goal of designing a structure that has the following qualities:

- High sound insulation below about $1kHz$
- Lightweight
- Relatively thin
- Appropriate structural integrity
- Cost effective and easily fabricated

2 THEORY

2.1 Sound transmission loss through partitions

In order to improve TL over a single leaf partition whilst maintaining low-weight and low cost, double leaf partitions are used. Internal wall structures are often constructed of two plaster boards panels with a wood or steel framing to separate the panels and provide structural integrity. Within the panels, a layer of sound absorption material is often added to improve the TL. The double leaf panel fabrication technique does not follow the mass law prediction. There are four distinct regions when observing the TL though a double leaf wall.

Region one relates to the low frequency range. The partition behaves like a single leaf partition with a combined mass of both leaves. The second region is known as the mass air mass (MAM) resonance. The MAM resonance has a large detrimental effect to the insulation of sound and is described in the following section. In the third region, above MAM, the leaf on the transmitting side of the panel (furthest away from the source of the sound) acts as a mass, driven by the motion of leaf on the source side through a spring provided by the air in the cavity. The fourth region at higher frequencies (typically above 1kHz), a thin plate, bending waves may be excited by an incident sound field and which travel along the partition. At any frequency above a certain critical frequency there can be found an angle of incidence for which the wavelength of the bending wave can become equal to the trace wavelength of the incident sound along the surface of the panel. This condition is known as coincidence and the frequency at which the coincidence phenomenon first occurs is when the wavelength of the bending wave in the material is equal to the wavelength of the projected incident sound in the air. This is called the critical frequency.

2.2 Mass air mass resonance

The mass air mass resonance (MAM) dip is a common problem found in most double leaf panel constructions. The dip typically occurs around $100Hz$. At a certain frequency the air spring and panel arrangement reaches a resonance where the panels are oscillating out of phase with each other. This problem is made worse when considering:

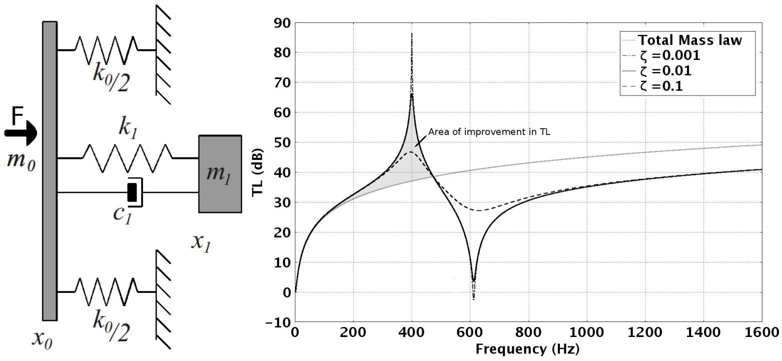
- Mass law behaviour of panels produces a poor insulation performance in this region,
- Most modern day home entertainment system include woofer or sub-woofer loudspeakers capable of creating high sound levels at low frequencies

- The trend in popular music towards bass driven music,
- The intensification of city living with higher density forms of dwellings and economies offered by light-weight construction methods
- Increases in traffic levels, construction and mechanical noise in general

A typical double-leaf gypsum system has a $50mm - 100mm$ air gap which may be filled with a fibrous sound absorption material (FM). The addition of FM material in the air gap improves the TL above the mass air mass resonance region due to its absorption properties and therefore reduction in cavity resonance. Around MAM there is no significant improvement in TL when absorption FM is added.

2.3 Locally resonant metamaterials

The LRSM concept can be generalized to a network of locally resonant units which can be elastically and acoustically connected in various ways. We refer to such networks of local resonators as locally resonant structures (LRS), where the local resonances provide a basic building-block from which a range of LRS can be constructed. It has been shown that the essential features of a local resonance can be captured by simple spring-mass models. Figure 1 is a single degree of freedom spring-mass model representation of a single resonator. This model shows a mass attached to a spring mounted on a backing layer suspended on two more springs. The point force applied to the layer represents the pressure applied by a plane wave sound field on the structure.



(a) Spring mass model (b) TL performance

Figure 1: Spring-mass model and an example of a TL vs Frequency performance plot for a single layer LRS

The response of the system shown in Figure 1 (where time dependence $e^{i\omega t}$ is assumed) is:

$$F = -m_o\omega^2 x_o + k_o x_o + k_1(x_o - x_1) + ic_1\omega(x_o - x_1) \tag{2}$$

and can be represented as the stiffness, damping and mass matrix:

$$\begin{pmatrix} F \\ 0 \end{pmatrix} = \begin{bmatrix} k_0 + k_1 - m_0\omega^2 + i\omega c_1 & -k_1 - i\omega c_1 \\ -k_1 - i\omega c_1 & k_1 - m_1\omega^2 + i\omega c_1 \end{bmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} \tag{3}$$

F is the externally applied force, x_0 and x_1 are the panel and resonator displacement respectively. m_0 and m_1 are the mass of the panel and resonator respectively while c_0, c_1, k_0 and k_1 are the damping coefficient and spring constant of the panel and resonator respectively. By rearranging and solving the matrix and assuming no damping it is possible to obtain the systems effective mass (m_T) as:

$$m_T = \frac{F}{a_{m_o}} = m_0 + m_1 \frac{w_1^2}{(w_1^2 - w_2)} \tag{4}$$

where ω_1 is the resonance frequency of the resonator. The features of a single frequency single layer LRS have been modelled and are shown in Figure 1. There is a large increase in sound transmission loss (TL) at ω_1 which occurs at $400Hz$ in the case illustrated. At this frequency the host material has its lowest acceleration magnitude and the LRS has a high effective mass. ω_1 may be manipulated by changing the mass and stiffness of the resonator spring and mass. The large dip in TL soon after this peak is the result of a high acceleration magnitude of both the host and resonator mass and therefore a low total effective mass. Single layer locally resonant units can be joined together to form layers which are then combined to form multilayered locally resonant structures (LRS) that can provide richer performance envelopes.

3 METHODOLOGY

3.1 Aim

This research was aimed at designing and building large-scale metamaterial partitions with taylored TL performance characteristics. Two TL performance features were targeted in these large-scale experiments.

- The first performance goal was to produce a band gap of very high TL around $500Hz$. This partition system was called the Single Resoannce LRS.
- The second performance goal was to reduce the $100Hz$ TL dip caused by the mass-air-mass resonance phenomenon in conventional walls. This partition system was called the Mass air Mass cancellation LRS.

A significant design constraint was that the panels had to be incorporated into existing building structures using conventional construction methods.

3.2 Partition Design

Large scale metamaterial partitions were designed to be integrated into conventional double leaf gypsum plasterboard partition systems. A conventional partition system can be described as a series system with two layers. With the addition of resonators attached to each layer, the double leaf system may be manipulated into a LRS with two layers in series, with each layer having parallel resonators attached. From the previous research (Hall 2013; Hall et al. 2011; Calius et al. 2009) we know that metallic resonators have a lower damping factor and can be applied in parallel with different resonance frequencies. This means metallic resonators have the most potential to achieve the goals stated earlier and for this reason it was proposed to fabricate a metallic cantilever beam arrangement. The design consisted of strips of multiple independent resonators. Samples were designed using lumped parameter mass and FEA modelling.

Normal incidence impedance tube samples were then fabricated and tested for proof of concept. Large scale partition samples were then fabricated and installed between two reverberation chambers. The samples were $2.65x0.9m$ and consisted of standard $0.01m$ thick gypsum plasterboard panels with resonator strips attached. Samples were then subjected to diffuse field white noise and TL measurements were carried out. Diffuse field TL results are given as the sound reduction index (R). This is a ISO unit standard measurement of the sound transmission loss through a partition and is equivalent to the TL. R will be referred to as TL when discussing results (for simplicity when comparing model and experimental results).

3.3 Diffuse field setup

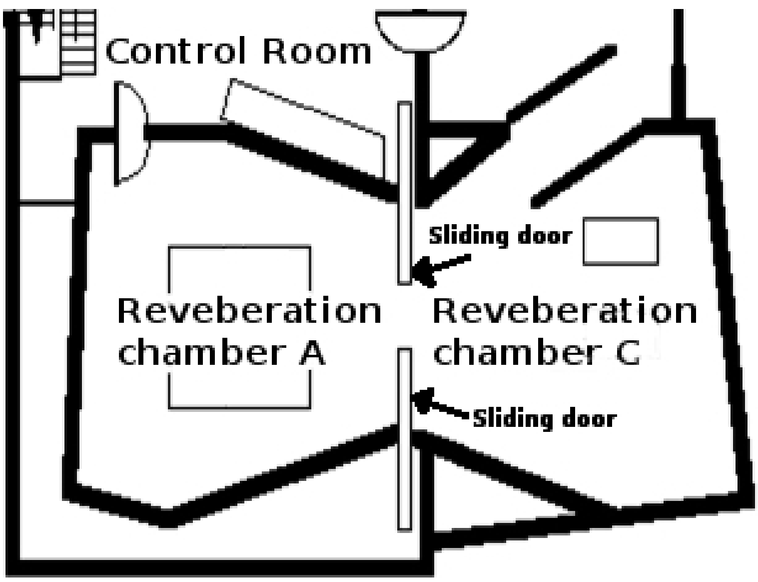


Figure 2: This figure shows the diffuse field testing facility

The room-to-room testing facility shown in Figure 2 used for full-scale diffuse field testing was designed to $ISO140-3$. Two reverberation rooms (202 and 208 m^3) are used to measure the sound reduction index of the samples. The test specimen was built to fill the adjustable gap between two well-insulated sliding doors that separate the two rooms. A broadband pink noise source signal is then placed in one of the rooms. The spatial average sound pressure and reverberation times (RT) in the emitting and receiving rooms is then measured and the TL found. The process is then repeated with the noise source in the other room. The absorption area of the receiving room was found using:

$$A = \frac{0.163V}{T_{60}} \tag{5}$$

where T_{60} is the reverberation time, V is the volume of the receiving room. The level difference (δL) of the specimen was then calculated from:

$$\delta L = 10log_{10}[P_0] - 10log_{10}[P_1] \tag{6}$$

where P_0 and P_1 are the reverberant sound pressures in the source and receiving rooms. Under the assumption of diffuse sound fields in the transmitting and receiving rooms the actual sound reduction index of the specimen was found using:

$$R_d = \delta L + 10log_{10}\left(\frac{S}{A}\right) \tag{7}$$

where S is the area of the wall specimen.

3.4 Reference testing

Testing was undertaken on a blank $2.65x0.9x0.01m$ double gypsum leaf wall with and without absorption material. to provided a basic performance comparison for the LRS panels. The results shown in Figure 3 have three main areas of interest including the MAM zone, the mass law zone and the coincidence zone. It can be seen that the MAM region ranges from $70-160Hz$, and was lowered in frequency and improved slightly with the addition of absorption material in the cavity. The reduction in the frequency of the cavity resonance due to the absorption material as a result has improved the TL above the MAM region significantly. At around $3500Hz$ a dip is evident which is the so-called coincidence dip. This dip is a common feature of both single and double-leaf constructions and is due to bending waves being excited in the panels when the incident sound field is diffuse (i.e. comprises of waves incident at a wide range of angles such as from reverberant room sound field).

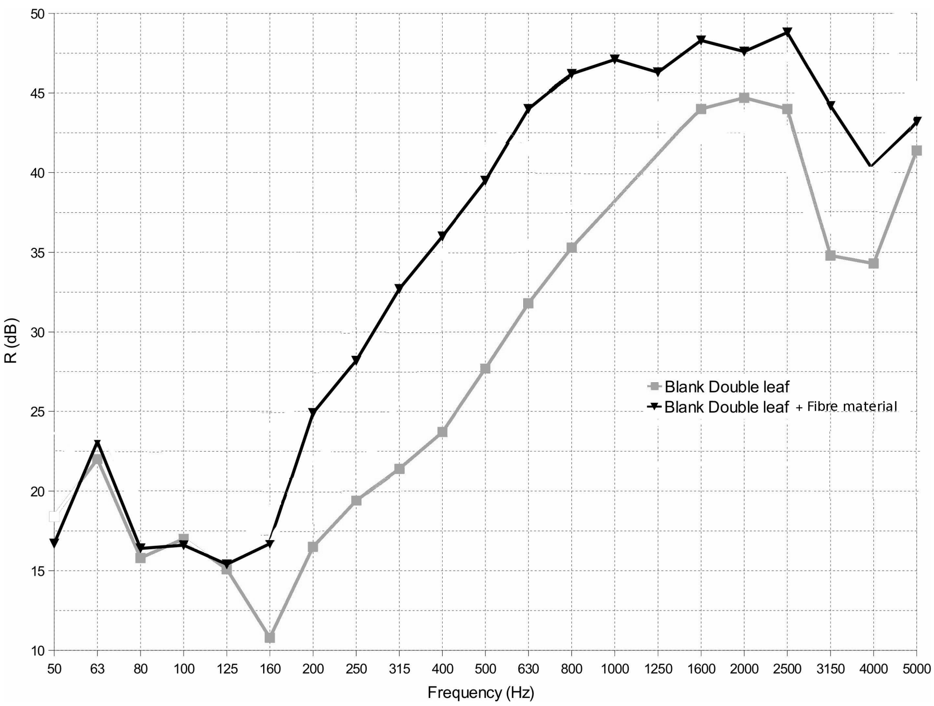


Figure 3: This figure shows reference sample diffuse field testing results

4 SINGLE RESONANCE LRS EXPERIMENTATION

4.1 Design

The single resonance LRS panel (SRLRS) was designed to integrate into the typical double leaf gypsum partition system found in light weight building structures with a single peak of high attenution. The resonator beam design used for the SRLRS is shown in Figure 4. The resonator design is constructed of 0.75mm gauge sheet steel.

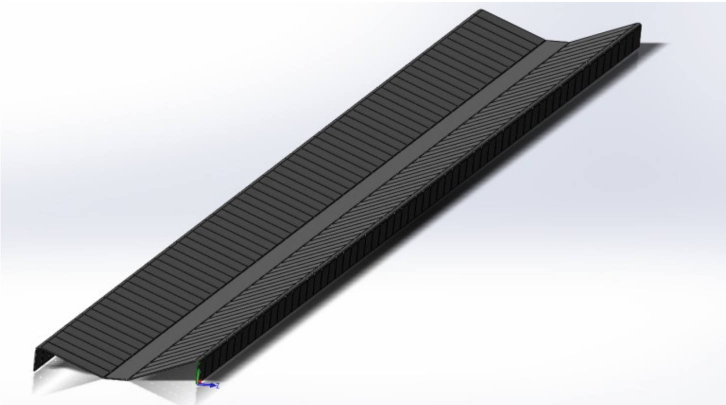


Figure 4: This figure shows an CAD model of the diffuse field resonator design

As shown in Figure 5, a folded section at the tip of the beam increases the tip mass of the resonator without the need of additional components. The folded 'M' section strips are $2.6m$ in length and are cut in to $40mm$ wide fingers. The finger width was determined by finding the minimum number of cuts per length of resonator strips whilst maintaining a torsion mode resonance frequency well above the first bending mode.

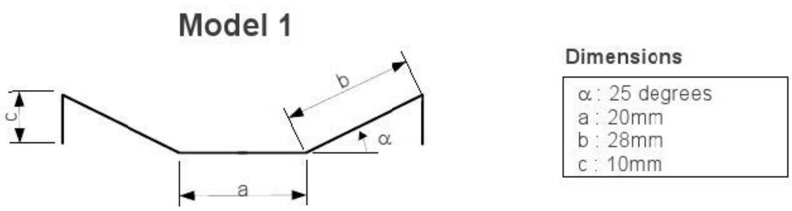


Figure 5: This figure shows the dimensions of the diffuse field resonator

4.2 Fabrication

Figure 6 shows the large-scale sample fabricated for diffuse field testing. The sample was constructed in a double-leaf gypsum wall configuration. Each layer of the panel was $2.65m$ tall $0.945m$ wide and $0.01m$ thick. Beam resonators were laser cut and folded into 2.6m length strips with the dimensions shown in Figure 5. The beam resonator finger width was determined by taking into account the need to keep the torsional mode frequency higher than the fundamental mode, and to minimise the number of cuts needed down the $2.6m$ length strips.

A beam resonator finger width of 40mm allowed for 126 resonators on each double-sided strip. Nine strips were attached to the inside of each gypsum wall layer using $3M$ double sided tape. The wall was then tested with and without FM within the cavity wall around the resonators. Impedance tube results showed a peak of high TL at $495Hz$ followed by a dip in TL at $520Hz$ corresponding to the resonance frequency of $500Hz$ predicted through lumped parameter mass and FE modelling.

4.3 Diffuse field testing results

Figure 7 shows the 3rd octave TL versus frequency results from the large-scale diffuse field testing in the reverberation chambers. The dashed line represents the TL results for the conventional double-leaf gypsum panel construction without absorption material in the cavity. The black line shows the TL for the same double-leaf construction with beam resonator strips. There is an improvement in TL between $125-500Hz$ with a maximum at $400Hz$. This peak in TL is the result of the beam resonators and reaches a TL of $45dB$, almost double that of the plain gypsum.

(a) One side of full scale wall (b) Resonators on metamaterial wall

Figure 6: An internal view of the SRLRS diffuse field sample

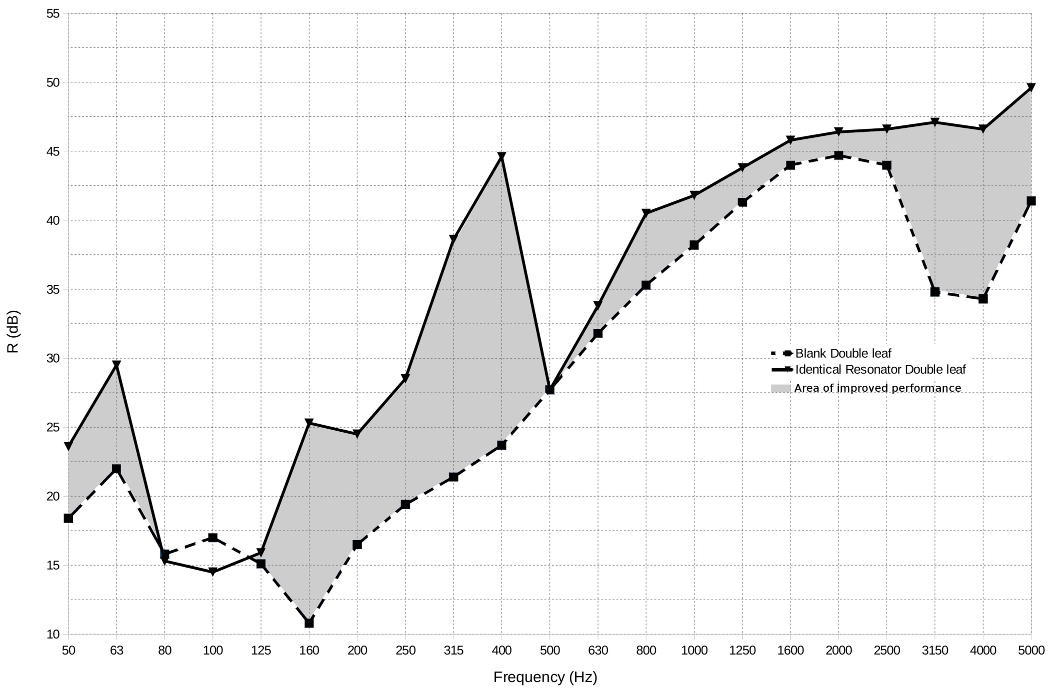


Figure 7: This figure shows the diffuse field results of the SRLRS without absorption material

The dip in TL at $500Hz$ drops to the same TL as the conventional panel before climbing and remaining approximately $3dB$ higher. The $3dB$ improvement is due to the added weight provided by the flat part of the ribs which are part of the beam resonator strips. The coincidence dip present in the dashed line has been removed almost completely by the LRS (black line). This is due to the rib-like construction of the beam resonator strips. The strips stiffen the panels in the longitudinal direction, effectively giving the material an anisotropic stiffness. This results in a smoothing effect over the coincidence region. Results from testing the same SRLRS wall with absorption material added to the cavity show similar improvement over a conventional conventional double-leaf gypsum panel construction with absorption material in the cavity. These results indicate it is possible to produce an LRS partition with high TL within a tailored frequency band for diffuse field applications.

5 MASS AIR MASS CANCELLATION LRS EXPERIMENTATION

5.1 Design

The Mass air mass cancellation LRS sample (MAMCLRS) was developed to improve the TL of the MAM resonance TL dip region. The system was based on a double layer parallel multi-resonance LRS which was designed to target two specific frequency regions, these are the MAM resonance region around $110Hz$ and the coincidence region around $3000Hz$. The resonator strips in the MAMCLRS have been based on the V design used successfully in the MAMCLRS. The resonator strips were $2.6m$ in length with a steel gauge of $0.75mm$. The strips were designed to have a spread of resonance frequencies over the MAM frequency region. As can be seen in Figure 8, a spread of beam resonance frequencies is achieved by changing the beam length of the resonator over the length of the strip while maintaining a constant tip mass. Beams were split in to 30mm widths to ensure the minimum frequency of resonance of the torsion modes was above the MAM resonance region. The system utilises the first bending mode of the cantilever beams. Each beam has a different resonance frequency created by the varying beam lengths. The lowest frequency chosen was $60Hz$ which required a beam length of $88mm$. The highest frequency was calculated to be 200Hz which led to a beam length of $45mm$.

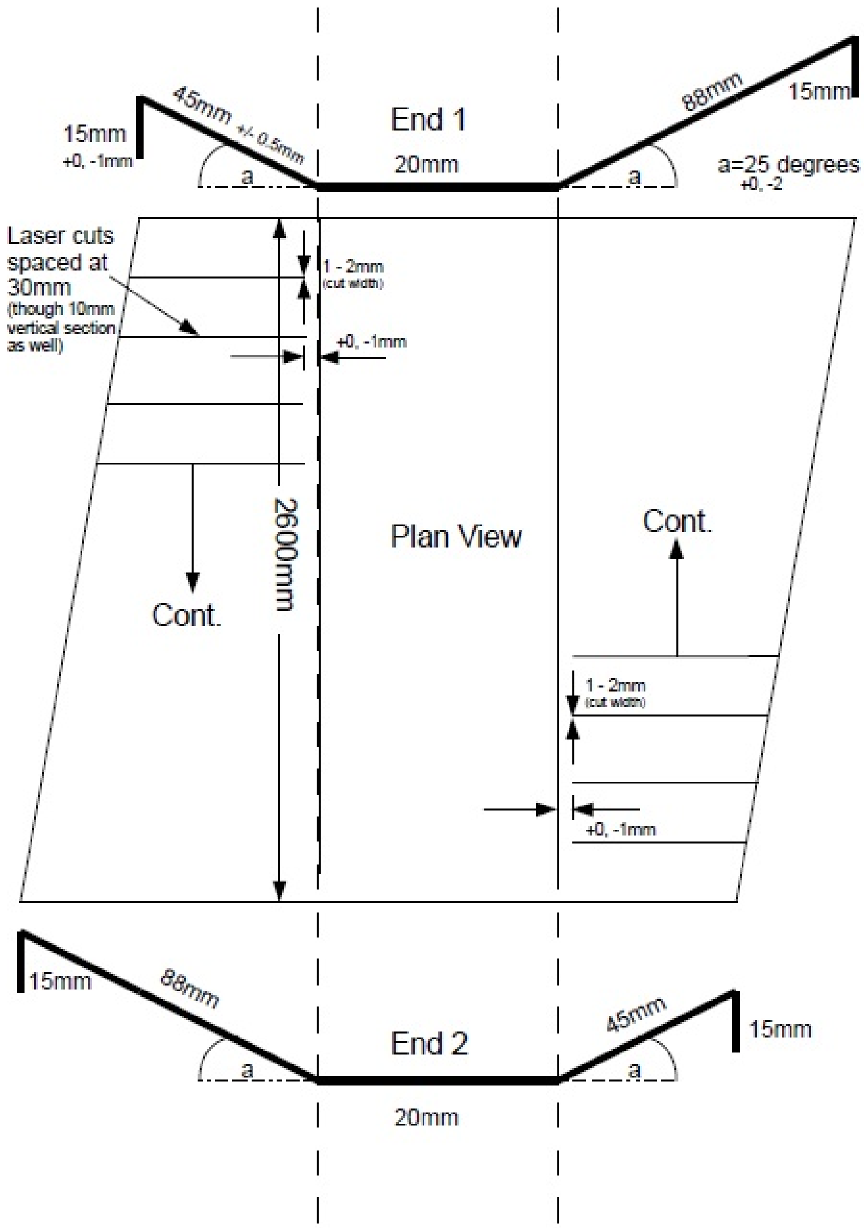
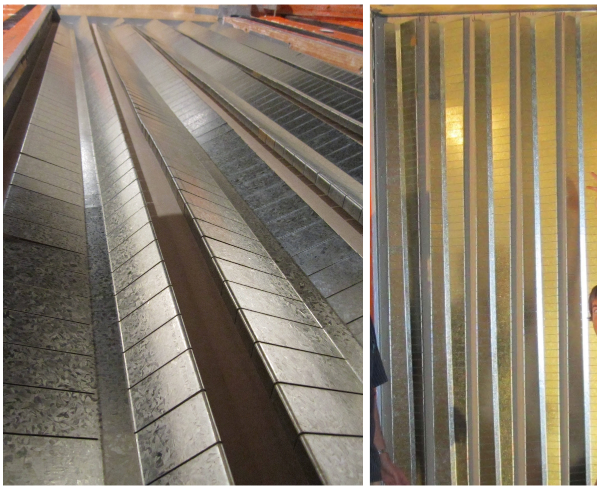


Figure 8: The dimensions of the diffuse field resonator

5.2 Fabrication



(a) One side of full scale wall (b) Metamaterial wall

Figure 9: An internal view of the MAMCLRS diffuse field sample

Much like the single resonance LRS panel, the base layer of the MAMCLRS was 2.65 tall 0.9 wide and $0.01m$ thick. The $2.6m$ resonator strips were $120mm$ wide. This allowed for a maximum of 5 resonator strips to be applied to each layer of gypsum plasterboard. For consistency the beam resonators were attached using 3M double sided acrylic tape. Figure 9 shows the MAMCLRS. Steel resonator beam strips are running vertically down the partition. The total mass added by the resonator strips to the gypsum panels makes up approximately 45% of the total mass. Both single and double layer systems were fabricated. Fibrous absorption material (FM) was included within the double layer sample.

5.3 TL results

Figure 10 shows the 3rd octave TL performance of the double layer MAMCLRS sample with absorption material compared to the equivalent conventional double leaf partition over a frequency range of $50-5000Hz$.

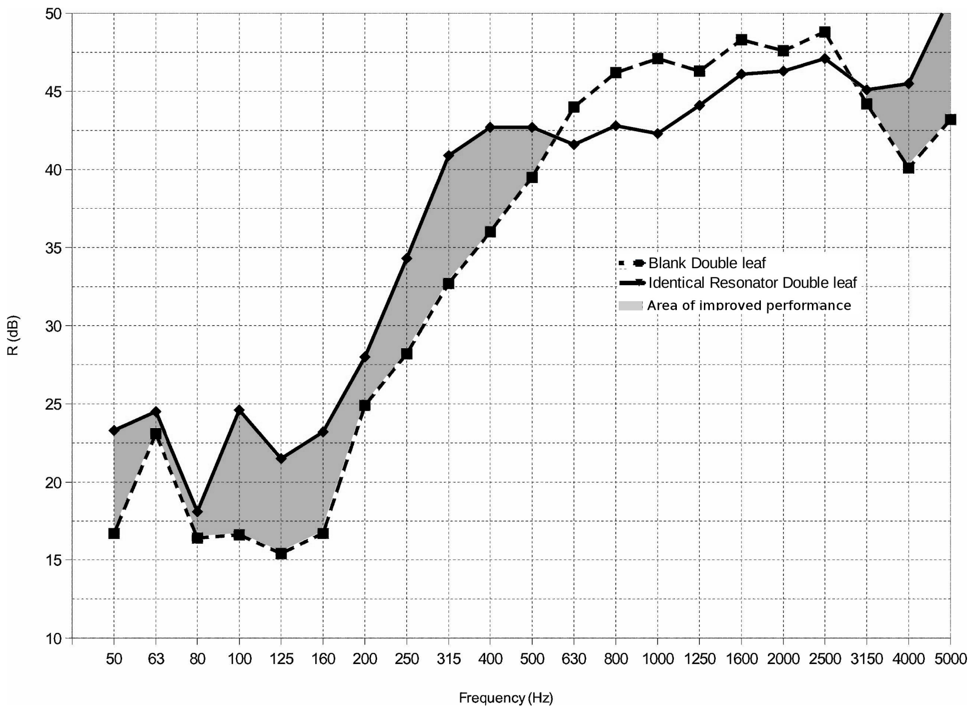


Figure 10: The diffuse field results of the MAMCLRS with absorption material in the cavity

There is an increase in TL in three different frequency regions. Around the MAM resonance ($110Hz$) there was an improvement in TL of around $8dB$ over the $65-200Hz$ region. A narrow dip in TL may be seen around $80Hz$. This indicates there was not enough momentum from the resonators within this region. In the coincidence region between $3150-4000Hz$, there was a significant improvement of around $6dB$ in TL. This was higher than the previous test without absorption material but still lower than results from the SRLRS test panel. In the region between $400-700Hz$ there was a large TL increase of up to $9dB$ over a wide band range similar to the results obtained without absorption material. These results suggest the higher modes of the cantilever beam do have a significant effect on TL. A similar performance improvement was seen without fibrous material in the cavity.

Table 1: ISO standards for wall samples with fibre material

Standard type	Conventional	SRLRS	MAMCLRS
STC	38	44	42
Rw	38	43	42
$Rw+C$ (50-3150)	35	39	40
$Rw+C_{tr}$ (50-3150)	29	30	34

6 SUMMARY AND DISCUSSION

Table 1 shows the STC, Rw, $Rw+C$ and $Rw+Ctr$ values for the SRLRS and MAMCLRS sample. The STC is the sound transmission class integer rating for how well a partition attenuates the airborne sound of speech. Rw is the weighted sound reduction index which is also a single integer number indicating the attenuation of an updated speech spectrum. C and Ctr are additional weighings for different types of incident sounds (i.e music and traffic noise respectively). C represents a higher weighting towards mid frequency sound while Ctr is used for a traffic noise spectrum. It can be seen from these results that the panels have taylored performance for the purpose they were designed for. The SRLRS has the highest STC and Rw of all three and is over $20dB$ higher in TL at $400Hz$. The MAMCLRS sample performs well in the $50-3150Hz$ region where that range includes the improvements in the MAM region. There is an improvement of $5dB$ over the conventional panel in both the $Rw+C$ and $Rw+Ctr$ values which highlights the performance gains in low frequency sound insulation over traditional partition constructions.

REFERENCES

Beranek, L. L., and I. L. Ver. 1992. *Noise and Vibration Control Engineering, Principles and Applications.* New York: Wiley.

Calius, Emilio, Xavier Bremaud, Bryan Smith, and Andrew Hall. 2009. “Negative mass sound shielding structures.” *Phys. Status Solidi B* 246 (9): 2089–2097.

Hall, Andrew. 2013. “Development and Application Of Locally Resonant Metamaterials for Acoustic Barriers.”

Hall, Andrew, Emilio Calius, George Dodd, and Eric Wester. 2011. “Modelling and experimental validation of complex locally resonant structures.” *New Zealand Acoustics* 24 (2).

Ho, K.M, Z Yang, X.X Zhang, and P Sheng. 2005. “Measurements of sound transmission through panels of locally resonant materials between impedance tubes.” *App. Acoust* 66 (751).

Liu, Zhang, Mao, Zhu, Yang, Chan, and Sheng. 2000. “Locally resonant sonic materials.” *Science* 289, no. 5485 (September): 1734–6. ISSN: 1095-9203.

Lyne, M., and R. Moore. 2004. “The Potential Health Impacts of Residential Intensification in Auckland City.” *School of Population Health, University of Auckland, and School of Applied Sciences AUT* (August).

Nivison, Mary Ellen, and Inger M. Endresen. 1993. “An analysis of relationships among environmental noise, annoyance and sensitivity to noise, and the consequences for health and sleep.” *Journal of Behavioral Medicine* 16, no. 3 (June).

Patterson, Matthew, and Norm Bowen. 2004. “Recent Building Code of Australia changes to sound insulation.” *AIRAH acoustics conference.*

Rudman, Brian. 2006. “War on inner-city noise leaves residents reaching for earplugs.” *NZ Herald,* no. 30.

S., Werner, Weiglhofer, and Akhlesh Lakhtakia. 2003. “Introduction to Complex Mediums for Electromagnetics and Optics.” *SPIE press.*

Santos, P., and A. Tadeu. 2002. “Acoustic insulation provided by a single wall seperating two contiguous tunnels via bem.” *Journal of Sound and Vibration.*

Sounds, City. 2008. “Melbourne Community Sound Survey City of Melbourne and RMIT New Zealand Acoustics.” *City Sounds* 19 (2).

Wright, P, CJ Skinner, and CJ Grimwood. 2001. “Building Research Establishment Client Report No:203938f.” *The National Noise Incidence Survey* England and Wales.