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Evaluation of a hard-walled rectangular room model with a planar absorption cavity

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ABSTRACT

This study evaluates an approach to providing absorption to a hard-surfaced rectangular room. The concept is that planar cavities are established behind each room surface, with narrow openings to the room around their edges. While there is some potential for tuning such cavities to the axial and tangential modes of the room, such precise tuning may be impractical – so we examine the broad effect of this approach. The concept is evaluated in a scale model room by measuring and comparing the transfer functions between fixed transducers (in room corners) for various interventions, using a single planar cavity. Interventions include the size of the opening around the edge of the planar absorber, the depth of the planar absorber, and the presence or absence of resistive material within the plane.

INTRODUCTION

Hard-walled rectangular rooms and boxes present an acoustic problem in that strong modes are formed when the room is excited with sound. The theoretical basis for this phenomenon is well known, and is developed in most classical texts on acoustics and room acoustics (e.g., Cremer & Müller 1978; Kutruff 1991). The control of such modes can be approached in a variety of ways. One approach has been to consider optimal distribution of modes in the frequency domain, by considering room dimensions (e.g., Bolt 1946; Cox & D'Antonio 2001; Louden 1971; Walker 1996). Another approach is to increase the diffusivity of the soundfield by introducing scattering elements that are effective at low frequencies. A third approach is to optimise the position of transducers in rooms, so that over the desired frequency range modes are suppressed. Furthermore, introducing multiple loudspeakers can be used to cancel out mode activity when such loudspeakers are appropriately positioned. Perhaps the most straightforward approach, though, is to introduce sound absorption, which has the potential to suppress room modes to some extent, and to broaden their bandwidth.

There are many ways in which sound absorption can be added, and this paper considers a particular type of sound absorber: the plane absorber. A plane absorber is similar in concept to a Helmholtz resonator or pipe resonator – except that a rectangular plane absorber could involve internal resonant modes in its two dimensions (i.e., with both axial and tangential modes). This concept has some appeal for the problem of rectangular room absorption because: there is the potential for such modes to match some of the modes of a rectangular room; and because a plane absorber is easily built by introducing a 'false' floor, wall or ceiling which is open around the edges. Even if the first of these points of appeal is impractical to realise, the second alone makes this concept of some interest.

In this paper we examine this idea using a physical model: i.e., a rectangular box. Into this box we introduce a planar absorber (on the floor), and test various configurations of it: the depth between the false floor and the box floor; the gap around the edges of the false floor; and the effect of resistive material in the interstice between the false floor and box floor. The acoustic effect of this is evaluated by measuring transfer functions between a loudspeaker and microphone within the box. From this we can identify mode behaviour, and can examine gross features of the transfer function such as the deviation of the spectrum from 'flat'.

EXPERIMENT SET-UP

To conduct this experiment we used a one eighth scale model of the University of Sydney's rectangular reverberant room. Constructed with 10 mm thick, clear Perspex, it is 793 mm long, 638 mm wide and 494 mm deep and has a sealed removeable lid (ceiling) See Figure 1.

The room has an EV 1829BT compression driver, rated at 60 W installed in the top corner as a sound source. This loudspeaker driver is powered by a Bruel & Kjaer Type 2716 power amplifier. In an adjacent corner we have a Bruel & Kjaer Type 4135 ¼"free-field condenser microphone connected into a Bruel & Kjaer Type 2669 pre-amplifier, into a Bruel & Kjaer Nexus Type 2690-OS2 conditioning amplifier. The output from the Nexus is connected to an input channel of an Edirol UA-25Audio Capture analogue to digital convertor. The input of the Bruel & Kjaer Type 2716 is connected to the output of the same Edirol UA-25 unit. The Edirol is connected by USB 2 to a Dell Precision M4300 portable computer running Farina's Aurora Version 4 acoustic measurement software plug-in, inside Adobe Audition version 1.5 recording software.

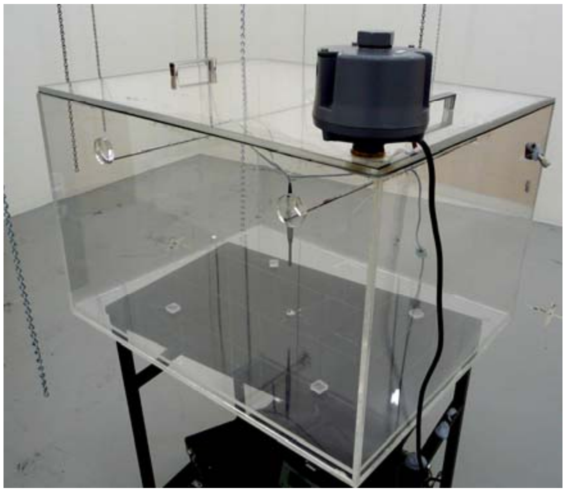
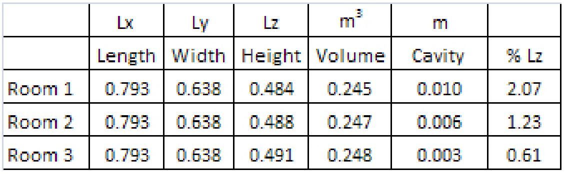


Figure 1. Rectangular Perspex room (793 x 638 x 494) mm

Using Aurora we play a logarithmic sweep from 20 Hz to 20 kHz into the room through the loudspeaker and record the sweep with the microphone. Convolving the recorded wave file with the inverse of the original sweep gives us an impulse from which we can obtain the transfer function of the room between the loudspeaker and microphone corners. The corners of the room are positions of high pressure and allow us to see all the axial, tangential and oblique room modes.

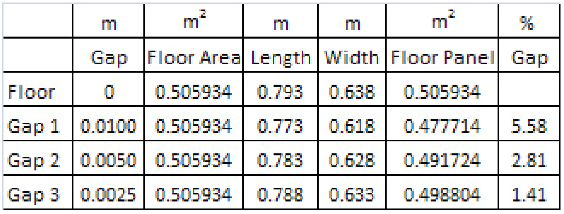
To give three different cavities we introduced a false floor with an interstice of 10 mm, 6 mm and 3 mm. The false floor was made of the same 10 mm Perspex as the existing floor with a gap around its edges of 10 mm, 5 mm, 2.5 mm and 0 mm (ie sealed around the edges for reference measurements). All combinations of interstice depth and edge gap were tested. The depth of the interstice changed the room dimensions, and the three room sizes determined by the interstice depth are labelled Room # 1, Room # 2 and Room # 3 with 10 mm, 6 mm and 3 mm depths respectively. Table 1 shows the three room dimensions.



	Lx	Ly	Lz	m^3	m	
	Length	Width	Height	Volume	Cavity	% Lz
Room 1	0.793	0.638	0.484	0.245	0.010	2.07
Room 2	0.793	0.638	0.488	0.247	0.006	1.23
Room 3	0.793	0.638	0.491	0.248	0.003	0.61

Table 1. Room dimensions in metres and cubic metres

There is only a small variation in each room size. The difference is simply to allow the introduction of various depth cavities beneath the floor. To make these distances more meaningful Table 1 expresses the cavity depth as a percentage of the height of the room to which it is related. The cavity volume as a percentage of the total room volume is the same for each as only one dimension is being changed. To put the various edge gap sizes into context of the room size they are also expressed as a percentage of the floor area in Table 2. The length and width do not vary between rooms despite different cavity sizes. The floor dimensions that accommodate the openings to the cavity vary by that respective degree in each room.

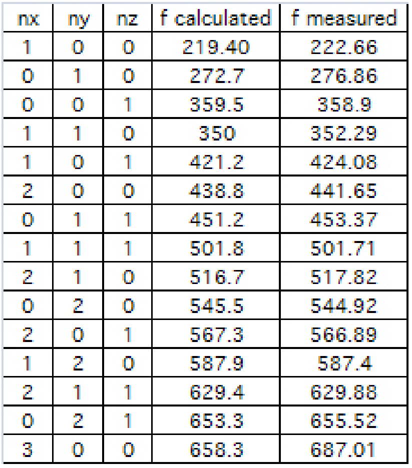


	m	m^2	m	m	m^2	%
	Gap	Floor Area	Length	Width	Floor Panel	Gap
Floor	0	0.505934	0.793	0.638	0.505934	
Gap 1	0.0100	0.505934	0.773	0.618	0.477714	5.58
Gap 2	0.0050	0.505934	0.783	0.628	0.491724	2.81
Gap 3	0.0025	0.505934	0.788	0.633	0.498804	1.41

Table 2. Gap dimensions in metres expressed as a percentage of the floor area

MEASUREMENT PROCEDURE

Firstly we measured the transfer function of each room configuration and identified the axial and tangential modes by their order and by their spatial configuration. From the theory we calculated a table of modes. Table 3 lists the orders of horizontal axial modes created by the two sets of parallel walls, where *x* represents the length and *y* represents the width. It also lists the vertical axial modes, *z*, created from reflections between the floor and the ceiling. The notation *n* indicates the harmonic stature of the modes such that 1*n* represents the first harmonic, (fundamental), and 2*n* the second harmonic. The calculated and measured frequencies are in Hz and vary a little due to inaccuracies in the model room construction, but are close enough to be confidently identified. Figure 2 is a graph showing the modal response of the transfer function of Room # 1well below the Schroeder frequency of the room which is approximately 4 kHz (Schröeder 1954; Schroeder 1996). As the length and width of the room have not been altered we did not expect any effect of the planar cavity on those modes in this model, only those that have a *z* component to their spatial configuration.



nx	ny	nz	f calculated	f measured
1	0	0	219.40	222.66
0	1	0	272.7	276.86
0	0	1	359.5	358.9
1	1	0	350	352.29
1	0	1	421.2	424.08
2	0	0	438.8	441.65
0	1	1	451.2	453.37
1	1	1	501.8	501.71
2	1	0	516.7	517.82
0	2	0	545.5	544.92
2	0	1	567.3	566.89
1	2	0	587.9	587.4
2	1	1	629.4	629.88
0	2	1	653.3	655.52
3	0	0	658.3	687.01

Table 3. The first fifteen mode frequencies in Hz as calculated and measured for Room # 1

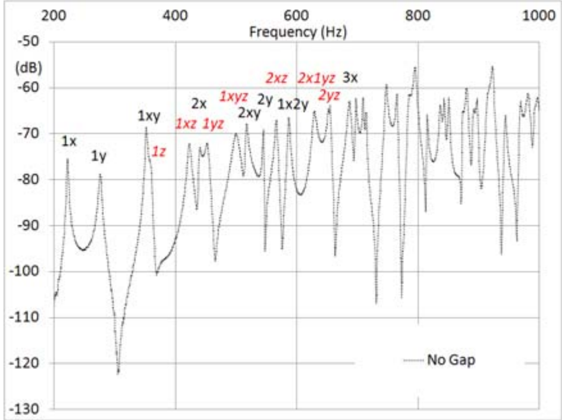


Figure 2. Room # 1 transfer function with no opening and with low order modes identified. Modes with z components are in italics.

Next we measured the transfer functions for Room 1, 2 and 3as a reference. As there is less than 2% variation between the three room sizes, there was, as expected, little variation in the frequencies selected for comparison from 200 Hz to 1,000 Hz. Figure 3 shows this.

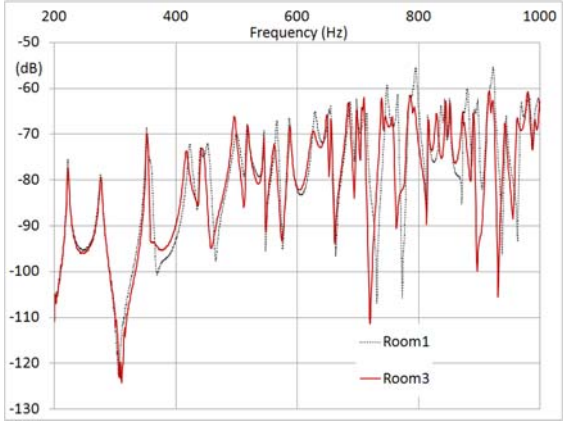


Figure 3. Room 1and 3 transfer functions with the false floor sealed around its edges.

As a way of summarising the transfer function, in terms of how flat the spectrum is, we have taken the simple approach of differencing the level spectrum (dB), and dividing the mean difference by the component spacing (Hz). This yields a deviation value in decibels per Hz. Considering that the lowest mode is in the vicinity of 220 Hz, we evaluated deviation over the range 200 Hz – 1 kHz. Table 4 gives a comparison of the three rooms' performance with their respective interstice depths, of the planar absorber, and their various sized openings around the edge.

Room 1	Opening to cavity in metres			
0.010 m Cavity	0	0.0025	0.005	0.010
Deviation (dB/Hz)	1.42	1.18	1.32	1.30
Room 2				
0.006 m Cavity	0	0.0025	0.005	0.010
Deviation (dB/Hz)	1.43	1.36	1.33	1.34
Room 3				
0.003 m Cavity	0	0.0025	0.005	0.010
Deviation (dB/Hz)	1.53	1.35	1.37	1.43

Table 4. Spectral deviation of different size openings to the different sized cavities expressed in decibels / Hz

From Table 4, it can be seen that the least variation of magnitude over the frequency is with the larger cavity and the narrowest opening to it. These results are obtained solely by the introduction of the planar cavity. The same measurements were conducted again but this time a 3 mm sheet of porous polyester absorption material was place in the cavity. These results are listed in Table 5 below.

Room 1	Opening to cavity in metres			
0.010 m Cavity	0	0.0025	0.005	0.010
Deviation (dB/Hz)	1.417	0.882	0.973	1.002
Room 2				
0.006 m Cavity	0	0.0025	0.005	0.010
Deviation (dB/Hz)	1.43	1.02	1.08	1.02
Room 3				
0.003 m Cavity	0	0.0025	0.005	0.010
Deviation (dB/Hz)	1.53	1.08	1.06	1.03

Table 5. Spectral deviation of different size openings to the different sized cavities expressed in decibels / Hz with a 3 mm layer of porous polyester sheet in the cavity.

The introduction of the absorptive material increases the spectral density further. The 10 mm cavity with the 25 mm (1.41%) gap again outperformed the other configurations and was chosen then to look at more closely. Figure 4 is a graph of the two above optimum configurations. The larger cavity offered the opportunity to increase the thickness of the resistive material. A 10 mm thick sheet was placed in the 10 mm (2.07%) cavity and this resulted in a figure of 0.79 dB/Hz. Reducing the deviation by over 0.5 dB /Hz is a large difference when considered over 800 cycles (40 dB).

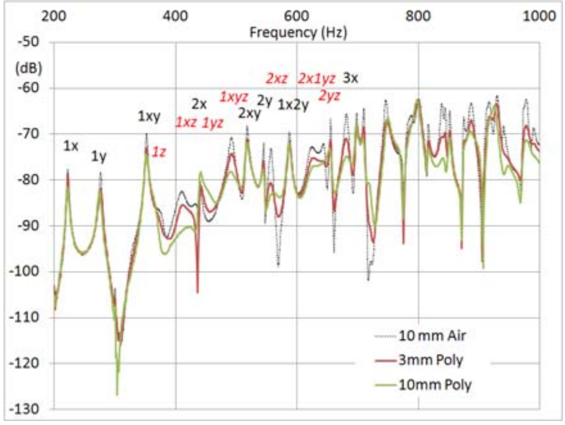


Figure 4. Room #1 with 1.41% opening to a 10 mm interstice transfer functions with an empty cavity, 3 mm thick polyester and 10 mm thick polyester material installed.

It can be observed in Figure 4 that the attenuation occurs at the modes that are formed by frequencies associated with the height or *z* floor and that the *xy* only formed modes are not affected by the empty cavity.

INVESTIGATION

To observe what is causing the attenuation we varied the microphone position inside the room by installing another Bruel & Kjaer Type 4135 ¼"free-field condenser microphone. Figure 5 shows the transfer function from a microphone position in the corner of the room near the floor with no absorptive material and Figure 6 shows the transfer functions from a microphone position in the centre of the room. Again we see that the introduction of the cavity below the floor only attenuates the modes with propagation in the *z* dimension.

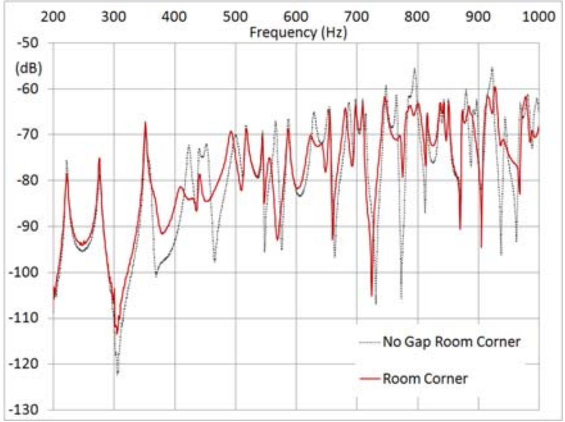


Figure 5. Transfer function measured from a microphone positioned in the corner in the room above the cavity of Room #1

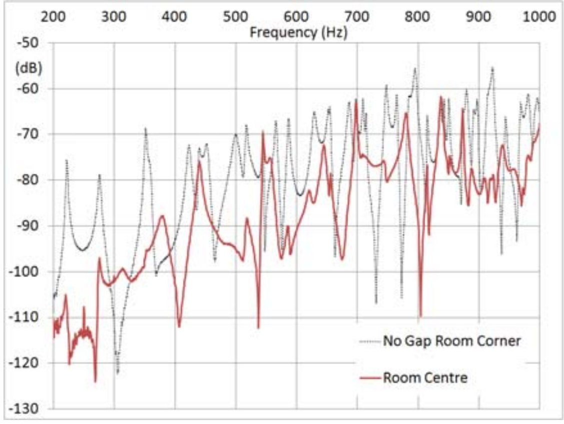


Figure 6. Transfer function measured from a microphone positioned in the centre of the room above the cavity of Room #1

The centre positioned microphone used in Figure 6 is in a pressure null and so there are no axial modes present. We then measured transfer functions from the corresponding corner and centre microphone positions inside the planar cavity. Although lower in level to the room corner microphone position the transfer function from the cavity corner microphone position follows the same modal outline except for the attenuation of the *z* frequencies as above. The first vertical axial mode is attenuated by the cavity as discussed above. The cavity has the same *x* and *y* dimensions as the room but a much smaller height (*z*). However, the boundary conditions around the edges of the interstice are quite different to those of a room. The transfer function from the microphone in the centre of the cavity (Figure 6) reveals that neither of the first order horizontal axial modes is present. If the interstice was resonating with the same horizontal axial and tangential modes as the room, we might expect a pressure maximum at this point because the edges of the plane are open rather than closed. The most likely reason for this not to be seen, though, is that the resonant frequencies in the plane are in fact different to the horizontal room modes, and the measurement appears to indicate that they occur at higher frequencies. Figure 7 shows the transfer function measured from a microphone position in the corner of the cavity referred to the transfer function from the room corner. Figure 8 shows the transfer function measured from a microphone position in the centre of the cavity referred to the transfer function from the room corner.

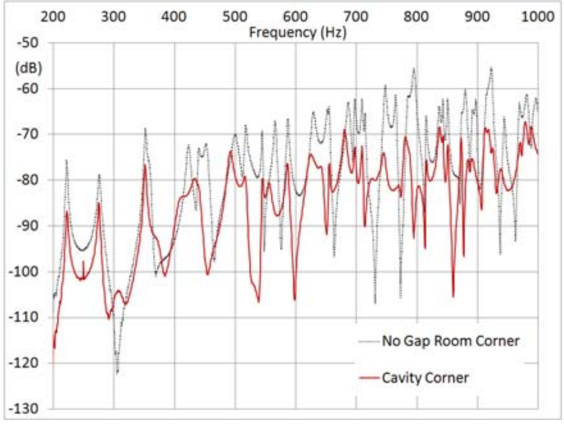


Figure 7. Transfer function measured from a microphone positioned in the corner, inside the cavity of Room #1

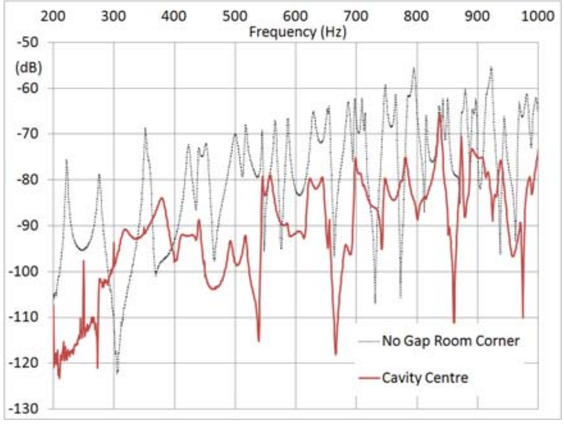


Figure 8. Transfer function measured from a microphone positioned in the centre of the cavity of Room #1

In order to examine this more closely, we dampened the room above the false floor to reduce its effect on the sound measured in the interstice. This was done by almost filling the room with polyester absorbing material. The results, shown in Figure 9, indicate that there is no *strong* modal activity in the interstice (as such would be characterised by strong peaks).

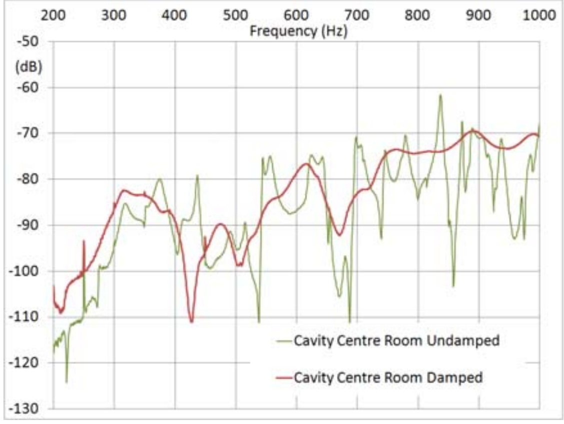


Figure 9. Transfer functions measured from microphone in the centre of the cavity of Room #1 with the room above damped and undamped (green)

DISCUSSION AND CONCLUSIONS

By introducing three different depth cavities beneath a scale-model room and measuring the transfer functions of the room with three different sized openings, we found that the most absorption and improvement in spectral deviation came from a combination of the larger cavity and the smaller opening. The absorption was improved significantly more with the inclusion of resistive material in the cavity. Investigating this configuration with microphones in various positions in the room and cavity spaces revealed that the absorptive nature of the system was not driven by strong modes in the interstice but by broadband attenuation.

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