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Damping of flexural vibrations in composite plates and panels containing one- and two-dimensional acoustic black holes

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In this paper, the results of the experimental investigations into the addition of one-dimensional and two-dimensional acoustic black holes into composite plates and their subsequent inclusion into composite panels are reported. The composite plates in question are sheets of composite with one-dimensional or two-dimensional indentations of power-law profile materialising acoustic black holes for flexural waves. A panel is a sheet of composite with the indentations encased within the sample. This makes a panel similar in surface texture to an un-machined composite sheet (reference plate). In the case of quadratic or higher-order profiles, the above-mentioned indentations act as one- or two-dimensional acoustic black holes for flexural waves that can absorb a large proportion of the incident wave energy. For all the composite samples tested in this investigation, the addition of one- or two-dimensional acoustic black holes resulted in further increase in damping of resonant vibrations, in addition to the already substantial inherent damping due to large values of the loss factor for composites (0.1 - 0.2). Note in this connection that due to large values of the loss factor for composite materials used, no increase in damping was seen with the addition of a small amount of absorbing material to the indentations, as expected.

1 Introduction

Passive damping of structural vibrations is usually achieved by adding layers of highly absorbing materials to structures in order to increase energy dissipation of propagating (mostly flexural) waves [1-3] or by suppressing resonant vibrations of structures via reduction of reflections of structural waves from their free edges [4].

A new method of damping flexural vibrations based on the 'acoustic black hole effect' has been recently developed and investigated [5-7]. This method, that implements the approach of [4] in a more efficient way, can be materialised using 'one-dimensional acoustic black holes' (plates of power-law profile (wedges)) [5-9] and 'two-dimensional acoustic black holes' (circular indentations of power-law profile) [9-11]. In both these cases, the power-law exponent m should be equal or larger than two, and the black hole areas have to be covered by narrow strips of absorbing layers near sharp edges. Under these conditions, the energy of incident flexural waves is being lost to heat almost entirely, which constitutes the acoustic black hole effect. It has been established theoretically [5,6] and confirmed experimentally using steel structures [7-11] that this method of damping structural vibrations is very efficient even in the presence of edge truncations and other imperfections.

When investigating practical applications of 'acoustic black holes' (ABH) one is drawn to a material of increasing popularity and versatility; composites. This paper looks at glass fibre composite and its integration with both 1D and 2D acoustic black holes. One of the main problems faced by this method of damping is having the wedge tip at the centre of a circular indentation exposed. The tip of the indentation is not only delicate, but sharp, presenting an exposed structurally weak edge with a health and safety risk. A composite panel with smooth outer edges is one of the most commonly found composite structures. The construction of such a composite panel that can incorporate the damping abilities of the acoustic black holes forms the ultimate aim of this paper.

Four configurations are explored in this paper: a composite strip with a wedge of power-law profile at its edge (1D acoustic black hole), a composite plate containing a circular indentation of power-law profile inside a plate (2D acoustic black hole), combined composite plates containing circular indentations of power-law profile, and smooth composite panels with enclosed circular indentations of power-law profile.

2 Manufacturing of experimental samples

Thirteen glass fibre composite samples were created for this investigation. Among them were two strips of dimensions 25 x 50 mm and a thickness of 5 mm; the additional wedge being 50 mm long and of power-law profile with $m = 2.2$. The eleven glass fibre composite plates were of dimensions 310 x 185 mm and consisted of two 2.5 mm thick plates and nine 5mm thick plates. The circular indentations of power-law profile with $m = 4$ had a diameter of 110 mm with a central hole of 10 mm, leaving a profile length of 50mm. A CNC (Computer Numerically Controlled) milling machine operating at a cutter speed of 1200 rpm with a carbide cutter was used to produce the wedges and circular indentations.

The main problem encountered when utilizing this method of manufacturing was that it is not possible to construct directly a panel with internal cavities while utilizing a 'vacuum only processing' method. This can lead to a more lengthy manufacturing time.

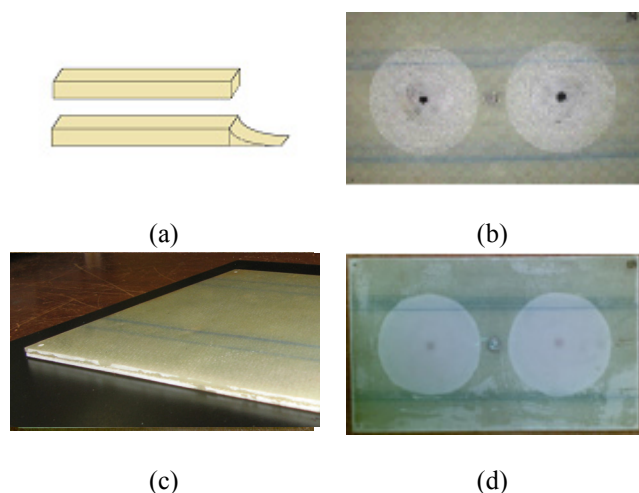


Figure 1: (a) Strip with and without a wedge, (b) Plate (5 mm) containing two 2D ABH's, (c) Combined composite plate (5 mm), (d) Composite panel (5 mm)

These thirteen samples consisted of a reference strip and strip with an additional wedge (Figure 1(a)), Examples of the other 3 types of plate can be seen in Figure 1 (b-d). Figure 2 displays the cross-sectional views of the plate samples when viewed from the narrow end.

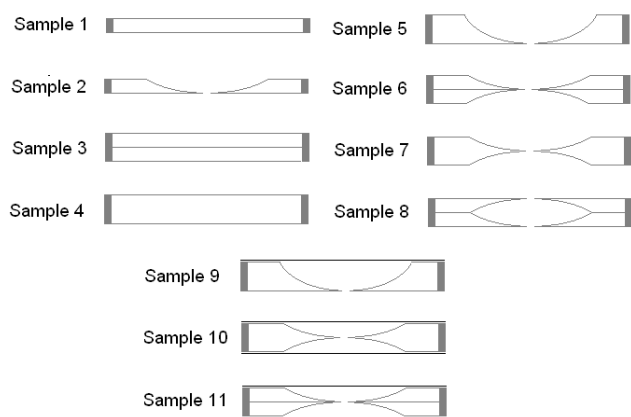


Figure 2: Cross-sectional views of Sample plates 1-11

3 Experimental set up

The experimental set-up utilised a traditional vertical suspension of experimental samples to allow nearly free vibration of the sample plates. The excitation force was applied centrally on the plate via an electromagnetic shaker attached to the plate using ‘glue’ and fed via a broadband signal amplifier. The response was recorded by an accelerometer (B&K Type 4371) that was attached to the one surface, directly in line with the force transducer (B&K Type 8200), also attached using ‘glue’, see Figure 3.

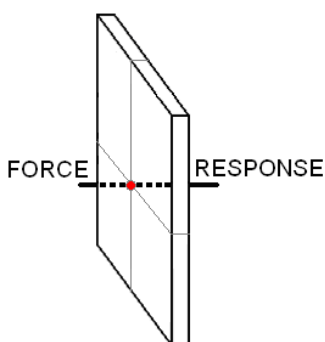


Figure 3: Locations of the shaker (Force) and of the accelerometer (Response) on an experimental sample

The acquisition of the point accelerance was utilised using a Bruel & Kjaer 2035 analyser and amplifier. A frequency range of 0- 6 kHz was investigated; above this range no discernable response could be detected.

4 Results and Discussion

4.1 Wedge of power-law profile in a composite strip

In the first instance, it seemed prudent to ascertain whether the introduction of a wedge of power-law profile to a composite strip could produce an ‘acoustic black hole effect’, as seen in previously tested steel samples [7-11]. In this section, two types of samples were tested: a reference

strip and a strip with a machined wedge of power-law profile (1D acoustic black hole). It was found during the initial testing that a composite sample, unlike the steel samples, required no additional damping layer to be attached to the wedge tip to produce the acoustic black hole effect. This is primarily due to the increased loss factor of the composite material itself (~0.1-0.2). For this reason, all of the following results are for the samples without any additional damping layers.

A comparison of the measured accelerance levels for a strip with and without a power-law profile wedge is shown in Figure 4. It can be seen that there is no difference between the two samples below 250 Hz. After this point, an increase in the reduction of the resonant peaks is seen up until a maximum reduction of 3.5 dB from the reference sample which is seen at 2.2 kHz. At 2.6 kHz the two peaks match and no reductions are seen. Beyond this point the sample with the wedge has damped all remaining peaks.

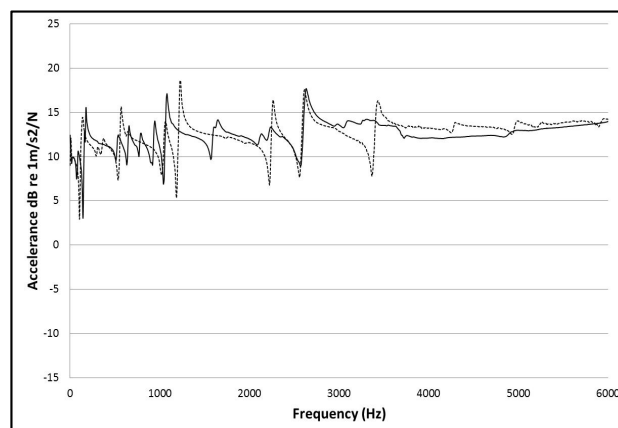


Figure 4: Accelerance for Strip with a wedge of power-law profile (solid line) compared to Reference Strip (dashed line)

4.2 Circular indentations of power-law profile in composite plates

The next step, as with the previously tested steel samples [11], was to introduce circular indentations of power-law profile (2D ABH’s) into glass fibre composite plates. This section looks at the effect of the addition of two 2D ABH’s into both a 2.5 mm (Sample 2) and 5 mm thick plate (Sample 5) when compared to a respective thickness reference plate (Samples 1 and 4). This section also looks at the effect of a double profiled indentation of the same power-law (Sample 7) compared to the single profiled 5 mm thick sample (Sample 5) and the reference plate. The cross-sections of these profiles can be seen in Figure 5.

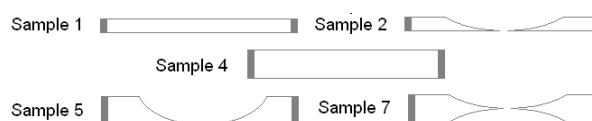


Figure 5: 2.5 mm reference plate (sample 1), 5 mm reference plate (sample 4); Cross-sections of samples containing tapered circular inclusions (samples 2, 5 and 7)

Figure 6 shows the results for the 2.5 mm samples; Sample 2 when compared to a plain reference plate; Sample 1. The effect of adding two circular indentations of power-law profile is immediately obvious, with considerable damping of resonant peaks easily observed. Below 500 Hz little to no damping is seen. An increase in the reduction of the peak responses of the reference plate is seen in the profiled sample until a maximum reduction from the reference plate of 7.5 dB can be observed at 1.2 kHz. After 2.7 kHz the response is smoothed, with all resonant peaks seen in the reference sample heavily damped if not completely removed.

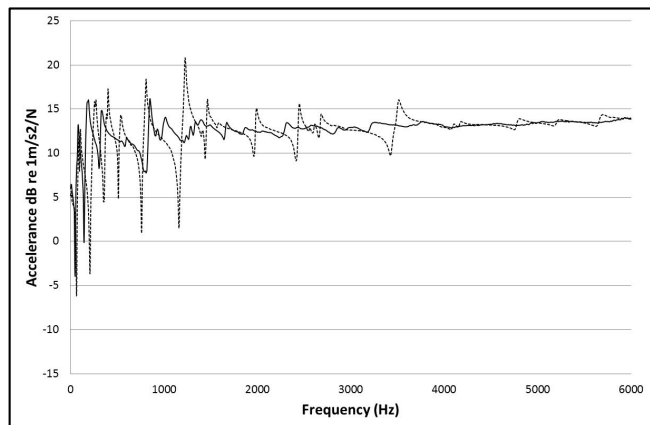


Figure 6: Accelerance for Sample 1 - 2.5mm Reference plate (dashed line) compared to Sample 2 - 2.5mm, with two 2D ABH (solid line)

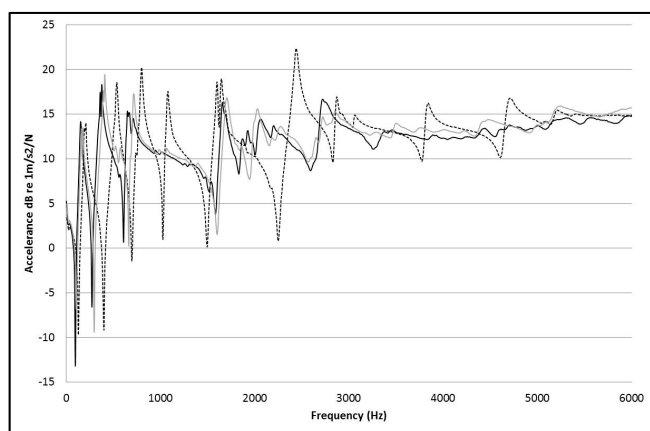


Figure 7: Accelerance for Sample 7 (solid black line) compared to Sample 5 – 5 mm, two 2D ABH (solid grey line), and to Sample 4 – 5 mm Reference plate (dashed line)

The same test was repeated for 5 mm thick plate with the addition of a third sample for comparison; Sample 7, a double profiled sample. From Figure 7, it can be seen that when the double profiled Sample 7 is compared to a plain reference plate (Sample 4) and to a single profiled plate (Sample 5), the damping achieved by Samples 5 and 7 is very similar. Sample 7 performs slightly (1-1.5 dB) more effectively than Sample 5 below 1 kHz. Above this frequency this trend is reversed, with Sample 5 slightly (again 1-1.5 dB) more effectively than Sample 7. As expected, below 450 Hz there is little to no damping. A maximum reduction of 8.5 dB from the reference plate by both Sample 5 and 7 can be seen at 2.4 kHz. After 2.7 kHz, both Sample 5 and 7 show a smoothing of the reference

plate resonant peaks. Samples 5 and 7 can therefore be classified as interchangeable, whether a sample has a double profile, as with Sample 7, or a single profile, as with Sample 5, the damping performance obtained is the same.

4.3 Combined plates containing circular indentations of power-law profile

In this section, different ways of combining 2.5 mm plates were considered in order to maximise the damping performance of the composite plates. The initial motivation for this combining of plates was due to the two main drivers. The first was to create a profile combination that could easily be converted into a panel with a continuous outer surface and also to increase the ease of manufacture of the double profiled indentations. The cross-sections of these profiles can be seen in Figure 8. The plates were combined using a long cure epoxy resin.

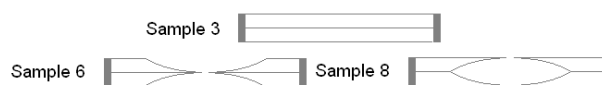


Figure 8: Cross-sections of Combined composite samples: Sample 3 - reference plate, Sample 6 and Sample 7

Sample 7 from Section 4.2 was also used for comparison in this Section, as it could show a direct comparison between a sample manufactured from two separate composite sheet and then combined to a sample manufactured from a single sheet of composite.

Two different styles of reference plates were considered in order to gauge the effect of combining the plates and to determine which should be used for comparison. A plain plate (Sample 4) and a combined plate (Sample 3) were considered as both had merit as a reference. Both reference plates were of the same dimensions as the profiled plates, the combined plate consisted of two 2.5 mm plates combined with epoxy resin.

The results showed that the effect of the combination of the two plates and the addition of the epoxy resin had no quantifiable effect on the response of the plate by either increasing, decreasing or shifting the resonant peaks of the plain reference plate. Both samples therefore had merit as a reference plate. However, as the main comparison in this paper was for the effect of these changes on existing complete panels, Sample 4 (the plain reference plate) was chosen to be used for comparison both in this and the following section.

A comparison of the two combined double profiled Samples 6 and 8 and Sample 7 is shown in Figure 9. Below 500 Hz, little to no difference in the response of the three samples is seen. It can be said that the amplitudes of the resonant peaks for Sample 8 are generally lower than for other two samples, and therefore it performs more efficiently at damping resonant peaks. Sample 8 shows a maximum reduction from Sample 6 of 3 dB at 640 Hz and the same reduction from both of the other two samples at 1.65 and 2.7 kHz. Above 2.9 kHz the response of all three samples is smoothed with resonant peaks heavily damped if not completely removed.

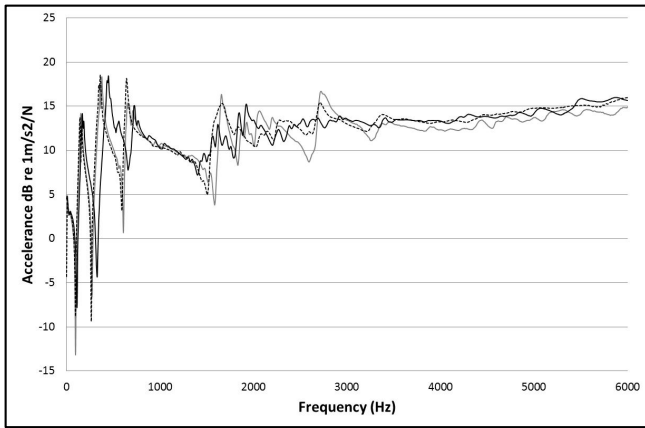


Figure 9: Accelerance for Sample 8 (solid black line) compared to Sample 7 (solid grey line) and to Sample 6 (dashed line)

Figure 10 shows the results for Sample 8 when compared to a plain reference plate. Below 450 Hz little to no damping is seen. The reduction in the amplitude again increases until a maximum reduction from the reference plate of 10 dB can be seen at 2.4 kHz. After this point, the response is smoothed with resonant peaks heavily damped if not completely removed. It should be noted that the resonant peak seen at 1 kHz in the reference sample has been completely damped in Sample 8.

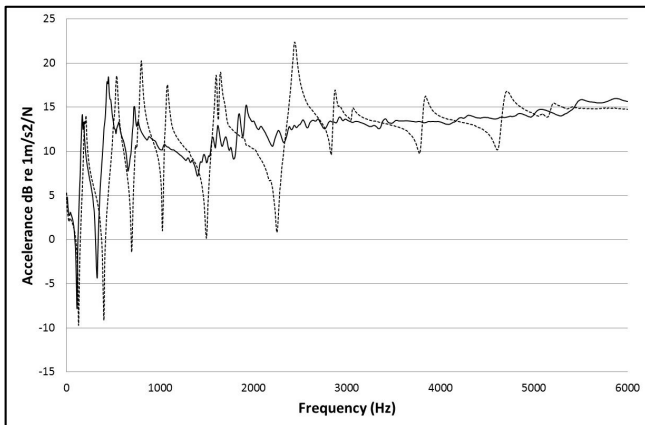


Figure 10: Accelerance for Sample 8 (solid line) compared to Reference Plate, Sample 4 (dashed line)

4.4 Comparison of composite panel constructions

Finally, this section looks at encasing Samples 5-7 with a single sheet of pre-preg glass fibre composite in order to form a panel with a continuous outer surface, as shown in Figure 11. Despite the Damping performance of Sample 8, the two 10 mm diameter holes on the either side of the outer surface of the panel meant that this configuration would be impractical to convert to a smooth surfaced panel without interfering with the circular indentations at the tip. It was therefore decided that this configuration would not be taken forward for experimentation in this section.

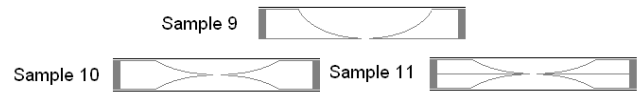


Figure 11: Cross-sections of Samples 9, 10 and 11

This section will investigate the responses of the three enclosed panels when compared to each other, a reference plate and finally when compared to the equivalent sample without the additional casing. This final comparison will show if there are any adverse effects to encasing the sample and whether such an effect, if present, can be off set against the advances gained by encasing the panels.

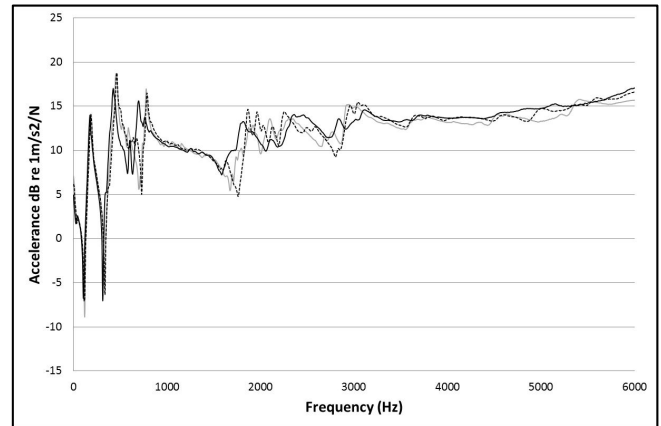


Figure 12: Accelerance for Sample 11 (solid black line) compared to Sample 9 (solid grey line) and to Sample 10 (dashed line)

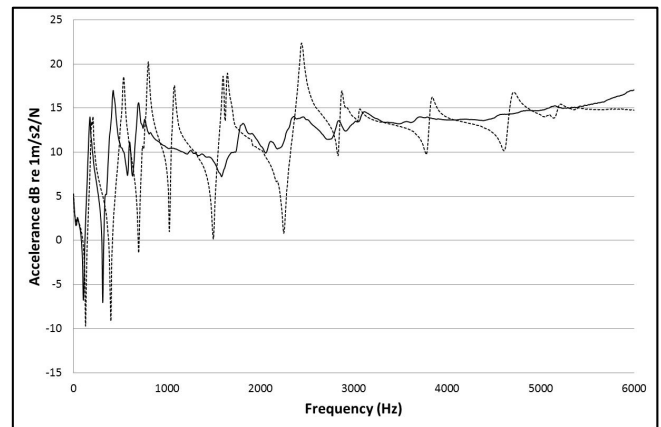


Figure 13: Accelerance for Sample 11 (solid line) compared to Reference Plate, Sample 4 (dashed line)

From Figure 12, it can be seen that when the composite panels, Samples 9, 10 and 11, are compared, there is very little difference between the three samples. For Samples 9 and 10 there is no quantifiable difference between the resonant peaks. However, as Sample 9 has two 10 mm diameter holes on one side of the plate, it does not have two smooth surfaces. Therefore, Sample 10 would best fit the specification. Sample 11 shows a reduction of 0.5-1 dB at 460 and 700 Hz and 2 kHz from the other two samples.

A comparison of the most effective damping panel; Sample 11, to a reference plate is shown in Figure 13. There is no difference between the two samples below 450 Hz. After this frequency, the dB reduction of the peak

amplitudes increases until a maximum reduction of 10dB from the reference plate is achieved at 2.4 kHz. It can also be seen that the reference plate resonant peak at 1 kHz has been damped completely in Sample 11.

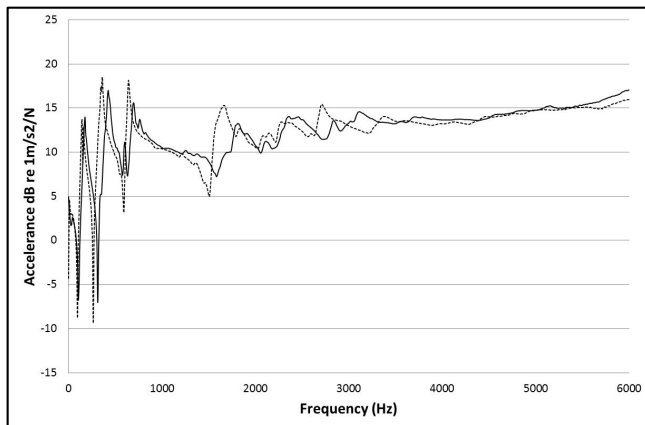


Figure 14: Accelerance for Sample 11 (solid line) compared to Sample 6 (dashed line)

Finally, from Figure 14 it can be seen that when Sample 11 is compared to its exposed indentation equivalent; Sample 6, the damping achieved by Sample 11 is in fact greater (1-2 dB) or equal to that of Sample 6. A maximum reduction of 3dB can be seen at 650Hz and 1.6kHz. These results show that circular indentations of power-law profile can be successfully enclosed in smooth surface panels.

5 Conclusions

It has been demonstrated that glass fibre composite strips with one-dimensional acoustic black holes (1D ABH) behave in much the same way as steel 1D ABH. The maximum vibration reduction for the tested sample was 3.5 dB at 2.2 kHz.

Two-dimensional acoustic black holes (2D ABH) in composite plates perform rather well, with a maximum reduction of 7.5 dB at 1.2 kHz in a 2.5 mm thick plate and 8.5 dB at 2.4 kHz in a 5 mm plate, when compared to a reference sample.

The composite plates can be combined to attain more effective damping and achieve a more time/cost effective method of production. A combined plate provides an identical if not better reduction of the resonant peaks as a sample machined out of a single plate. A maximum reduction of 10 dB at 2.4 kHz was achieved for Sample 8.

When a plate is covered with thin sheets, there is relatively little reduction in damping performance in comparison with an unenclosed plate. A maximum reduction of 10 dB at 2.4 kHz was achieved for Sample 11. Thus, enclosed smooth surfaced composite panels can be manufactured to give the same level of damping that can be achieved for plates with exposed indentations.

Acknowledgements

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