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4aEA7. Damping of flexural vibrations in glass fibre composite plates and honeycomb sandwich panels containing indentations of power-law profile

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In this paper, the results of the experimental investigation into the addition of indentations of power-law profile into composite plates and panels and their subsequent inclusion into composite honeycomb sandwich panels are reported. The composite plates in question are sheets of composite with visible indentations of power-law profile. 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) or conventional honeycomb sandwich panel. In the case of quadratic or higher-order profiles, the above-mentioned indentations act as two-dimensional acoustic black holes (ABH) 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 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. Due to large values of the loss factor for composite materials, there was no need to use attached absorbing layers to implement the acoustic black hole effect.

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1. Introduction

Traditional methods of damping structural vibrations are often based on surface treatment of structures by adding layers of highly absorbing materials to the structure in order to increase energy dissipation of propagating (mostly flexural) waves¹⁻³. Another approach to suppression of resonant vibrations of different structures is to reduce reflections of structural waves from their free edges⁴.

To implement the latter approach in a more efficient way, a new method of damping flexural vibrations based on the so-called ‘acoustic black hole effect’ has been developed and investigated⁵⁻⁷. This method has been initially applied to one-dimensional plates of power-law profile (wedges) and two-dimensionally to plates with circular indentations of power-law profile, both having to be covered by narrow strips of absorbing layers near sharp edges. Ideally, if the power-law exponent is equal or larger than two, the flexural wave never reaches the sharp edge and therefore never reflects back⁸. However, ideally sharp power-law wedges do not exist in reality. Therefore, for materials with low internal loss factors, such as steel, the addition of narrow strips or pieces of absorbing materials to the sharp edges is paramount for achieving very low reflection coefficients of flexural waves (1-3%), which constitutes the acoustic black hole effect⁵⁻⁷. It has been established theoretically^{5,6} and confirmed experimentally^{7,9} that this method of damping structural vibrations is very efficient even in the presence of edge truncations and other imperfections.

The present paper describes the results of the experimental investigation of vibration damping in glass fibre composite plates and panels containing 1D and 2D ‘acoustic black holes’, i.e. recesses and indentations of power-law profile with added pieces of absorbing layers. A composite plate with smooth outer edges is one of the most commonly found composite structures. The development of such a composite plate that can incorporate the damping abilities of the ‘acoustic black holes’ forms the initial aim of this paper. The next step is to consider further configurations incorporating the use of smooth surfaced combined panels with acoustic black holes. The natural progression of these investigations led to the incorporation of enclosed indentations of power-law profile into composite honeycomb sandwich panels.

2. Experimental samples and procedure

Fifteen glass fibre composite samples were manufactured for this investigation; two strips of dimensions 250 x 50 mm and a thickness of 6 mm; the additional wedge being 50 mm long and of power-law profile with $m = 2.2$. A wedge of power-law profile with $m = 2.2$ was also produced in order to be attached to a steel

strip, dimensions being the same as for the composite strip. The eleven glass fibre composite plates were of dimensions 310 x 185 mm and consisted of two 3 mm thick plates and nine 6 mm 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.

The glass fibre composite used for these samples was SE84LV - Low Temperature Cure Epoxy Prepreg System. This composite has a high compressive strength, and it is widely used in such structural components as yacht hulls, spars and in aviation panels. SE84LV is also widely used in sandwich structures with honeycomb. Each sheet had a thickness of 0.2 mm.

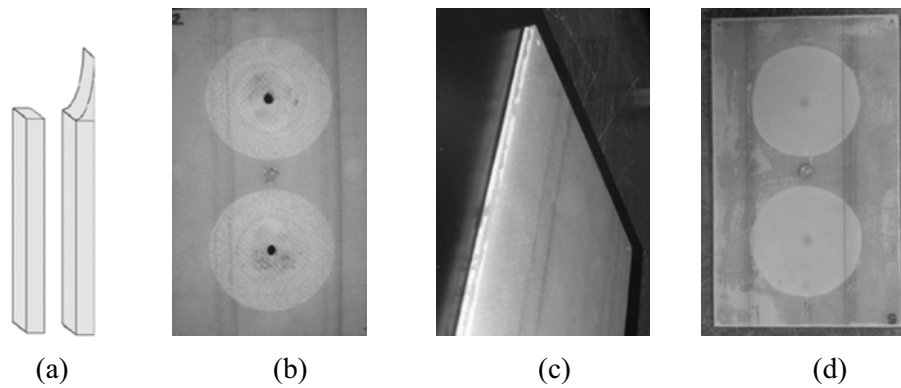


Figure 1: (a) Strip with and without a wedge, (b) 6 mm plate with two 2D ABH's, (c) Combined composite plate 6 mm, (d) Composite panel 6 mm.

Of the above-mentioned samples, thirteen samples were composite plates/strips consisting of a reference strip and strip with an additional wedge (Figure 1(a)), Examples of the other 3 types of plates can be seen in Figure 1(b-d). Figure 2 displays the cross-sectional view of the plate samples when viewed from the narrow end. The average profile tip thickness for each of the samples is given in the Table 1.

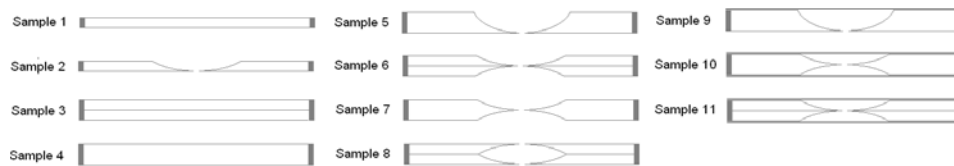


Figure 2: Cross-section view of Sample plates 1-11.

Sample	5	6	7	8	9	10	11
Tip thickness (mm)	0.10	0.11	0.10	0.10	0.10	0.10	0.11

Table 1: Average profile tip thickness for each sample, in mm.

Two types of glass fibre composite honeycomb sandwich panels were created for this investigation, Figure 3. A Reference composite honeycomb sandwich panel and a composite honeycomb sandwich panel containing two acoustic black holes in each of the composite plates.

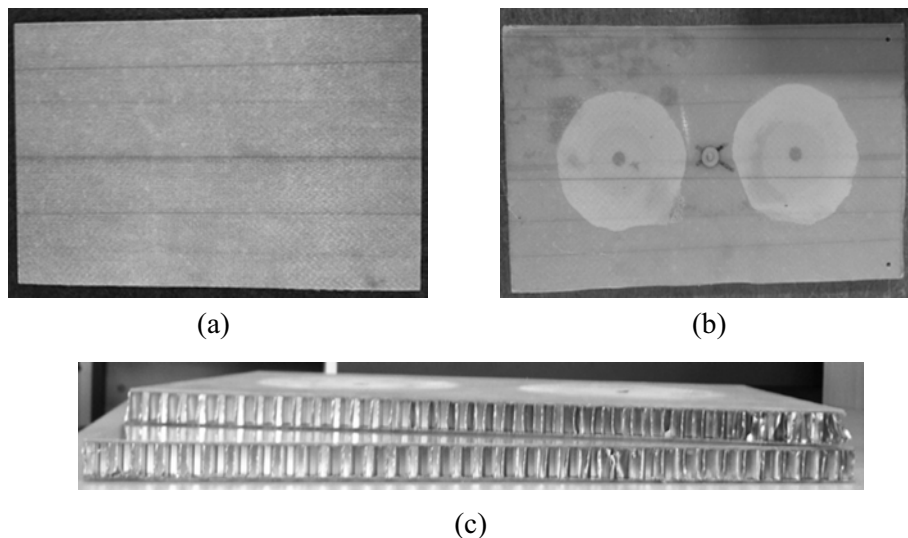


Figure 3: (a) Composite honeycomb sandwich panel (reference plate), (b) Composite honeycomb sandwich panel with acoustic black holes, (c) Side view of the panels.

The experimental set-up has been designed to allow nearly free vibration of the sample plates (i.e. to eliminate clamping of edges) and introduce minimal damping to the system. To achieve this, all experimental plates and panels have been suspended vertically using a metal frame.

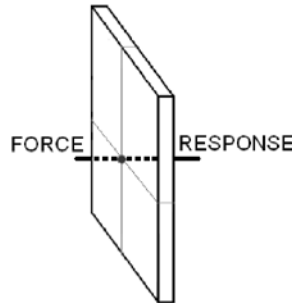


Figure 4: Locations of the shaker (Force) and of the accelerometer (Response) on an experimental sample.

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

3. Results and discussion

3.1 *Introduction of a wedge of power-law profile to a composite strip*

In the first instance it seemed prudent to first 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^{7,9}. In this section, two types of sample were tested: a reference strip and a strip with a machined wedge of power-law profile (1D acoustic black hole). It was found during 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 material itself (~0.1-0.2). For this reason all of the following results have been obtained for the samples without any additional damping layers.

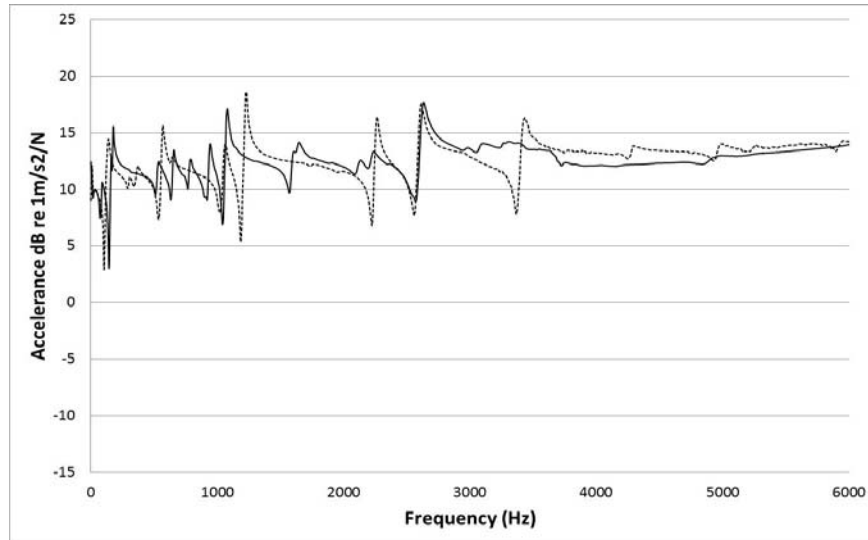


Figure 5: Results for a strip with a wedge of power-law profile (solid line) compared to a reference strip (dashed line).

A comparison of a strip with and without a power-law profile wedge is shown in Figure 5. One can see 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.

3.2 Circular indentations of power-law profile in glass fibre composites

The next step, as with the previously tested steel samples⁹ 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 2.5mm thick plate (Sample 2) and 5mm thick plate (Sample 5) when compared to a respective thickness reference plates (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 5mm thick sample (Sample 5) and the reference plate. The cross-sections of these profiles can be seen in Figure 6.

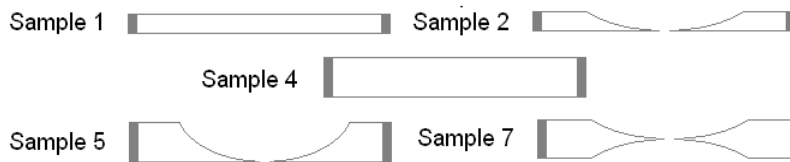


Figure 6: 2.5 mm reference plate (sample 1), 5 mm reference plate (sample 4), Cross-sections of samples containing tapered circular inclusions (samples 2, 5 and 7).

Figure 7 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.

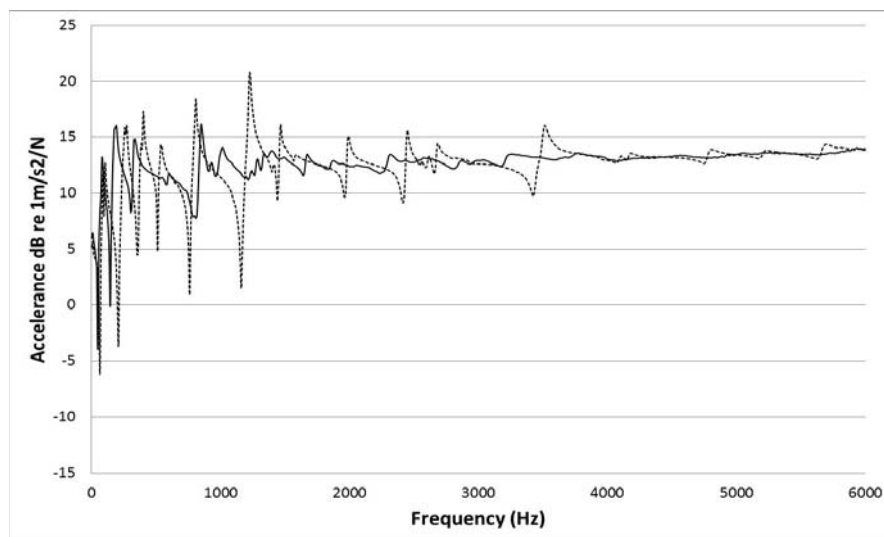


Figure 7: Results for Sample 1; 2.5 mm (Reference plate, dashed line) compared to Sample 2 (2.5 mm, 2x2D ABH, solid line).

3.3 Composite panels containing circular indentations

The present section looks at encasing Samples 5-7 with a single sheet of pre-preg glass fibre composite in order to create a panel with a continuous outer surface as shown in Figure 8.



Figure 8: Cross-section of Samples 9, 10 and 11.

The responses of the three enclosed panels have been investigated when compared to each other, a reference plate and finally when compared to the equivalent sample without the additional casing. This final comparison shows if there are any adverse effects to encasing the samples.

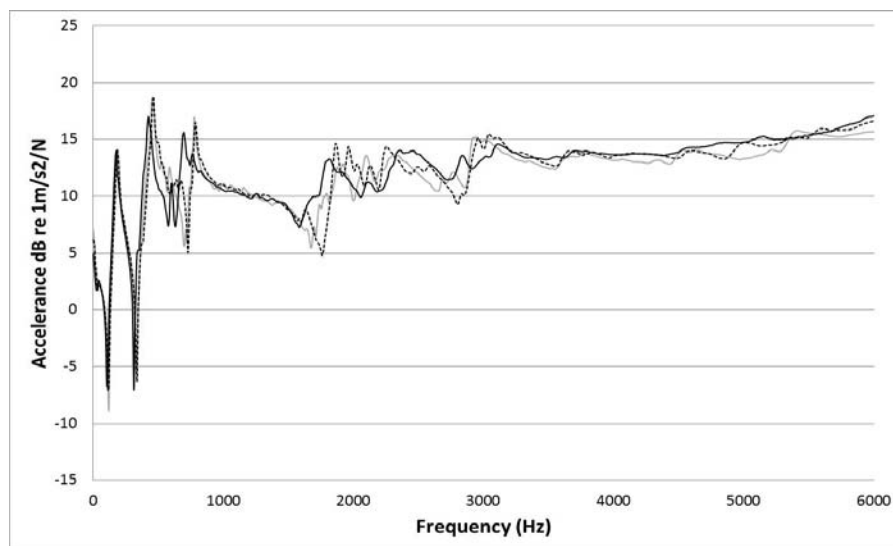


Figure 9: Results for Sample 11 (solid black line) compared to Sample 9 (solid grey line) and Sample 10 (dashed line).

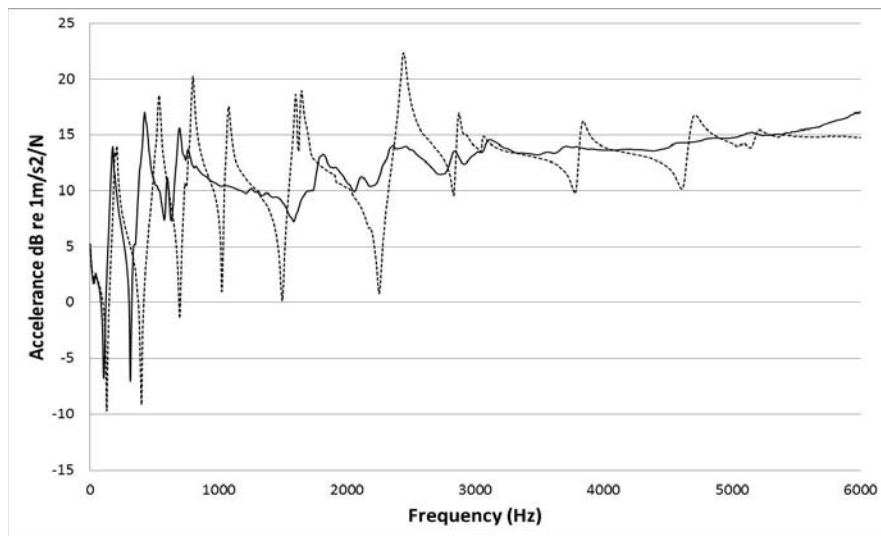


Figure 10: Results for Sample 11 (solid line) compared to a reference plate, Sample 4 (dashed line)

From Figure 9 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. Between 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. Below 460 Hz there is no difference in the response of the three samples and above 3 kHz the response is smoothed with resonant peaks heavily damped if not completely removed, thus producing a similar response.

A comparison of most effective damping panel; Sample 11 when compared to a reference plate is shown in Figure 10. A peak shift to the left from reference is observed. However, in the case of the combined composite plates this effect occurs at a much lower frequency than previously observed, with the peak shift occurring as low as 500 Hz. 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 10 dB 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. The combination of the composite plates and sheets results in an effective method of damping flexural waves in smooth surfaced composite panels.

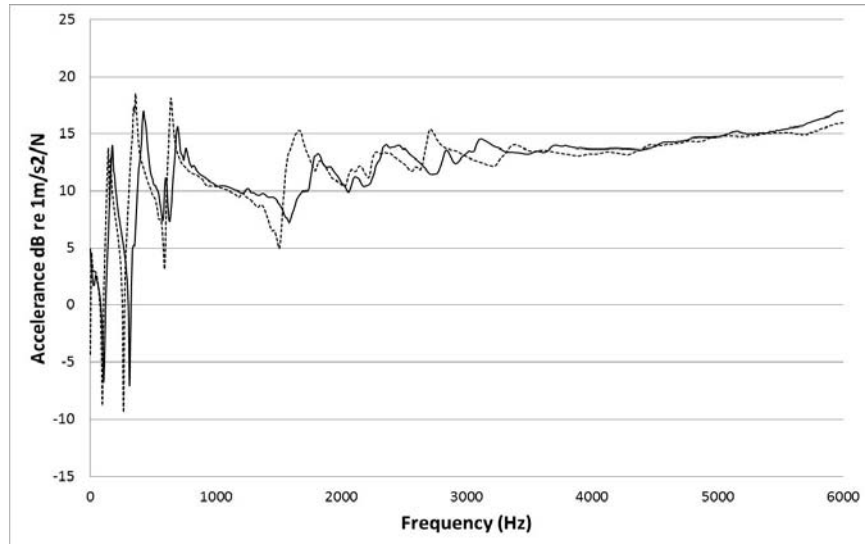


Figure 11: Results for Sample 11 (solid line) compared to Sample 6 (dashed line).

Finally, Figure 11 shows 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. This result shows that circular indentations of power-law profile can be successfully enclosed in a smooth surface panel with a positive effect on the damping performance of the plate. There also appears to be little to no significant ‘drum skin effect’ over the area of the enclosed indentations.

3.4 Indentations of power-law profile in a honeycomb sandwich panel

One of the important aims of this paper was to investigate the possibility of manufacturing composite honeycomb sandwich panels incorporating the smooth surfaced composite panels containing circular indentations of power-law profile described above.

Figure 12 shows the measured accelerance for a composite honeycomb sandwich reference panel compared to a composite honeycomb sandwich panel with enclosed indentations of power-law profile. As expected, there is a peak shift to the left as a result of reduced mass and stiffness. Above 1 kHz, the resonance peaks of the acoustic black hole plate show increasing reductions in amplitude compared to the reference sample. Above 2.4 kHz, the response is smoothed, with

all resonant peaks seen in the reference sample heavily damped if not completely removed. A maximum reduction of 6 dB is seen at 2.5 and 3.4 kHz.

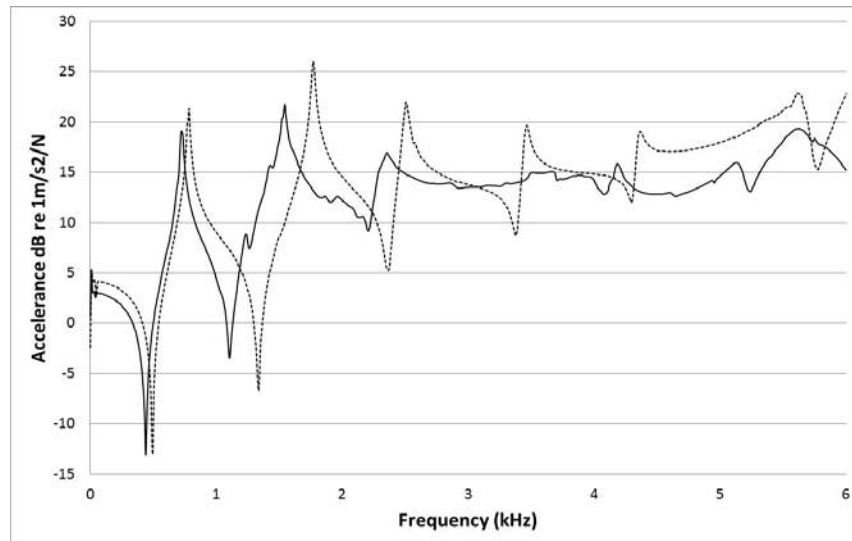


Figure 12: Results for a composite honeycomb sandwich reference panel (dashed line) compared to a composite honeycomb sandwich panel with enclosed indentations of power-law profile (solid line).

4. Conclusions

Glass fibre composite strips with attached wedges of power-law profile (1D ABH) show significant damping of flexural vibrations. A 1D ABH in a strip produces a maximum reduction of 3.5 dB at 2.2 kHz.

Composite plates containing circular indentations of power-law profile (2D ABH) perform well, with a maximum reduction of 7.5 dB at 1.2 kHz in a 2.5mm thick plate and 8.5 dB at 2.4 kHz in a 5mm plate, when compared to the reference samples.

When a composite plate is enclosed by a composite sheet to form a smooth surfaced panel, there is relatively little reduction in damping performance when compared to an unenclosed plate. A maximum reduction of 10 dB at 2.4 kHz was achieved by Sample 11. Therefore, enclosed smooth surfaced composite panels can

be manufactured to give the same level of damping of flexural waves that can be achieved by plates with exposed indentations.

A composite honeycomb panel with enclosed circular indentations of power-law profile shows a good damping performance. A maximum reduction of 6 dB is seen at 2.5 and 3.4 kHz, with heavy damping or elimination of resonant peaks above 2.4 kHz.

Enclosing circular indentations of power-law profile within composite panels results in a surface texture similar to that of an un-machined conventional honeycomb sandwich panels. In the same time, it increases the damping performance of the panels. Honeycomb sandwich panels can be made with either both sides or a single side machined, depending on the application and damping requirement. It is important to note that further testing is required into the structural effects of the indentations on the composite and honeycomb panels.

Acknowledgements

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