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Damping of flexural vibrations in rectangular plates by slots of power-law profile

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It has been shown in our previous publications that the addition of power-law profiled wedges to edges of rectangular plates or strips results in substantial increase in damping of resonant flexural vibrations in plates or strips due to the acoustic black hole effect associated with power-law wedges. One of the problems faced by this method of damping is having the wedge tip exposed on the outer edge of the plate or strip. One of the solutions to the problems listed above is to move the wedges inside a plate, so that they form edges of power-law slots within the plate. The present paper reports the results of the experimental investigations into the effects of such slots on damping flexural vibrations. Four experimental investigations are described: the effect of power-law tapered slots on vibration damping in steel and composite plates, the effect of positioning of slots in a plate, and finally the effect of a combined slotted plate. The obtained experimental results show that introducing power-law profiled slots within plates is an effective method of damping flexural vibrations, which is comparable with the method using power-law wedges at plate edges.

1 Introduction

Passive damping of structural vibrations is usually achieved by adding layers of highly absorbing materials to the structure in order to increase energy dissipation of propagating (mostly flexural) waves [1,2]. Another well-known approach to suppression of resonant vibrations of different structures is to reduce reflections of structural waves from their free edges [3].

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 investigated [4-6]. This method has been initially applied to one-dimensional plates of power-law profile (wedges) that had 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 back [4-7], which constitutes the acoustic black hole effect. It has been established theoretically [4,5] and confirmed experimentally [6] that this method of damping structural vibrations is very efficient even in the presence of edge truncations and other imperfections (see also [8]).

One of the main problems faced by this method of damping is having the wedge tip exposed on the outer edge of the plate or strip, the tip of the wedge is not only delicate but sharp, presenting an exposed structurally weak edge with a health and safety risk. A wedge on the edge of a strip or plate also presents a difficulty in integrating this damping technology into panels/plates that need securing at the edges. One possible approach to overcome the problems listed above is to move the power-law wedges inside plates, so that they form slots within the plates. This solution will be the focus of this paper. Another possible approach is to drill cylindrical pits of power-law profile inside plates [9,10]. However, such an approach is not considered here.

2 Manufacturing of experimental samples

Eleven samples were designed for this investigation; six of which were manufactured from 5 mm thick hot drawn mild steel sheets; which are more resistant to mechanical stresses incurred in the manufacturing process than cold drawn steel sheets, resulting in fewer internal defects. The dimensions of the steel rectangular plates were 320 x 240 mm, with a slot size of 100 x 75 mm. The other five samples were made from 5 mm thick carbon composite. These samples were made using pre-preg carbon composite

sheets that were layed up, cured and then machined. The dimensions of the carbon composite plates were 280 x 175 mm, with a slot size of 140 x 80 mm. Four of the samples are shown in Figure 1.

A CNC (Computer Numerically Controlled) milling machine operating at a cutter speed of 1200 rpm was used to produce the slots in both the steel and composite plates. There are two main problems encountered when utilising this method of manufacturing. The first being that at the centre of the indentation, where the machining stresses and resulting heat are high and the material thickness is less than 0.2 mm, blistering in the steel can occur. The second is wedge tip tearing, this is particularly prominent in the composite samples where the tip thickness is less than 0.2 mm, see Figure 1(d). This effect can occur during the profiling of the wedge itself or during the insertion of the central gully.

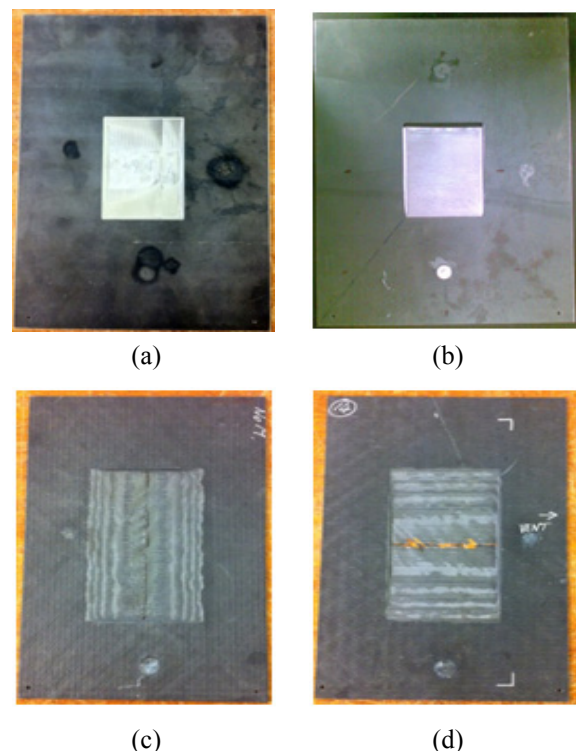


Figure 1: (a) Sample A - Steel, (b) Sample C - Steel, (c) Sample E - Composite, (d) Sample F - Composite

The six steel samples consisted of a plain reference plate, a punched slot reference plate and four profiled samples noted as Samples A, B, C and D, the longitudinal

cross-sections of which are shown in Figure 2. All the wedges comprising the slots are of power-law profile, with the power-law exponential $m = 2.2$. The five carbon composite samples consisted of a plain reference plate, a combined reference plate and Samples E, F and G, the longitudinal cross-sections of which are also shown in Figure 2. The wedges of this series of slots are of power-law profile with $m = 4$.

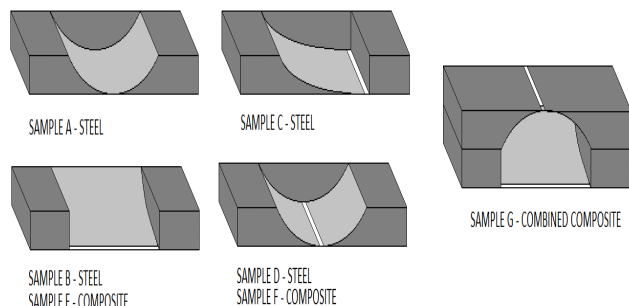


Figure 2: Longitudinal cross-sections through the slot area of Samples A-G

3 Experimental set up

The experimental set-up has been designed to allow nearly free vibration of the sample plates (i.e. to eliminate clamping of edges), take the weight off the plate edges and introduce minimal damping to the system, see Figure 3.



Figure 3: Experimental Set up

The excitation force was applied to three locations on the plate (see Figure 4) via an electromagnetic shaker attached to the plate using ‘glue’ and fed via a broadband signal amplifier. Position 1 represented top dead centre, position 2 was centrally located, and position 3 represented bottom dead centre. The response was recorded by an accelerometer (B&K Type 4371) that was attached to the surface, directly in line with the force transducer (B&K Type 8200), also attached using ‘glue’. The acquisition of the point accelerance was utilised using a Bruel & Kjaer 2035 analyser and amplifier. The frequency ranges of 0-9 kHz for the steel samples and 0-4.5 kHz for the carbon composite samples were used.

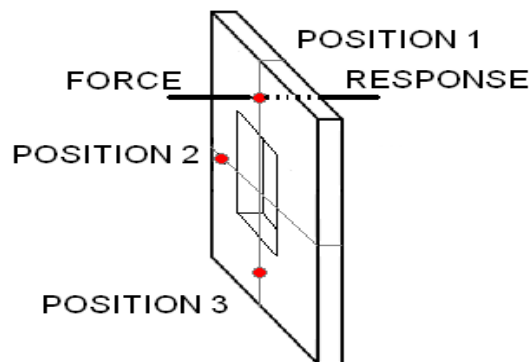


Figure 4: Locations of the shaker (Force) and of the accelerometer (Response) on an experimental sample

4 Results and discussion

4.1 Tapered slots in steel plates

Two different styles of steel reference plate were considered in order to determine if there is any significant difference between them. A plain plate and a plate with a punched rectangular hole were considered as both had merit as a reference. Both reference plates were of the same dimensions as the profiled plates, the punched rectangular hole plate contained a through hole of the same dimensions and position as the machined power-law profile slots. After some preliminary measurements, it has been decided to use a plain reference plate for comparison, and all tests in this section were performed at position 1.

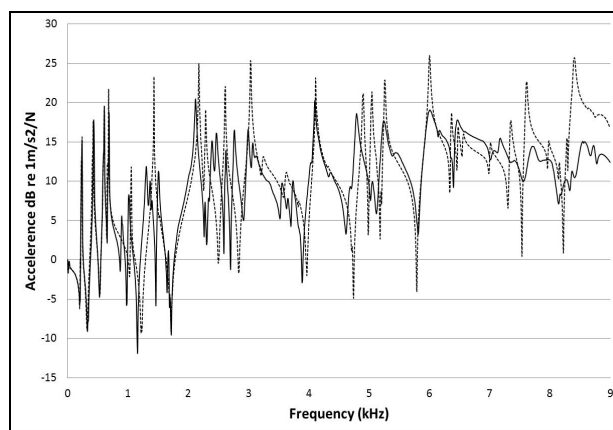


Figure 5: Accelerance for Sample C (solid line) compared to Reference Plate (dashed line)

Figure 5 shows the measured accelerance for Sample C when compared to a plain reference plate. The effect of adding an internal wedge into the slot is immediately obvious, with considerable damping of resonant peaks easily observed. Below 900 Hz little to no damping is seen. The reduction in resonant peaks and therefore damping increases throughout the frequency range. A matching of peak amplitudes between the two samples occurs at 6.5 kHz after which the response of Sample C flattens out the distinct resonant peaks seen in the reference sample. A maximum reduction from the reference plate of 11 dB can be observed at four frequencies: 1.4, 2.2, 5 and 8.3 kHz.

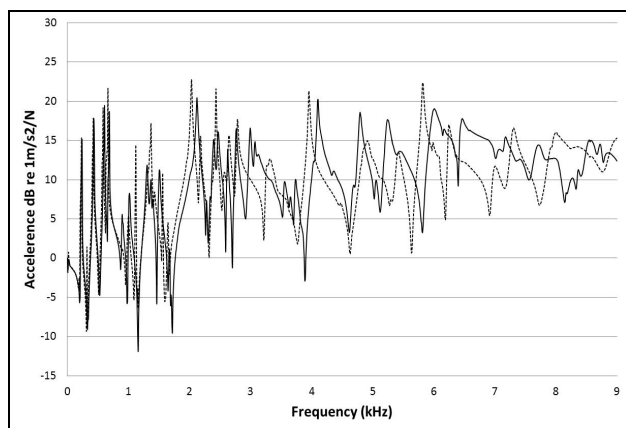


Figure 6: Accelerance for Sample C (solid line) compared to Sample D (dashed line)

A comparison of Samples C and D is shown in Figure 6. As in our previous work for external wedges [8], a peak shift to the left from reference is seen to varying degrees in the slot samples. Sample D has a more pronounced peak shift compared to Sample C. Note that Sample D as a damper outperforms Sample C between the ranges 4.5-5.7 kHz and 6-7 kHz. But a maximum reduction of 7 dB is achieved by Sample C at 2.2 kHz.

The next step was to investigate the effect of doubling the number of wedges within the slot. Although this would half the length of the existing wedge (with two opposite new wedges within the slot, both 47mm x 70mm), it was expected that by doubling the number of internal wedges the damping capabilities of the slot would increase.

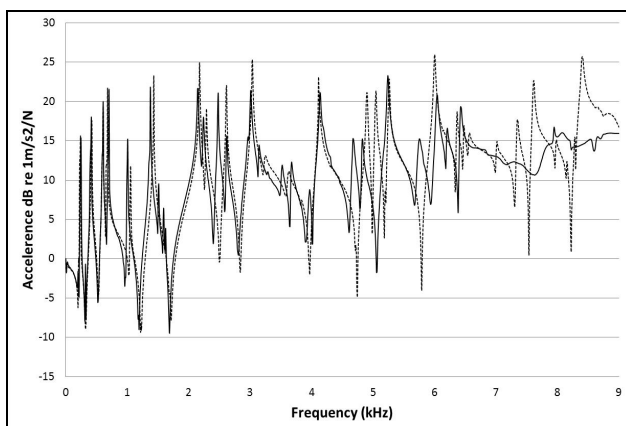


Figure 7: Accelerance for Sample B (solid line) compared to Reference Plate (dashed line)

From Figure 7 it can be seen that when Sample B is compared to a plain reference plate and excited from position 1, the damping achieved is less than that achieved when Sample C or Sample D configurations are used. As expected, below 900 Hz there is little to no damping, and at 1 kHz an increase in 4 dB can be seen. A maximum reduction from the reference plate of 8.5 dB can be seen at 7.6 kHz.

The results for Sample A as compared to the plain reference plate are shown in Figure 8. A maximum reduction from the reference plate of 9 dB can be seen at 3 kHz, with a 6dB reduction at 1.4 and 8.3 kHz. Despite this large reduction in peak amplitude, the majority of peaks are reduced only by 0-3dB.

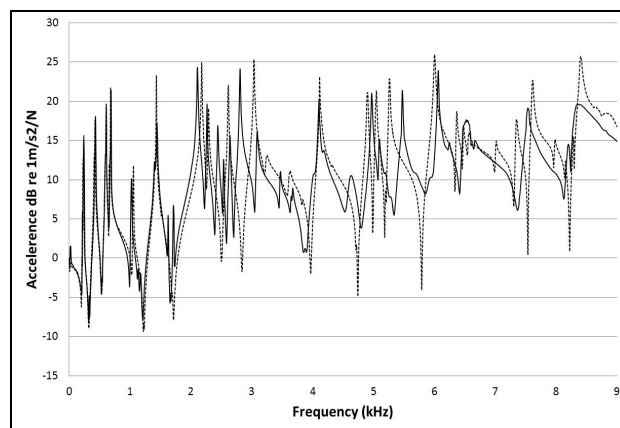


Figure 8: Accelerance for Sample A (solid line) compared to Reference Plate (dashed line)

One of the drives towards creating the slot plates was the protection of the wedge tips. However, they are still fragile and prone to tearing during and post manufacture. Another solution was to remove the central gully by creating a 'slot pit', Sample A.

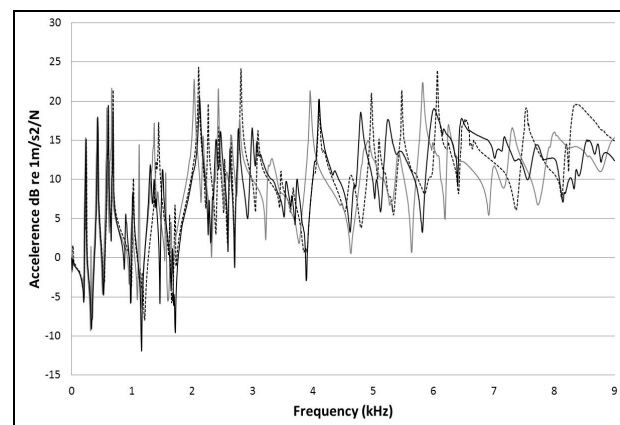


Figure 9: Accelerance for Sample C (solid black line) compared to Sample D (solid grey line) and to Sample A (dashed line)

From Figure 9 it can be seen that when Sample C, Sample D and Sample A are compared, Sample A is clearly the least effective at damping flexural vibrations in the steel plate. As expected, there is no difference between the three samples below 900 Hz. A maximum reduction from Sample A of 9 dB to Sample D can be seen at 3 kHz as seen in the previous result. Obviously, the gap at the end of the wedge tip is essential for increased damping performance.

4.2 Tapered slots in carbon composite plates

In this section, the effects of tapered slots on damping flexural vibrations in composite plates are investigated. A plain reference plate was used for comparison in this section, and no additional visco-elastic damping layer was added to any of the composite samples. All tests in this section were performed at position 1, as shown in Figure 4. The two slot configurations were chosen to be tested in

carbon composites were Sample E and Sample F (see Figures 1c and 1d).

Figure 10 shows the results for Sample F compared to a plain reference plate. Below 250 Hz little to no damping is seen, but the second resonance after this area, at 600 Hz, does however show an increase in peak amplitude by 6 dB compared to the reference plate. After this point, the response is smoothed, with resonant peaks heavily damped if not completely removed. A maximum reduction from the reference plate of 11.5 dB can be seen at 800 Hz.

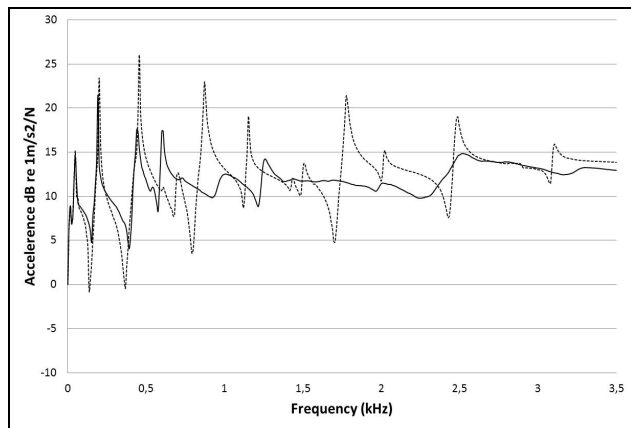


Figure 10: Accelerance for Sample F (solid line) compared to a plain reference plate (dashed line)

The results for Sample E compared to a plain reference plate are shown in Figure 11. Again, below 250 Hz there is little to no damping, there is also an increase in the second peak amplitude of Sample E, increasing the reference value at 650 Hz by 5 dB. A maximum reduction from the reference plate of 12 dB can be seen at 800 Hz despite this slightly higher maximum.

When compared to each other, the two composite samples, as expected, showed the same trends as their steel plate counterparts. The only differences in the observed trends are down to the changes in material properties. After 1.5 kHz, Sample F is consistently the more effective damper of the two samples when excited from position 1.

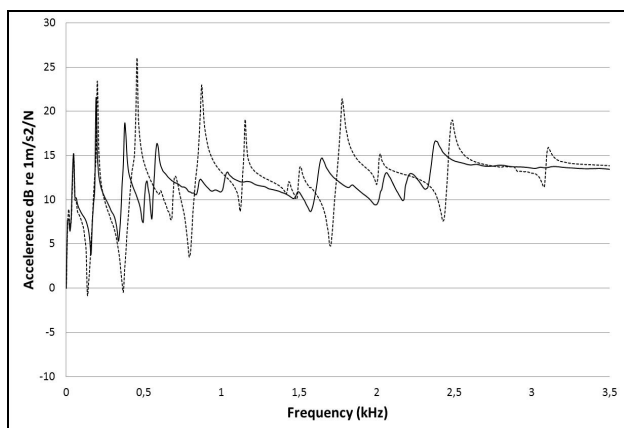


Figure 11: Accelerance for Sample E (solid line) compared to a plain reference plate (dashed line)

One of the most interesting results obtained from this section is the experimental confirmation of the fact that, due to high values of the material loss factor, no additional damping layer is needed for composite plates to obtain

substantial reductions in the amplitude of the resonance peaks.

4.3 The effect of vibration source position

This section investigates changes in the levels of damping that can be observed when changing the position of the excitation point relative to a slot. The reason for such changes in the levels of damping is a highly anisotropic nature of a slot as a 2D acoustic black hole. For example, theoretically one would not expect any damping if a plane flexural wave propagated in an infinite plate in the direction parallel to the slot direction. In finite plates though, different vibration modes can be interpreted as the results of superposition of plane flexural waves propagating at different angles, which makes the behaviour of power-law slots in finite plates more difficult to predict.

Three steel samples were used for the investigation: Sample C, Sample D and Sample B along with the two composite samples. Initially Sample C was excited in three different positions in relation to the slot (see Figure 4).

From Figure 12, it can be seen that when Sample C was excited from positions 1, 2 and 3, the position of the wedge root relative to the excitation position determined the level of damping achieved. However, the increase in the damping performance over the frequency range is small; approximately only 1-2 dB per rotation of the excitation position.

Samples B and E performed more effectively when excited from position 2. The composite sample results concurred with the conclusions obtained above.

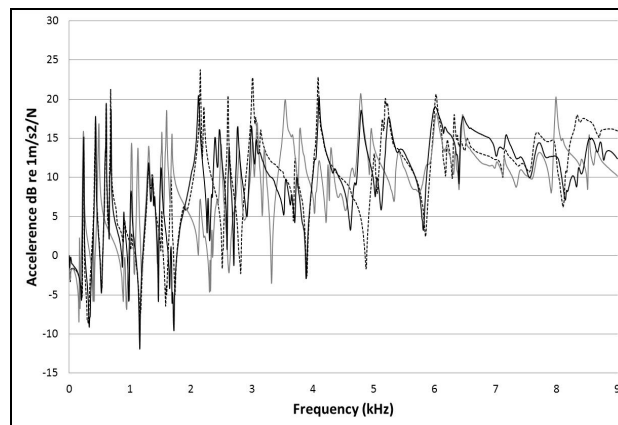


Figure 12: Accelerance for Sample C: excitation positions 1 (solid black line), 2 (grey line) and 3 (dashed line)

4.4 Combined slot composite plate

In this section, the possibility of combining two styles of slotted plates was considered in an attempt to obtain a more efficient damping performance. The composite samples that would best suit amalgamation, as they could be easily bonded together using a long cure epoxy resin, were Samples E and F. The amalgamated Sample G was excited in both positions, 1 and 2, and was compared to the sample that produced the most effective damping for each respective excitation point. Both excitation positions for the combination plate were then compared.

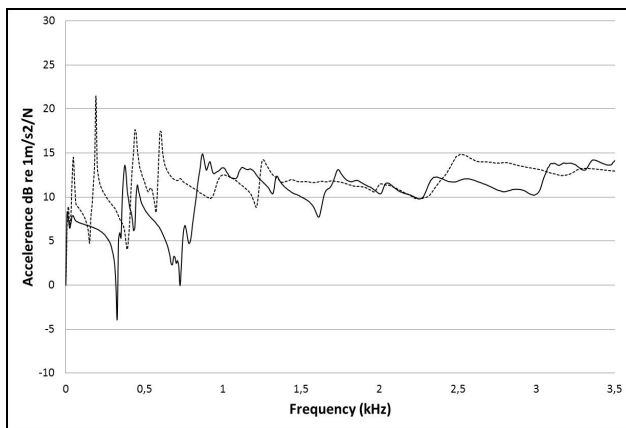


Figure 13: Accelerance for Sample G (solid line) compared to Sample F (dashed line), excitation position 1

From Figure 13, it can be seen that, when Sample G is compared to Sample F for excitation position 1, the samples respond in much the same way, with little to no defined resonant peaks visible. The peak at 200 Hz from Sample F is completely damped. An additional peak in Sample G has emerged at 850 Hz and is likely due to the bonding of the two plates.

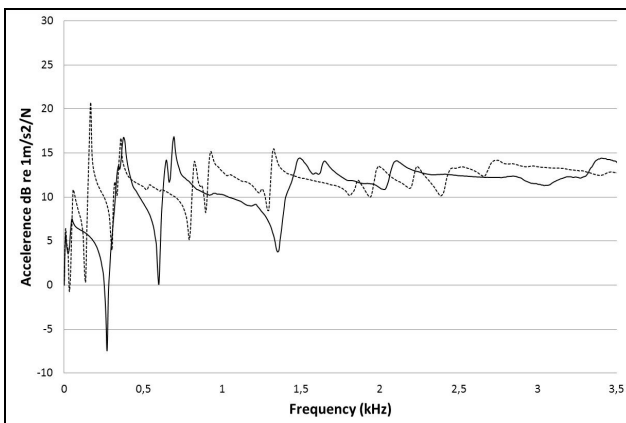


Figure 14: Accelerance for Sample G (solid line) compared to Sample E (dashed line), excitation position 2

Figure 14 shows the results for Sample G when compared to Sample E for excitation position 2. It is seen that after 1.5 kHz the samples respond in much the same way. As with the peak in Sample F at 200 Hz, the equivalent peak in Sample E has been completely damped, showing the maximum reduction of 18 dB for Sample G.

5 Conclusions

It has been demonstrated in this work that slots of power-law profile located within plates materialise a specific type of acoustic black holes for flexural waves and represent an effective method of damping structural vibrations. The maximum damping achieved on a steel slot plate (Sample C) was about 11 dB.

Carbon composite slot plates follow the same trends as the steel slot plates. Note that no damping layer is required for the composite plates to achieve comparable damping

performance to the steel plates. This is due to large values of material loss factor for composites. The maximum damping achieved using a composite slot plate (Sample E) was about 12 dB.

It has been shown that the shaker position does influence the damping performance of the slot plates.

The combined carbon composite plate (Sample G) damps all the modes above 1.5 kHz that are damped by the individual slot plates before amalgamation, irrespective of the excitation point.

Acknowledgements

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