Experimental Investigations into the Acoustic Black Hole Effect and its Applications for reduction of Flexural Vibrations and Structure-Borne Sound

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Introduction

Damping of structural vibrations remains a challenging problem for different branches of engineering, especially for aeronautical and automotive applications. 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 [1-3]. A common means of damping resonant flexural vibration in a structure is to reduce the reflection of flexural elastic waves from the structure's free edges [4]. The Acoustic black hole effect utilizes this method of damping via using wedges of power-law profile. This method has recently been developed and investigated [5-7]. It has been applied as one (1D)- and two (2D)-dimensional acoustic black holes (ABH) in the form of power-law wedges and circular indentations respectively, see Figure 1. Ideally, if the power-law exponent is equal or larger than two, the flexural wave never reaches the sharp edge of a wedge and therefore never reflects back [5-8], which implements an 'acoustic black hole' (ABH). However, ideally sharp wedges do not exist in reality; therefore the presence of a small strip of damping layer at wedge tip is paramount to obtain very low reflections from these free edges, which then constitutes the acoustic black hole effect [5-7]. It has been established theoretically [5, 6] and confirmed experimentally [7] that this method of damping structural vibrations is very efficient even in the presence of edge truncations and other imperfections.

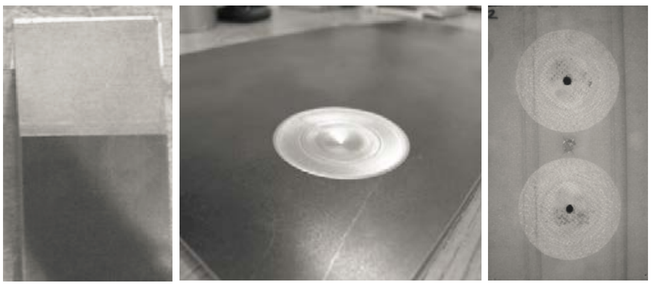

Figure 1: 1D ABH (wedge of power-law profile), 2D ABH (circular indentation of power-law profile) in steel and two 2D ABH's in glass fibre composite.

This paper will give an overview of four investigations into the ABH effect, the aim of which was to facilitate the integration of this effect into real world applications: Fan Blades, Composite Panels, Honeycomb Sandwich Panels, and Sound Radiation from plates with 2D Arrays of ABHs.

Experimental Procedure

The results presented in this paper were obtained using a variety of different experimental techniques. The standard vibration test was carried out using a force transducer, accelerometer and shaker, with the sample suspended to allow nearly free vibration of the sample plates (i.e. to eliminate clamping of edges), Figure 2.

Two further vibration tests techniques were used, the first of which utilised a scanning laser vibrometer, shaker and suspended sample. The second utilised airflow as the excitation source and was performed in a closed circuit wind tunnel, Figure 2. Flow visualisation tests where also performed in the wind tunnel; with a max speed of 34 m/s. The final investigation into the sound radiation of suspended plates with arrays of ABHs was performed in a fully anechoic chamber in accordance with ISO 3744.

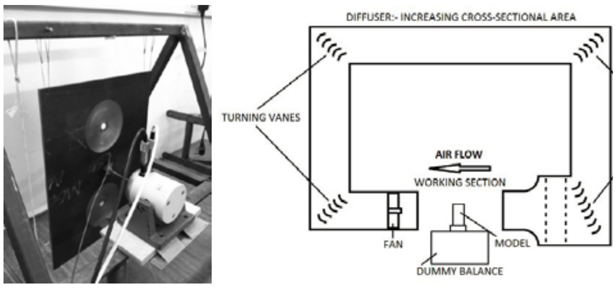

Figure 2: Standard Vibration set up with suspended sample and Closed circuit wind tunnel schematic.

Results and Discussion

Fan Blades

This section describes the effect of the introduction of a wedge of power-law profile to a fan blade and examines whether this could produce an 'acoustic black hole effect' as seen in previously tested steel samples [7]. To test the applicability of a 1D ABH on a fan blade a straight reference blade was compared to a straight blade with a 1D Acoustic black hole and damping layer.

This comparison is shown in Figure 3. As seen in previous work [7], the addition of a wedge of power-law profile to the end of an aluminium fan blade, shows the same trends seen in steel plates. Above 1.4 kHz an increase in the reduction of the resonant peaks is seen up until a maximum reduction of 12 dB from the reference sample at 4.2 kHz. Above this frequency the response is smoothed, with resonant peaks heavily damped if not completely removed.

A twisted blade more accurately represents the real world engine fan blades, therefore the effect of a twist (11 degrees) on the blade needs to be considered. When the twisted reference blade is compared to the twisted blade with a wedge of power-law profile, a damped response similar to that observed for the straight blades is clearly viable. A maximum reduction of 10.5 dB from the reference plate by the profiled sample has been obtained in this case.

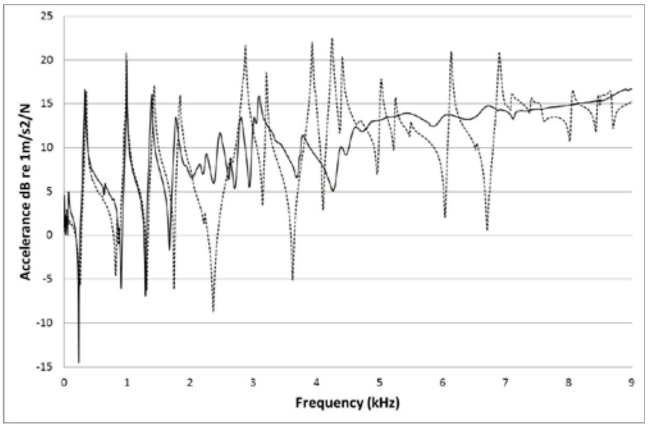

Figure 3: Accelerance for Reference blade (dashed line) compared to blade with 1D ABH and damping layer (solid line)

Flow Visualisation for a Fan Blade with a Wedge of Power-law Profile

This section describes the results of the flow visualisation tests for the straight fan blade. The fan blade is at an arbitrary incline of 10 degrees to the airflow. The aim of this investigation was to prove that, with adaptation of the damping layer attached to the wedge of power-law profile, the airflow over the underside of the blade could be returned to a similar state as that seen for the reference blade.

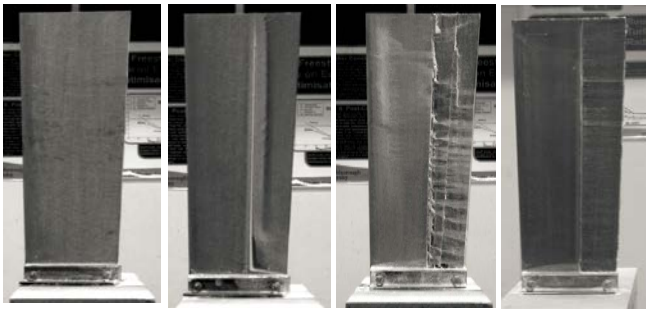

Figure 4: Flow visualization diagram for: (a) Reference fan blade, (b) Fan blade with power-law wedge, (c) Fan blade with power-law wedge with single damping layer, (d) Fan blade with power-law wedge and shaped damping layer

Figure 4 shows the progression of the flow visualisation tests from a reference fan blade to a fan blade with a wedge of power-law profile and a specifically shaped damping layer. The flow visualization for the reference fan blade, Figure 4(a), shows laminar flow across the blade surface with no separation. The effects on the airflow of the presence of the wedge are immediately obvious, Figure 4(b). A clear transition line, lamina separation bubble, and then reattachment of the flow towards the trailing edge of the blade is seen.

A narrow damping layer identical to that used in wedge vibrations tests was then attached. From Figure 4(c), a clear line of transition can be seen between the upstream laminar flow and the turbulent flow after the start of the damping layer. This flow is too turbulent to reattach to the blade. It is worth noting that with the damping layer attached in this way there is a step between the blade surface and the damping layer. This step is responsible for the increased turbulence of the airflow in the wedge area.

An obvious possible solution to the flow turbulence problem seen in Figures 4(b) and (c) would be to recreate the flow pattern seen in Figure 4(a), i.e. the original profile of the blade has to be restored. One method of partly achieving this is to shape the damping layer in order to recreate the original profile. This was achieved by building up layers of the damping material which, when covered by a layer of damping material of the same width as the wedge, would reproduce the original profile. The final diagram (Figure 4(d)) shows the resultant flow over the blade with this shaped damping layer. There is still a clear line of transition but the flow quickly reattaches to blade. This line of transition will always be seen with the ridge at the edge of the damping layer. This result shows that if the damping layer could be more effectively blended into the blade the line of transition would disappear and a laminar flow would cover the blade.

Composite Panels

A 2D Acoustic black hole has an exposed delicate tip that is prone to damage. In order to make ABHs more applicable in the real world they can be enclosed in a smoothed surface panel. This section considers the production of such a panel in glass fibre composites. Each panel contains two ABHs

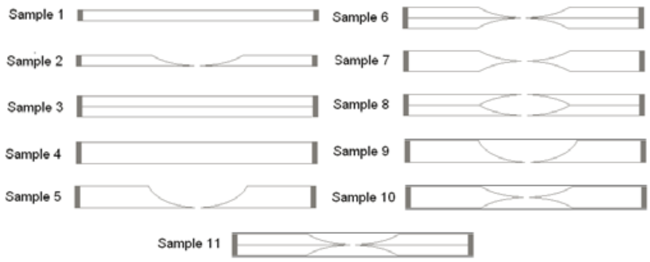

Figure 5: Cross-section view of Sample plates 1-11

First the effectiveness of a 2D ABH was tested in 3 mm composite panels (Sample 1, 2) Figure 5. 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.

To be able to enclose 2D ABH’s into a smooth surfaced panel the tip of the indentation is required to be in the centre of the thickness of the panel, Figure 5 (Sample 6,7). A conventional ABH plate (Sample 5) and a plate with only the central hole visible on the outside edge of the plate (Sample 8) was also considered. There was very little difference in the response of samples 5, 6, 7 and 8. Reductions of approximately 10 dB from reference in each case were seen.

Samples 5, 6 and 7 were then enclosed beneath a layer of composite to form a smooth surfaced panel (Samples 9, 10 and 11). Again there was little difference in the responses of these plates. Sample 11 slightly (1-3dB) outperformed the other samples. The response of Sample 11 compared to a reference plate is shown in Figure 6. A maximum reduction of 10 dB from the reference plate is achieved at 2.4 kHz.

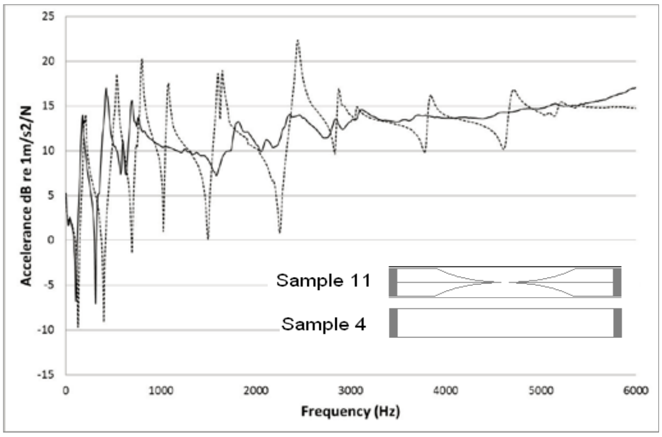

Figure 6: Accelerance for Sample 11 (solid line) compared to Sample 4 (dashed line). Insert; cross-section of samples

The combination of the composite plates and sheets results in an effective method of damping flexural vibrations in smooth surfaced composite panels, e.g. internal aircraft skins.

Honeycomb Sandwich Panels

The natural progression of this research was to investigate composite honeycomb sandwich panels incorporating the smooth surfaced composite panels containing 2D ABHs described above.

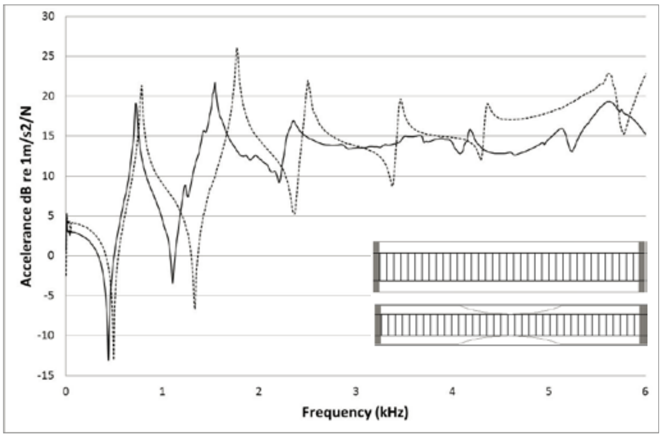

Figure 7: Accelerance for a composite honeycomb sandwich reference panel (dashed line) compared to the same style panel with enclosed indentations of power-law profile (solid line). Insert; cross-section of samples

Figure 7 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. A maximum reduction of 6 dB is seen at 2.5 and 3.4 kHz. Thus a composite honeycomb panel with enclosed circular indentations of power-law profile shows a good damping performance.

Sound Radiation from a Plate with a 2D Array

It has been found [9] that a hole needs to be present at the centre of the indentation of power-law profile in order for the acoustic black hole effect to occur efficiently. The paper [9] also looked at increasing the number of indentations in order to increase the damping performance of the plate. Arrays of 2 to 6 ABHs were tested, and it was found that the greater the number of indentations the greater the damping performance of the plate.

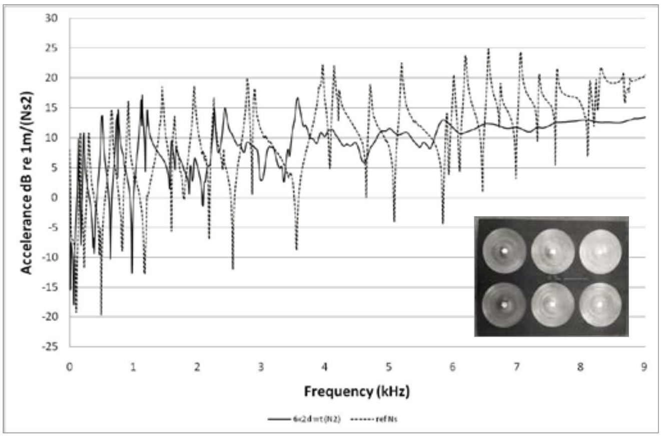

Figure 8: Accelerance for a plate containing six profiled circular indentations with 14 mm central holes and additional damping layers (solid line), as compared to a reference plate (dashed line).

The plate with six ABHs showed the greatest damping. Figure 8 shows the response of the six indentation plate when compared to a reference plate. It can be seen that after 4 kHz almost all peak responses are flattened and a maximum damping of 14 dB occurs at 6.5 kHz.

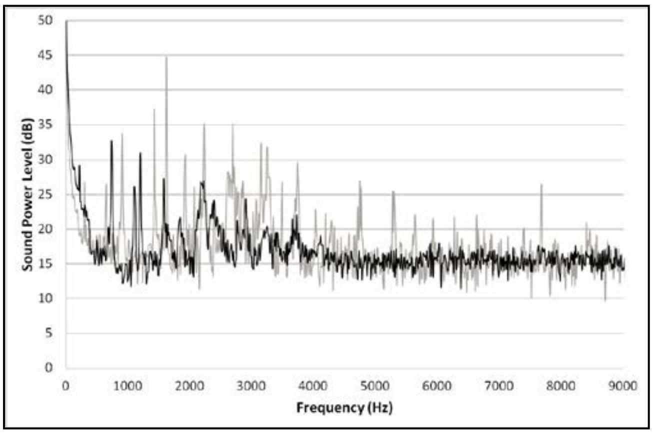

Figure 9: Sound power level comparison of a plate with six indentations of power-law profile with a damping layer (black line) compared to a reference plate (grey line)

As one of the main aims of this research was to explore practical applications for acoustic black holes, so the sound radiation from structures containing these indentations was considered. Figure 9 shows the results for a plate containing six profiled circular indentations compared to a reference plate. Below 1 kHz there is little to no reduction in the sound pressure level, as was the case with the reduction in vibration response. Between 1-3 kHz the sound power level response is reduced from the reference plate response by 10-18 dB, with the maximum reduction in the sound radiated occurring at 1.6 kHz.

We now consider the amplitudes of the plate's vibrational response in comparison to the levels of the associated sound radiation. As the frequency increases the amplitude of deflection over the constant thickness section of a plate containing circular indentations of power-law profile tends to zero. At lower frequencies, where no reduction in sound radiation or vibration response is seen, the plate behaves as a constant thickness plate, with a little difference from the plate without indentations.

In the frequency range where reductions in vibration response and sound radiation are seen, the plate vibration pattern changes substantially, with a noticeable amplitude reduction outside the indentations. In the higher frequency range the only displacement on the plate is seen in the last 2 cm of the indentation tip (centre). This corresponds to the area of maximum effectiveness of the damping layer.

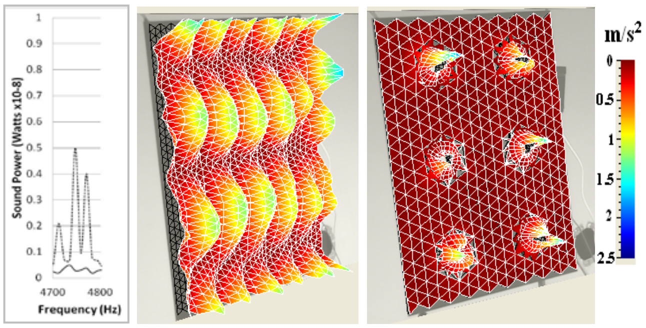

Figure 10: Results for resonant peak at 4.75 kHz; (a) Sound power in Watts for reference plate (dashed line) compared to the plate containing six indentations with damping layers, (b) Modal response of the reference plate, (c) Model response of the plate containing six indentations with damping layers, (d) Amplitude of response; key.

Figure 10 shows the results for the sound power (in Watts) at 4.75 kHz for a reference plate compared to the plate containing six indentations with damping layers, and the modal response of the reference plate and the plate containing six indentations with damping layers. It can clearly be seen, Figure 10(c), that other than a radius of 2 cm at the centre of the indentations the amplitude of the response over the entire plate is zero. The mode shape seen in Figure 10(b) had been eliminated in Figure 10(c). This 'active' area on the indentation plate, where a response is seen, corresponds to the area over which the damping layer was determined to be effective. The amplitude of the response in the 'active' area is approximately 1 m/s^2 greater than that seen on the reference plate. However, this does not affect much the sound radiation of the plate, as seen in Figure 10(a). Acoustic black holes thus result in a considerable reduction in sound radiation when compared to the reference plate.

Conclusions

It can be seen from the four investigations detailed above that both 1D and 2D ABHs are an effective method of damping flexural vibrations in fan blades, composite panels, honeycomb sandwich panels and steel plates.

It can be concluded that it is possible to design a fan blade with an acoustic black hole and built up damping layer that produces little interruption to the airflow while providing considerable damping to the blade. This could result in reduced internal stress and a longer fatigue life.

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. These panels without the exposed indentation centres are more versatile as the tips are protected. Such panels could be used in applications such as interior aircraft panels to reduce noise and vibration. Composite honeycomb panels with enclosed circular indentations of power-law profile also show a good damping performance.

The greater the number of indentations of power-law profile in a plate the greater the damping performance. Array plates provide a considerable reduction in radiated sound power when compared to a reference plate. There are many possible applications where such a reduction is invaluable.

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