Acoustic black hole manufacturing for practical applications and the effect of geometrical and material imperfections

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ABSTRACT

One of the main challenges in NVH engineering today is not only finding effective methods of reducing noise and vibration from structures, but also the integration of these new methods into a manufacturing process. Acoustic black holes reduce amplitudes of resonant flexural vibrations by reducing edge reflections from structures' free edges via the use of wedges of power-law profile (one dimensional acoustic black holes) or tapered circular indentations of power-law profile (two-dimensional acoustic black holes). Such acoustic black holes can absorb a large proportion of the incident flexural wave energy.

In this paper, the manufacturing of acoustic black holes for some practical applications is considered. The effect of geometrical and material imperfections associated with manufacturing on the performance of acoustic black holes is also investigated experimentally. These imperfections are: tip length and corrugations, edge truncations, etc. Also, the effects of commonly used joining techniques are considered. The reported results demonstrate that the effect of geometrical and material imperfections is not detrimental for the performance of the acoustic black holes. In spite of the presence of imperfections, they provide an effective damping of flexural vibrations, as well as an effective reduction of sound radiation from vibrating structures.

Keywords: Acoustic black holes, damping

1. INTRODUCTION

Investigations and interest in the Acoustic black hole effect have grown exponentially over the last decade. It is therefore only natural that now the focus of development engineers in industry is turning from the theoretical and laboratory experimentation to real world applications and production. The manufacture of a prototype in a specialized workshop has very different considerations from those faced by a company wishing to produce identical samples, within tolerance, at an affordable price, with the possibility of mass production. What works for the production of research samples may not be so cost effective and practical in the real world. The possibility of attaching Acoustic black holes to existing designs as well as integrating them into the first design of components and system is also a consideration in industry.

This paper will discuss some of the problems and solutions faced when wanting to move the manufacture of acoustic black holes from the laboratory to industry, along with the effect of manufacturing imperfections and attachment methods on the performance of Acoustic black holes. First an introduction to the Acoustic black hole effect is given. 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 structures free edges (4).

The 'acoustic black hole effect' utilizes this method of damping via the use of a wedge of power law profile. Using wedges as dampers is not a new concept and has been utilized for many years (3), but no previous wedge dampers have shown the same potential as the 'acoustic black hole' in

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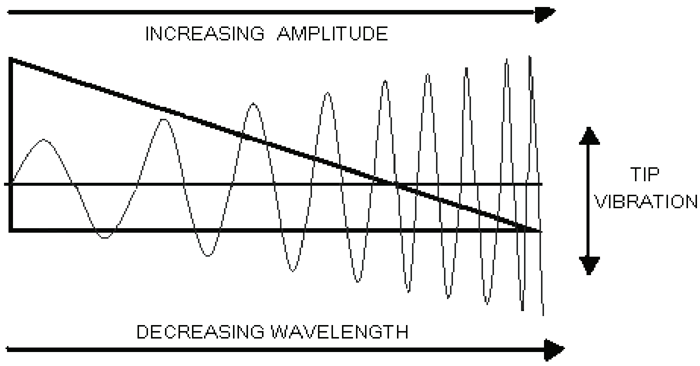
performance, versatility in manufacturing and feasibility. This method can be utilized to provide substantial damping over a wide frequency range in a wide variety of applications. This section gives a brief review of the progression of the acoustic black hole effect.

The first theoretical paper describing propagation of a flexural wave in a wedge of power-law profile (quadratic wedge) was published in 1988 (5). It has been shown in that paper that a wedge of power law profile with the power exponential *m≥2* acts as an acoustic black hole for flexural waves propagating towards its sharp edge by asymptotically decreasing the phase speed of the wave in such a way that the wave will never reach the end of the wedge and thus never reflect back into the plate (5), Figure 1(a).

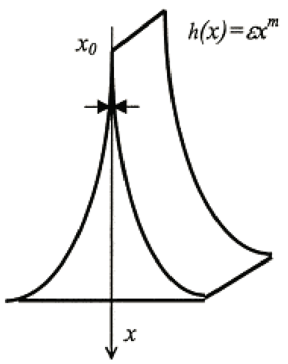
The power law profile described above is illustrated in Figure 1(b) and is defined by

$$h(x) = \varepsilon x^{m} , \quad (1)$$

where h(x) is the local thickness, m is the above-mentioned power exponential (a non-dimensional positive constant), ε is a dimensional constant, and x is the coordinate measured along the wedge axis.



(a)



(b)

Figure 1 - (a) Wave behaviour in wedge of power-law profile, (b) Wedge of power law profile

It has been shown (5) that reflections from a real (truncated) wedge are far from zero, and therefore in the case of materials with a low internal loss factor such as steal, such wedges cannot be used alone for large reductions of wave reflections. To resolve this problem it has been proposed (6,7) to attach a damping layer at the tip of a power-law wedge. The addition of a damping layer reduces the amplitude of the reflected wave very efficiently due to the high energy absorption due to a decreased thickness of the profile at the wedge tip, this leads to an overall reduction in the plates vibration response. Such dramatic reduction of reflected waves achieved by using a combination of a wedge of power-law profile and of an attached damping layer has been termed the 'Acoustic black hole effect' (6-9) This is due to the fact that when the wedge is viewed from a point outside of the profile a flexural wave enters the profile but ideally never returns, having been attenuated by the damping layer attached to the surface at the wedge tip. It has been established theoretically (8,9) and confirmed experimentally (10) that this method of damping structural vibrations is very efficient.

2. MANUFACTURING

Over the years, experimental investigation into the Acoustic black hole effect and the drive of researchers to move this effective damping method from the laboratory into the real world has meant that a wide variety of different material types, thicknesses, forms and manufacturing methods have been tested. There are many different manufacturing methods than can be used to produce both 1D and 2D acoustic black holes. The method that is used depends, strongly on the material and the manufacturing methods used to produce the component containing an Acoustic black hole.

2.1 Milling

The standard method used to produce an Acoustic black hole is computer controlled milling, this method can be used on the majority of metals, plastics, foams and composites; basically any material that can be milled. The correct rotation speed, bit tip angle and material are very important as it is easy to destroy the wedge or indentation profile when trying to machine the Acoustic black hole, Figure 2. It is also beneficial when trying to manufacture profiles above m=3 to secure the central area or tip of the Acoustic black hole to prevent the thin tip material from lifting off the bench and becoming damaged. Again care must be taken that the securing media can also be easily removed from the thin tip surfaces after manufacture. Machining metal results in high bit wear. This is a relatively time consuming method of production, especially if the material is thick (eg 4mm) and has a high Youngs modulus (e. g. steal).

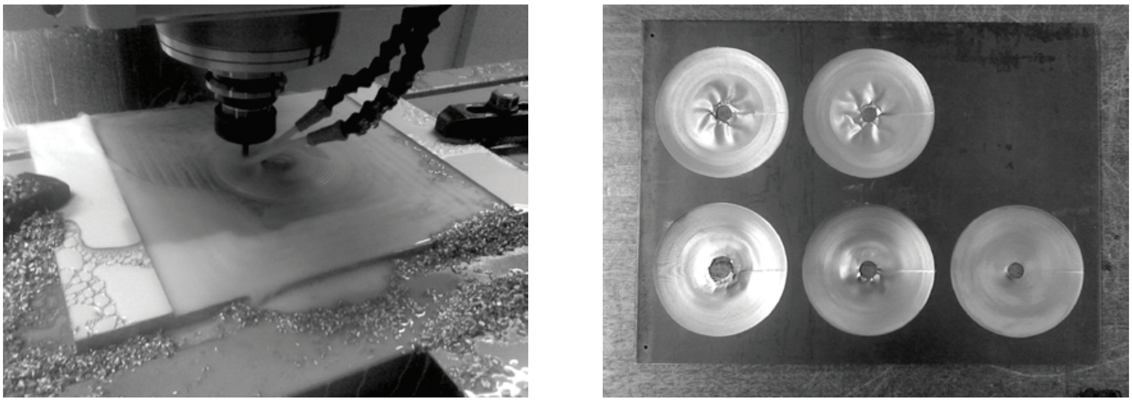
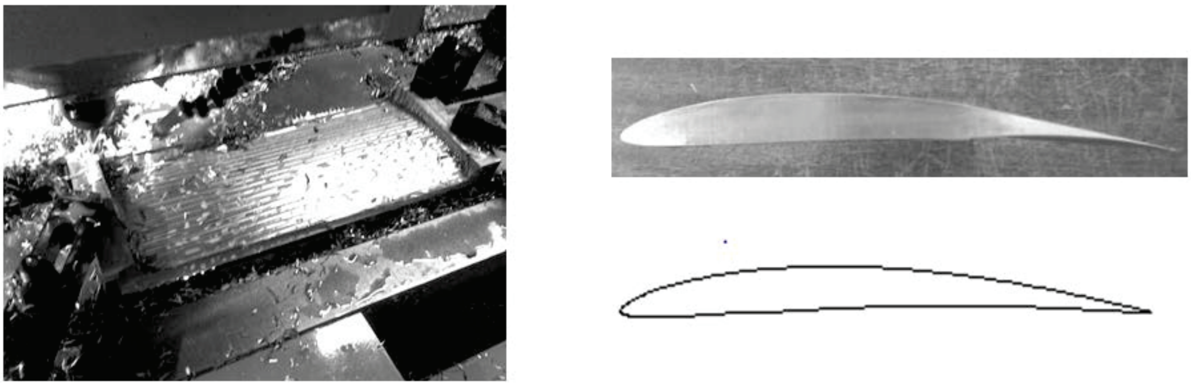


Figure 2 – Milling of a two dimensional acoustic black hole and manufacturing defects

One of the main problems with this method of manufacture comes when the acoustic black hole is required to be milled in to a more complicated surface than a plate. That been said, it is not impossible and, as shown (11), when the entire sample is milled a wedge can be manufactured into components such as a jet engine fan blade, Figure 3 (12).



(a) (b)

Figure 3 - (a) Manufacturing of a fan blade, (b) Fan blade profile with (top) and without (lower picture) wedge of power-law profile.

2.2 Casting and moulding

In reality a company would never individually mill such blades. The standard method for manufacture of this component is casting. This method of component manufacture is highly compatible with both 1D and 2D acoustic black holes and allows for very complicated forms to be produced. With casting the counter form of the required acoustic black hole can be simply incorporated into the component mould. At the end of the casting process the acoustic black hole is incorporated into the component structure with little to no extra processing required. This is particularly true in the case of plastic component moulding, where no additional damping material is required at the tip of the acoustic black hole (11,13). Some examples of where this could be implemented are vehicle engine covers and aircraft cabin wall panels.

2.3 Curing

Another material that is becoming increasingly popular in the modern transportation industry is composites, again the composite manufacturing method leads naturally to the possibility of the incorporation of acoustic black holes into the production process. Using composites as an example, it can be shown that it is possible to replace computer controlled milling with a manufacturing process more suitable to mass production, with little to no alterations to the current manufacturing process.

The example given below compares the standard milling method with a direct curing method for ABH production. It is a basic representation of the process for both 1D and 2D acoustic black holes; more complicated variants are possible.

With the direct curing method the ABH profile is directly cured into the sample, without any need for post curing manufacturing processes. The pre-preg composite sheets are cut to the required lengths and then layed-up on a mould containing the inverse of the power-law profile required. The power-law profile is then formed under a vacuum in a composite oven accordance with the manufacturers guidelines. Figure 4.

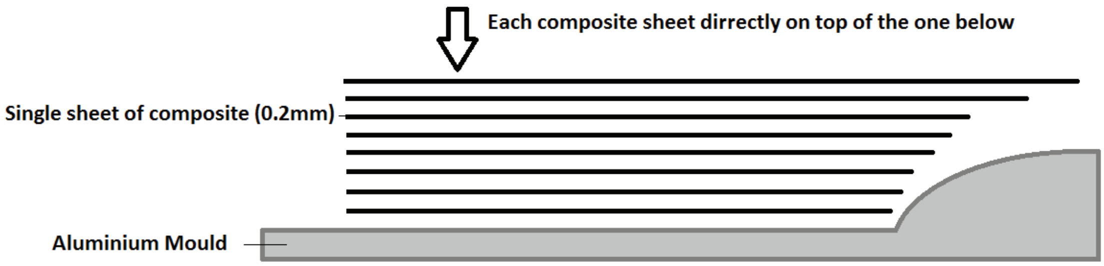


Figure 4 - Representation of the composites sheets layed-up on top of the mould

The 2D indentation can also be easily manufactured via the curing method of manufacture, in much the same way as the strip circles of increasing diameter are cut out of the composite and layed up on an inverse profile mould, then cured, Figure 5.

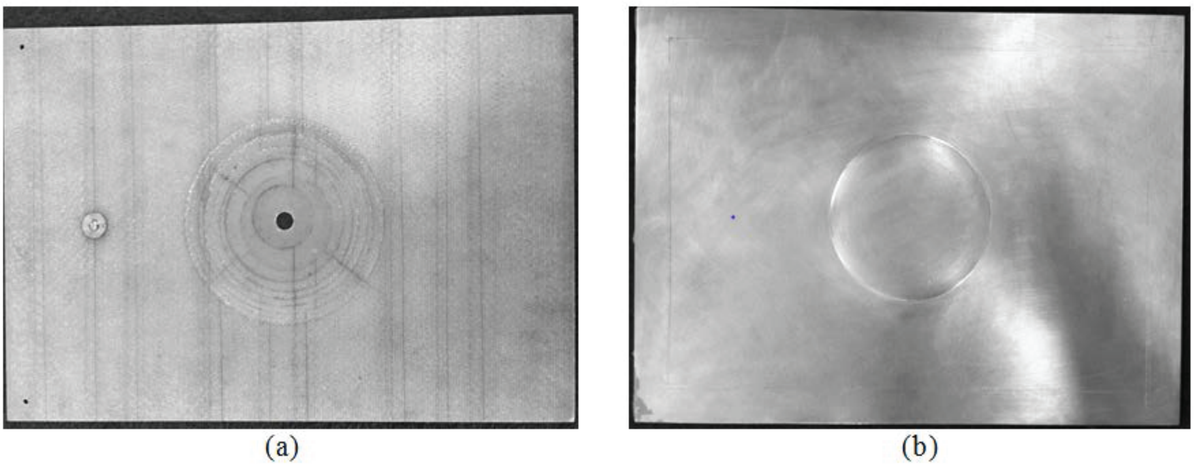


Figure 5 - (a) Cured indentation of power-law profile and (b) inverse mould

The results of a comparison of frequency response functions between a strip with a machined wedge of power-law profile compared to a strip with a cured wedge of power-law profile are shown in Figure 6. . Below 500 Hz there is little to no difference in the response of the two samples. The greatest variation in the responses is seen between 1-2.6 kHz with a pronounced peak shift to the left. The greatest reduction in peak amplitude is achieved by the machined sample at 2.5 dB at 2 kHz, although between 0.5-1 kHz and 2.5 kHz the cured sample has a reduced response of 05-1.5 dB. Above 2.6 kHz the resonance peaks of the reference sample are damped by both samples.

The main reason for the differences in the responses is down to the profile. The machined sample has 50 steps of 0.1mm whereas the cured sample had 20 steps of pre preg composite uncured 0.2 mm. The surface of the cured sample is smooth with the composite resin forming the profile against the mould. The difference in profile formation is responsible for the shift in response. The fact that fibers in the cured sample do not extend to form the profile is the most likely explanation for the distinct sharp responses seen at 1.3 and 2 kHz. The equivalent resonances in the machined sample show a rounded, damped response.

It can therefore be shown that within a 2 dB range and accounting for peak shift the responses are very similar and curing the profile is an acceptable method of manufacture to produce a wedge of power-law profile and the acoustic black hole effect.

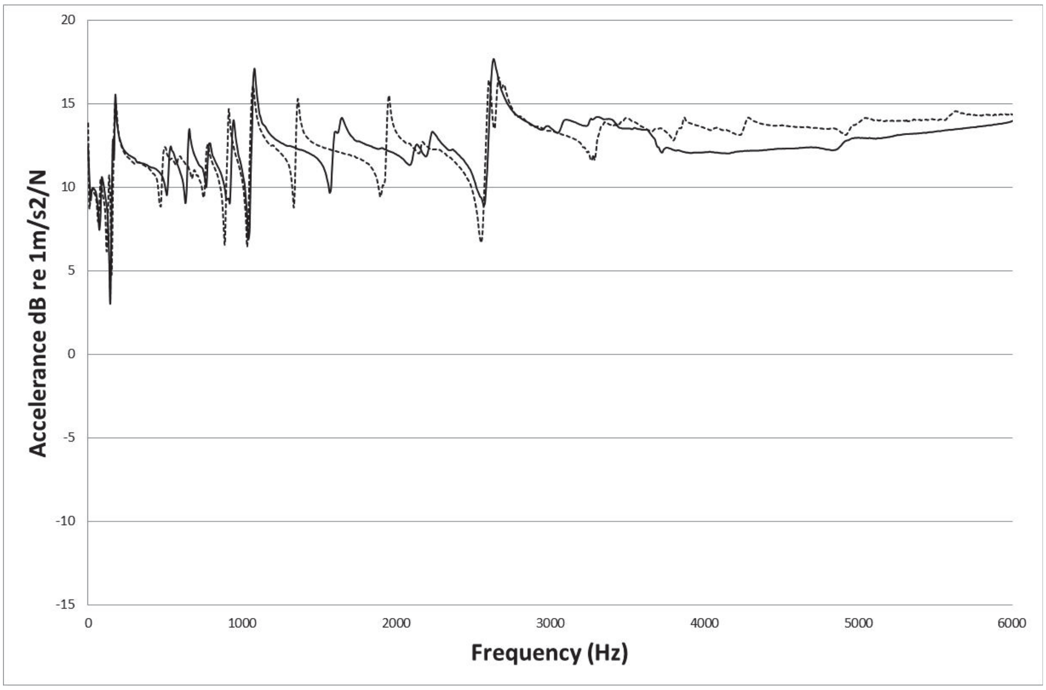


Figure 6 - Accelerance for the Machined-profiled strip (solid line) compared to Cured-profiled strip (dashed line)

2.4 Applications

There is no magic formula when it comes to acoustic black holes that can state if this is the right damping or noise reduction method for any given NVH problem. Like the majority of NVH solutions, the practicality of this method of NVH reduction depends heavily on the material, material thickness, component shape, the frequency range that needs to be targeted and the manufacturing method. Some key points to remember are:

- The thinner the material the lower the frequency at which the effect can first be seen (11,12).
- The greater the loss factor of the material, the lower the frequency at which the effect can first be seen.(11,14)
- The larger the diameter or wedge length of an acoustic black hole the greater the damping effect and lower the frequency at which the effect can first be seen (15,16).
- The greater the number of acoustic black holes the greater the damping effect and lower the frequency at which the effect can first be seen (15,16).
- For metals and materials with a low internal loss factor an additional damping layer is required at the wedge/indentation tip (6,7,15).

- Tip thickness is important for the damping performance of the acoustic black hole (16, 17)
- It is more effective to incorporated Acoustic black holes into an existing structure although attaching them is also effective (17).
- Focusing waves into an Acoustic black hole is very efficient method of vibration reduction (18).
- Manufacturing method; For example when considering the body in white (automotive vehicle shell), unless a non-milling method is used to incorporate the ABH into the body in white such as casting this is not a viable method of NVH reduction in a vehicle due to cost and time effectiveness.

2.5 Conclusions

Although milling was at the start of acoustic black hole manufacturing, with the exception of limited batch number components and prototypes, it is not the method that will take acoustic black holes into the real world and mass production. It is just not viable both in terms of time for production and cost effectiveness. The manufacturing methods that will lead acoustic black holes from the lab to industry are casting, moulding, curing and maybe even 3D printing.

3. IMPERFECTIONS

In this section, the effect of mechanical damage to the tips of 1D and 2D Acoustic black holes resulting from the use of cutting tools, including tip curling and early truncation will be reported,. Engineering structures are also rarely constructed from a single sheet of material and are likely to have joins (bonded sections). Another aspect simulated in this investigation is the bonding of a wedge to an existing structure, thus exploring practical ways of integrating Acoustic black holes into existing structures. The effects of bonding a wedge to basic rectangular plates (strips), via different welding techniques and gluing will also be reported. Finally the protection of the acoustic black hole tip is considered along with safety and aesthetics.

3.1 Effect of tip damage and early truncation on 1D or 2D Acoustic black holes

Especially when considering the milling method of manufacturing, the effect of the machining on the tip of the acoustic black hole should be considered. The relevance of this phenomenon on other methods of manufacture is not as prominent as the tip thickness and smoothness of the tip finish is dictated by the mould. With cured acoustic black holes in composite manufactured components the finish is always smooth due to the matrix component of the composite (resin). There is also a reduced possibility of tearing and blistering when a non-milling method of manufacture is implemented.

3.1.1 1D Acoustic black holes (wedges) (17)

This section describes the effect of tip damage in a wedge of the maximum possible (extended) length of 49 mm on its performance when compared to the same wedge when it has been cut to a reduced length of 39 mm, i.e. with a premature truncation, Figure 7.

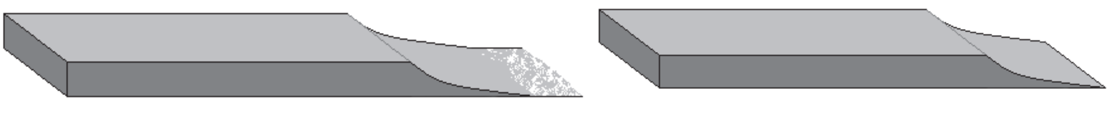


Figure 7 - Wedge with tip damage and wedge with premature truncation

Figure 8 shows the values of measured accelerance for a TIG welded sample (extended sample) of power-law profile compared to the TIG welded truncated sample. It can be seen that, in spite of the wedge tip damage, the resonant peaks of the extended sample show an increased amplitude reduction with increasing frequency. It ranges from 8.5 to 12.5 dB between 3.8 and 7.8 kHz, with a larger reduction of 15 dB recorded at around 8 kHz. This agrees with the predictions of (8, 9), the reflections from truncated wedge tips increase with the increased truncation, thus resulting in poor damping characteristics in samples containing truncated power-law wedges.

The same measurements were performed with the glued bond. The results followed a similar trend as in the case of the TIG welded sample, with the extended sample consistently performing better than the truncated sample. The maximum reduction of 7 dB occurred at 7.2 kHz in this case. The MIG welded sample and the homogeneous sample followed the same damping trend again, but with smaller increases in damping performance. The extended MIG welded sample achieved the maximum increase of 5.5 dB compared to the truncated sample and the extended homogeneous sample showed a 4.5 dB reduction over the truncated sample.

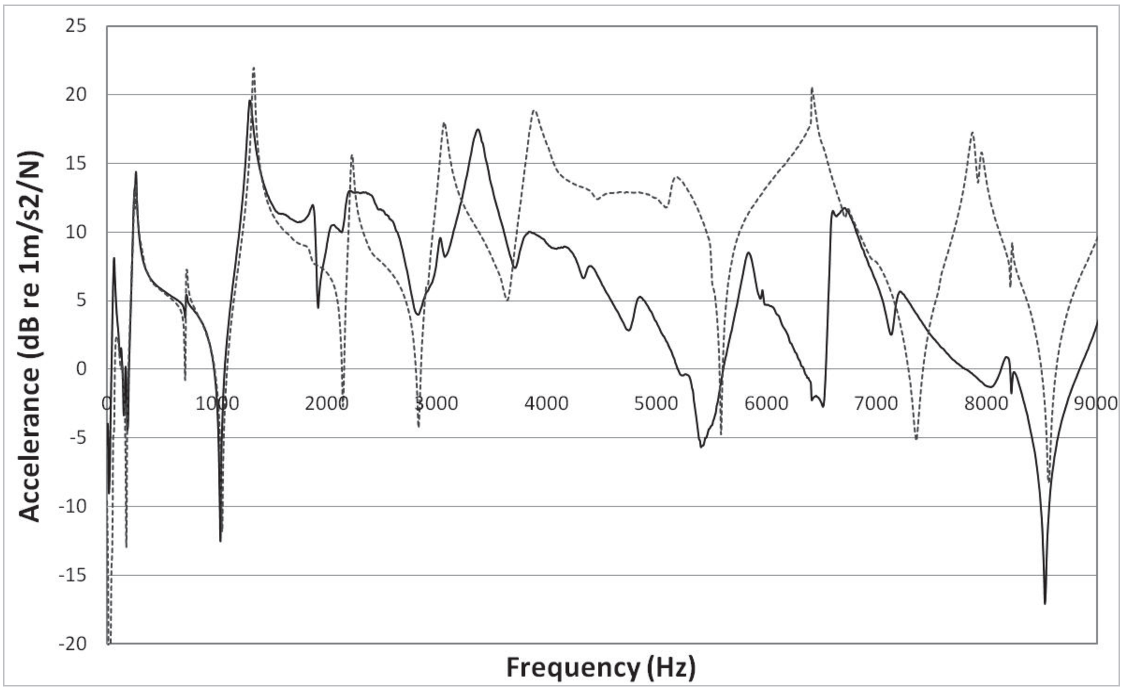


Figure 8 - Measured accelerance for a TIG welded sample (solid curve) with power-law profile (m = 2.2) compared to the TIG welded truncated sample (dashed curve).

Despite the damage to the extended wedge tip, the increased length and resultant decrease in tip thickness provided the most efficient damping, thus demonstrating that the longer and thinner the wedge tip the greater the contribution of the acoustic black hole effect into the overall vibration damping.

3.1.2 2D Acoustic black holes (circular indentations)

During investigations into arrays of acoustic black holes (16) it was found that one of the indentations was consistently underperforming with less than half the displacement amplitude seen in the other indentations of power-law profile, Figure 9. This prompted a closer physical examination of the indentation tips where it was found that one of the indentations was slightly thicker (0.14 mm) and had no damage (tearing or blistering), Figure 10(c), whereas the others were all similar, Figure 10(d)) with thinner (0.10 mm) slightly damaged tips. This reduction in tip displacement in the truncated acoustic black hole was seen across the active frequency range of the array plate.

As with a wedge of power-law profile, it was discovered that a thinner tip even if damaged was more effective at damping flexural vibrations than a thicker undamaged wedge tip. In this case with the aid of the scanning laser vibrometer the difference in the amplitude of the displacement of the indentation wedge tip of these two cases for '2D Acoustic black holes' can be seen, Figure 10 (a/b). As with a wedge of power-law profile, a circular indentation of power-law profile performs more effectively as an 'Acoustic black hole' with a thinner damaged indentation tip as it can reach higher deflection amplitudes when compared to a slightly thicker undamaged indentation tip. As a flexural wave enters a wedge of circular indentation of power-law profile by definition its wave speed and wave length decrease and its amplitude increases as it passes along the wedge. This result confirms the sensitivity of the thickness of the wedge tip on the performance of the 'Acoustic black hole' and the increase in amplitude that can be achieved.

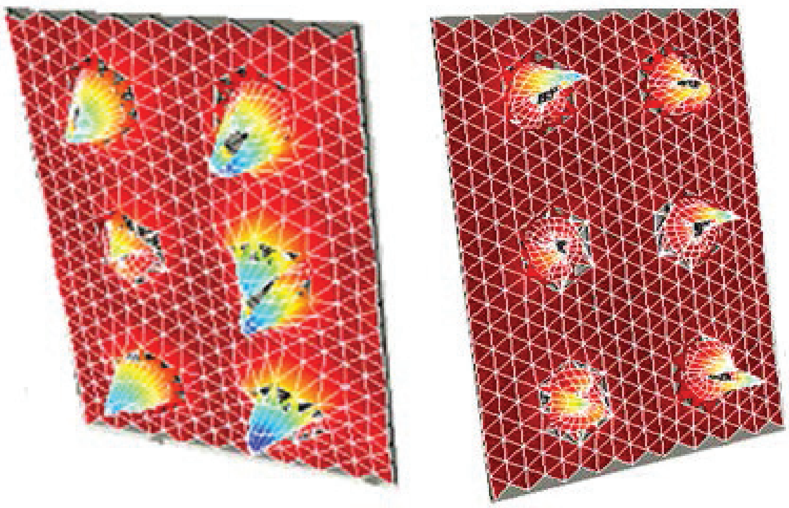


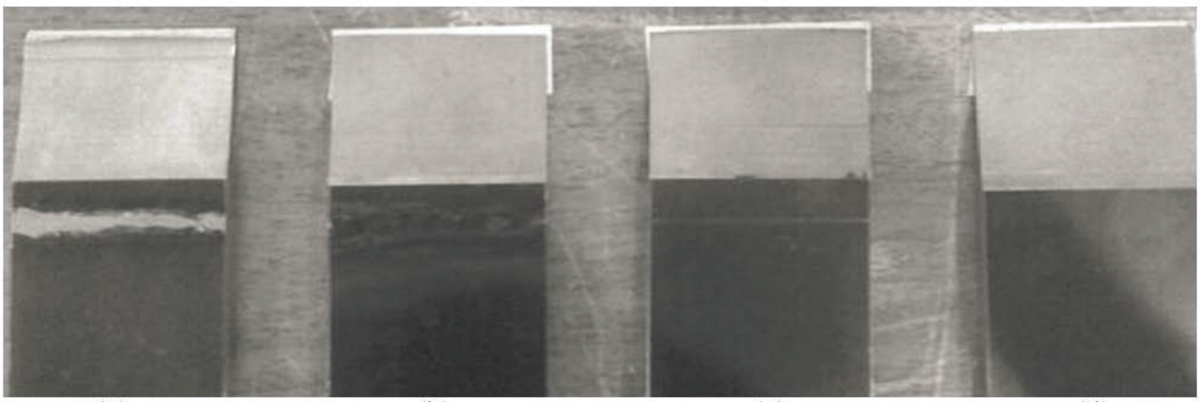
Figure 9 - (a) Model response of the plate containing six indentations with damping layers at 2.2 kHz, (b) Model response of the plate containing six indentations with damping layers at 4.75 kHz,

(a) (b) (c) (d)

Figure 10 - (a) Displacement of the indentation shown in c, (b) Displacement of the indentation shown in d, (c) Circular indentation with a thinner damaged tip, (d) Circular indentation with a thicker undamaged tip

3.2 Attachment methods (17)

When looking at attachment methods for the ABH samples four samples were considered; a TIG welded wedge, a MIG welded wedge, a glued wedge (standard 'super glue'), and a homogeneous wedge (reference sample), Figure 11.



(a) (b) (c) (d)

Figure 11 - Welded and glued samples: (a) -TIG welded wedge, (b) –MIG welded wedge, (c) - glued wedge (standard 'super glue'), (d) - homogeneous wedge.

Figure 12 shows measured values of accelerance for a sample with the TIG-welded in comparison with the results for the reference plate. It can be seen that there is a significant reduction in resonant peaks with increasing frequency, up to 8.0 – 10 dB between 5.5-9 kHz, with the greatest reduction of about 10 dB occurring at 7.2 kHz. It was demonstrated that attaching power-low profiled wedges to a rectangular plate (strip) by welding or via glue results in damping performances that generally isn't any worse than the performance of a homogeneous sample containing the same wedge. Out of the three bonds tested, the TIG-welded wedge proved to yield the most significant reductions in the amplitude of the reference strip resonance peaks over the largest frequency range.

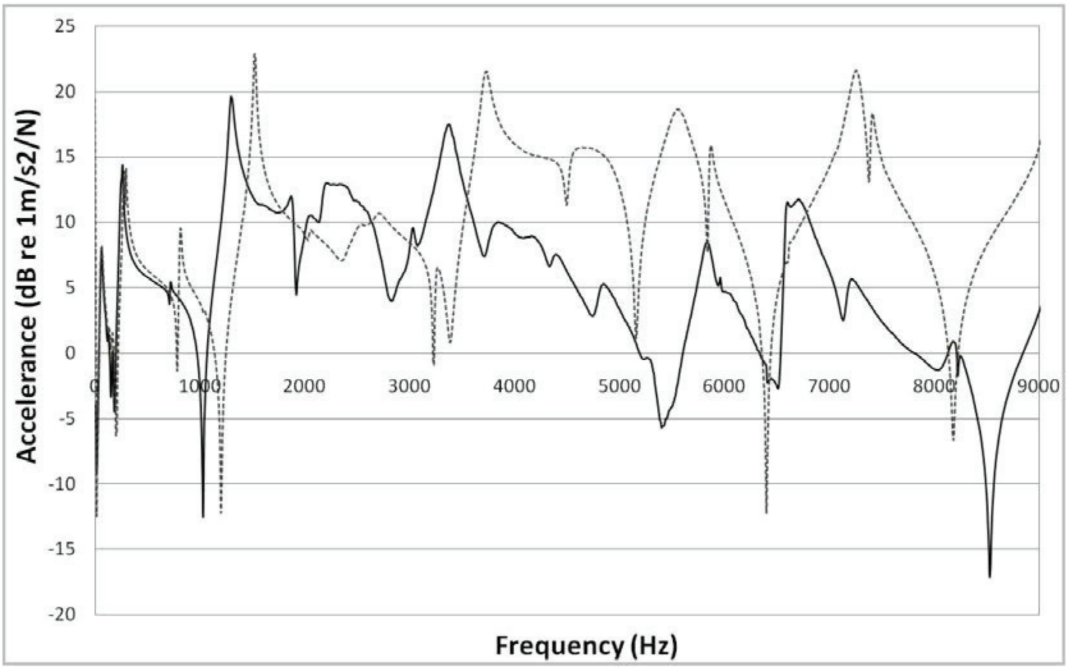


Figure 12 - Measured accelerance for a sample with the TIG welded power-law profile (m = 2.2) (solid curve) compared to the reference plate (dashed curve).

It has been shown (17) that acoustic black hole can be attached to existing structures in order to reduce the resonant vibration of the structure. This method is not as effective as integrating the acoustic black hole directly in to the component structure. The efficiency of the acoustic black hole is also affected by the type of bond utilized.

3.3 Tip protection, aesthetics and safety

For many applications the prospect of a fragile thin or often sharp tip is not optimum when the tip can become damaged or somebody may cut themselves, another consideration is the look of the panel. A solution for this has been documented (11) and is most easily explained using composite samples, however there is no reason why other materials cannot be enclosed in the same manner. By enclosing the acoustic black holes in a smooth surfaced panel the tips are protected and the potential for any small injuries is 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, see Figure 13. It is also possible to manufacture acoustic black holes in this way in any material where the standard acoustic black hole (sample 5) can be manufactured.

The response of Sample 11 compared to a reference plate is shown in Figure 14. After 450 Hz, the 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. Thus, the combination of the composite plates and sheets results in effective damping of flexural waves in smooth surfaced composite panels.

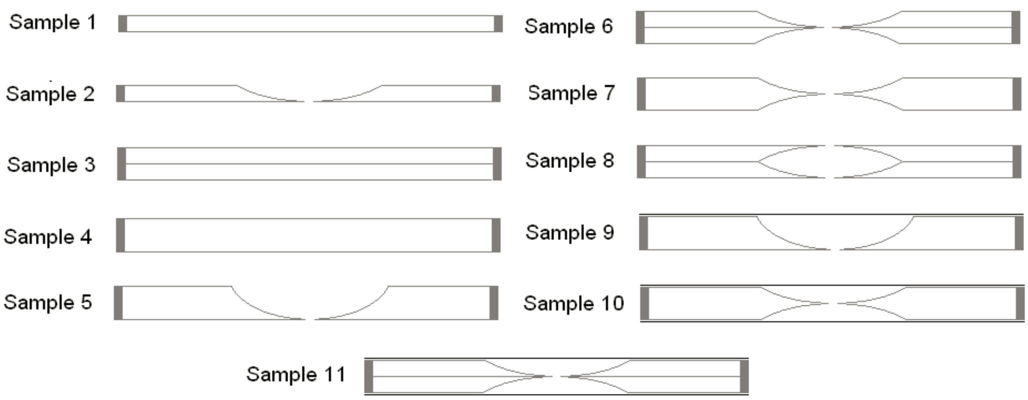


Fig. 13 - Cross-section view of Sample plates 1-11

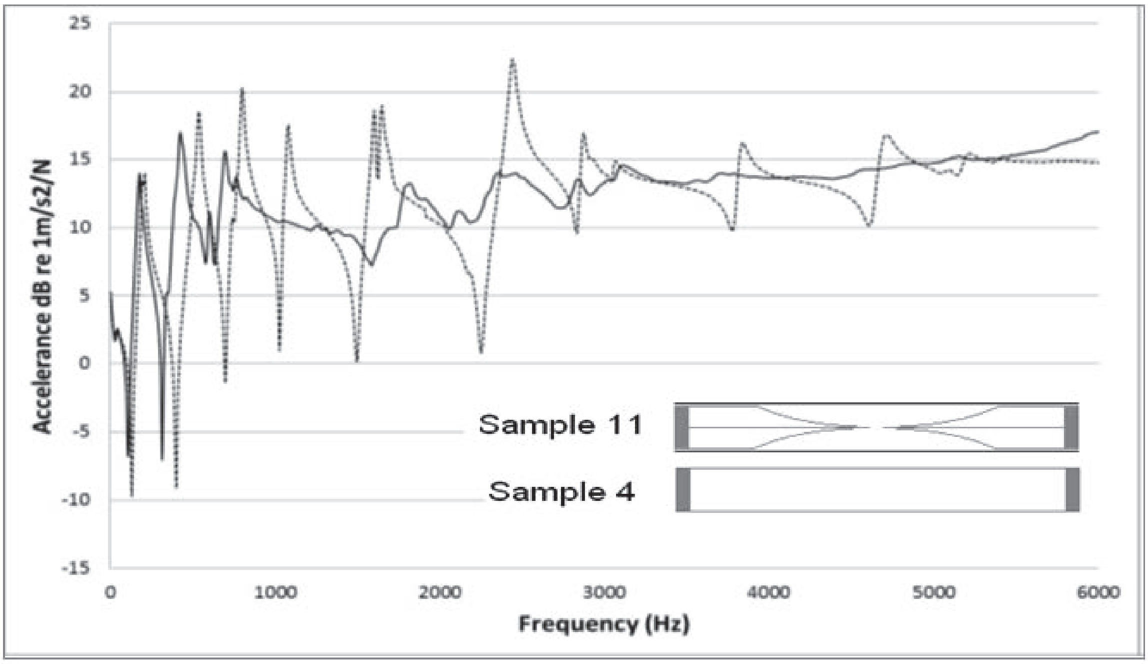


Figure 14 - Accelerance for Sample 11 (solid line) compared to Sample 4 (dashed line). Insert; cross-section of samples

4. CONCLUSIONS

Although milling was used frequently at the start of acoustic black hole manufacturing, with the exception of limited batch number components and prototypes, it does not seem to be the method that can bring acoustic black holes into the real world and mass production. It is just not viable both in terms of time for production and cost effectiveness. The manufacturing methods that could lead acoustic black holes from the lab to industry are casting, moulding, curing and maybe even 3D printing.

It was demonstrated that the effect of tip damage (curling) in a wedge of the maximum possible (extended) length allowed by manufacturing is not detrimental for its performance when compared to the same wedge that has been cut to a reduced length (truncated) in order to avoid curling. Despite the damage to the extended wedge tip, the increased length and resultant decrease in tip thickness provided the most efficient damping of flexural vibrations. The longer and thinner the wedge tip the greater the contribution of the acoustic black hole effect into the overall vibration damping, in spite of the resulting technological damage to the tip. Despite this increased damping performance, the practical applications of an extended tip are limited though due to an increased possibility of the tip braking off because of its increased fragility, although this can in part be countered by the addition of a damping layer.

It was concluded that, although geometrical and material imperfections reduce the damping efficiency to various degrees, the method of damping structural vibrations using the acoustic black hole effect is robust enough and can be used widely without the need of high precision manufacturing.

It has been shown that by enclosing the acoustic black holes in a panel there is no reduction in the performance of the acoustic black holes. Acoustic black holes can be protected, safe and retain the original aesthetic appearance of the component.

Finally, it can be said that Acoustic black holes are ready for the next steps into industry and mass production.

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