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Abstract

Granular materials can be used for damping structural vibrations by dissipating the vibration energy via collisions and friction between granular particles. In the present work, a series of experiments were conducted to investigate the effects of the main parameters of granular materials and the containers on vibration damping. In particular, it has been shown that smaller particles and particles made of a denser material damp vibrations more efficiently, which agrees with other published works. Further investigations have been carried out to study the effect of replacement of particles with powders. Other investigations included the use of larger irregular particles and small machine swarf particles. It was found that the larger irregular particles did make a successful damper. It should be noted that the use of irregular particles could dramatically reduce the cost in real life applications. Finally, direct comparisons were made between some traditional damping methods and the method using granular materials.

1 Introduction

The aim of this paper is to present the results of the experimental investigation into the application of granular materials to damping structural vibrations. This method of damping, sometimes called particle impact damping (PID) or simply Particle Damping (PD) [1-12], is often thought to be more efficient than traditional methods of damping, such as placement of viscoelastic layers over surfaces of structures [13, 14]. Damping by granular particles occurs because part of the energy of vibrating structures is passed to the granular particles that collide with each other. As a result, their kinetic energy is dissipated into heat due to frictional losses and inelastic collisions. The advantage of particle damping is its implicit simplicity and its ability to work over a broad range of frequencies. It also has the advantage of not being affected by high temperatures, and it is easy to install without affecting the structural integrity. Among the disadvantages of particle damping is that it is highly non-linear [2, 7] and implying a mass penalty [2].

A number of experimental works on particle damping have been conducted, mostly with the granular particles housed inside the object, in a series of holes [4-6]. It has been shown that the amount of granular material in each hole can affect the resultant damping. Another important parameter is the internal friction between particles, which is generally higher than that for two solid surfaces. Increasing the packing ratio and the number of particles increases the internal friction within the compartment. The greater the friction, the greater the energy dissipation and damping. It has been also shown that the size of the container can have an effect on the damping too. Some research has been carried out into the effect of particle shape on damping, with particles being of irregular shape and size. However, tests that have been completed [8] have shown to be inconclusive.

Existing theoretical studies have been undertaken on different particle dampers [3-5, 9, 10]. As was mentioned above most of the dampers under investigation involved cavities in the primary system, as opposed to containers attached separately. Such cavities can be undesirable as they have a direct effect on the structure of the primary system. However, the analysis of both methods is similar.

Although particle damping methods have been previously researched by a number of authors, there are still many questions to be answered. Further investigations into the factors effecting particle damping and the methods of testing its effectiveness are required. Some of such investigations are reported in this paper. In particular, a special attention is paid to the use of irregular particles and to comparison of particle damping with some other methods of damping structural vibrations.

2 Experimental set up and procedure

The experiments were performed using a suspended steel plate that was kept level (Figure 1). The plate dimensions were 400×300×5 mm, and it was supported on a sling formed using strings and a metal A-frame. The excitation force was applied to the centre of 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 that was attached to the upper surface, directly above the force transducer, also via glue. The acquisition of the Frequency Response Function (FRF) of this system, namely point accelerance, was utilised using a Bruel & Kjaer 2035 analyser and amplifier over a frequency range of 0–6 kHz.

Figure 1: Experimental set-up.

Particles were placed in Aluminium boxes that were attached to the surface of the plate using glue (see Figure 1). The dimensions of the boxes were 20×20×30 mm and 10×10×15 mm. The FRF of the plate was measured and compared to that of the reference (undamped) plate. The boxes were initially tested empty on a plate and found to have no damping effect.

In each experiment the plate was first tested without any boxes attached. This gave the experiments a reference from which to compare. Then the boxes were attached using glue. In each experiment the position and type of granular material varied. However, in each instance the frequency response function, the accelerance, was measured and compared to that of the free plate. In each experiment it was necessary to keep the plate level, and to make sure that the accelerometer, force transducer and plate did not move. It was also necessary, when testing differences in particles, to keep the boxes and their positions identical, so that the only variance was in what is being tested.

3 Results and discussion

3.1 Effect of orientation and surface area

Tests were performed to investigate the effect of surface contact area of Aluminium containers on particle damping. This was done by gluing full boxes 30x20x20 mm into the same position on the plate. The boxes were first glued on the 30x20 mm face, and then repeated on the 20x20 mm face. The frequency response function (accelerance) was recorded at each position, and the results were compared with each other and with the frequency response function of a reference plate. The plots are shown in Figure 2.

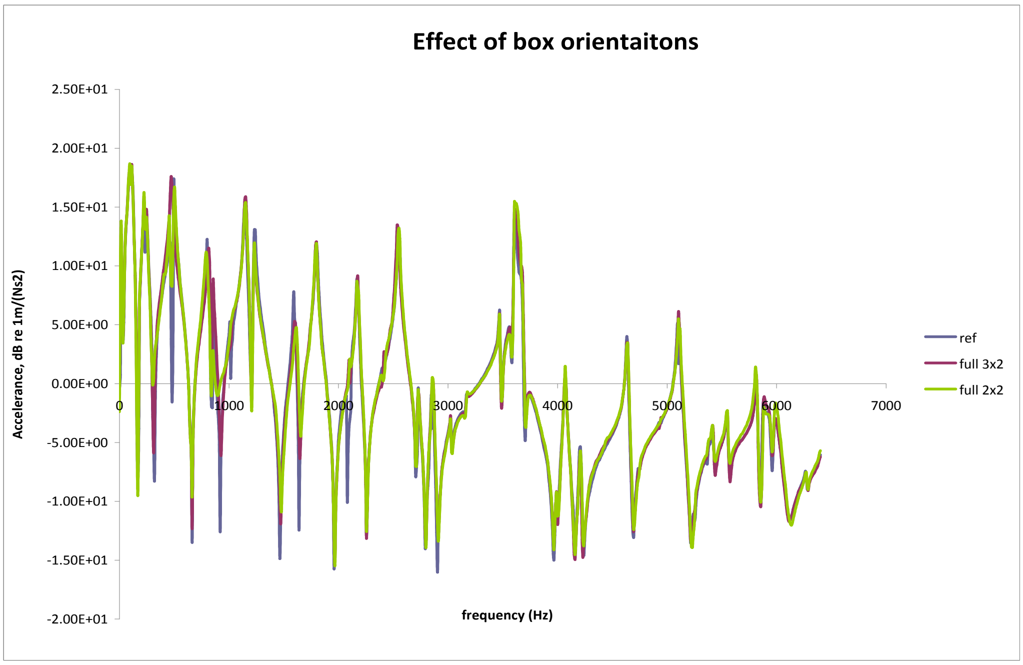

Figure 2: Effect of different orientations of particle containers on vibration response of a plate.

It can be seen from Figure 2 that at higher frequencies there is little difference between the two orientations of containers. However, up to 1000 Hz there is a lot more damping achieved from the small surface area than from the large surface area. This is contrary to the expectations, and the reason for this is yet unclear. At higher frequencies, above 3000 Hz, a larger surface area is indeed more effective at damping, as expected.

3.2 Effect of particle size.

The investigation of the effect of particle size on particle impact damping was carried out using steel ball bearings. These ball bearings were 1 mm, 2 mm and 5 mm in diameter (see Figure 3). The particles were packed into Aluminium boxes with dimensions 20x20x30 mm. The boxes were filled to the top and were weighed to make sure they all weighed the same. This was done to make sure that the damping due to mass was the same in each case. The same material was used to ensure that the damping due to the effects of material or density is the same.

The two boxes were then attached to the plate on either side of the accelerometer. The boxes were attached in the same place for each test using super glue. The boxes were attached in the same place in order not to effect different modes of plate vibration. It was expected that as the particles got bigger the amount of damping was reduced. The reason for this is that with the smaller particles there are more particles in the containers. This would suggest that there would be more collisions between the particles and hence a greater dissipation of energy. There are also a greater number of surfaces in contact with each other so that there are more energy losses due to friction between the particles and between the particles and surfaces of the containers.

Figure 3: Spherical particles used in the experiments.

It is also possible to pack particles closer together when they are small. There are less spaces between them and therefore for the same mass it is possible to fit the particles in a smaller space. This would be an advantage in engineering applications as greater damping can be achieved in a smaller container.

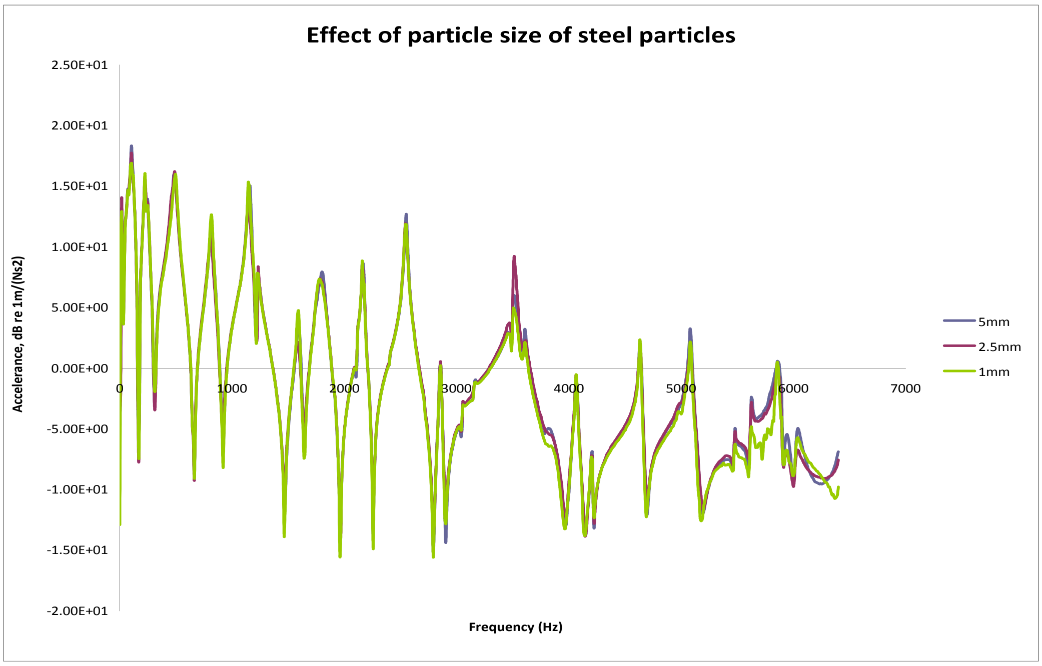

Figure 4: Effect of particle size on vibration response of a plate.

The results are shown in Figure 4. It can be seen that there is little difference in the damping by 2.5 mm and 5 mm particles compared to those that are 1 mm in diameter. This can most clearly be seen at between 3000-4000 Hz, where 1 mm particles show greater damping. At lower excitation frequencies there are little differences in the damping achieved by the different sized particles. At the higher frequencies, of over 5000 Hz, the smallest particles deviate from the general pattern of the larger particles. The peaks at natural frequencies occur at the same points, however the graph has a different shape than those for other particles.

3.3 Effect of particle materials

The experiments were performed using the same containers in the same positions. In each case the containers were super glued onto the plate either side of the accelerometer and frequency response was measured between 0 and 6000 Hz. The tests used particles of different materials: lead and steel. However in each case the packing ratio and the particle size remained constant. It was expected that the lead particles would achieve the highest damping. The lead is the most dense material and as a consequence the container with particles had greatest mass when filled with lead. The obtained experimental results are shown in Figure 5.

Figure 5 shows that, as expected, the more dense lead particles damp more than the steel particles. This did not happen to a great extent, which would suggest that the damping is due to the added mass rather than the collisions. More collisions and greater surface friction would damp vibrations more from the dissipation of energy through collisions compared to the lead damping due to the extra mass. These two forms of damping may explain the differences in damping with the two materials as they may be more prevalent at different frequencies.

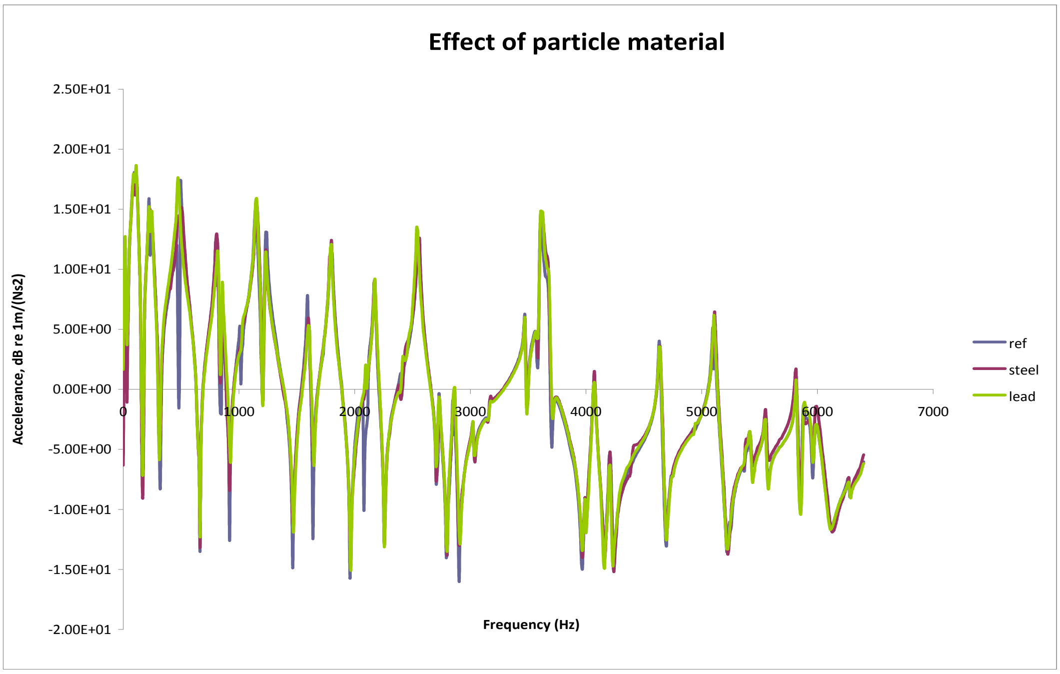

Figure 5: Effect of particle materials on vibration response of a plate.

In practical applications it may be undesirable to have a large amount of mass attached to a component. Therefore, these results would suggest that whilst using a more dense material does increase the damping at medium frequencies, it is to a lesser extent than would be expected. Therefore, if mass of a container filled with particles is an issue, it would be better to use a less dense granular material, which would result in only slightly lower vibration damping.

3.4 Effect of non-metal containers

All of the above-mentioned experiments have used Aluminium containers. Metals seem to be the best to transfer vibrations between the plate and the particles. However, other means of containing the particles also deserve to be investigated. The results of this investigation are described in this section. The containers tested were a rubber 'balloon', a polythene 'bag', and latex 'bags'. The bags contained the same contents as the boxes and were attached in the same places. The results are shown in Figure 6.

It can be seen that, as expected, the non-metal containers do not damp the vibrations as much as the metal ones do. The reduction in damping is likely to be due to the fact that non-metal boundaries do not transfer the energy of plate vibrations to the particles as well as metal does.

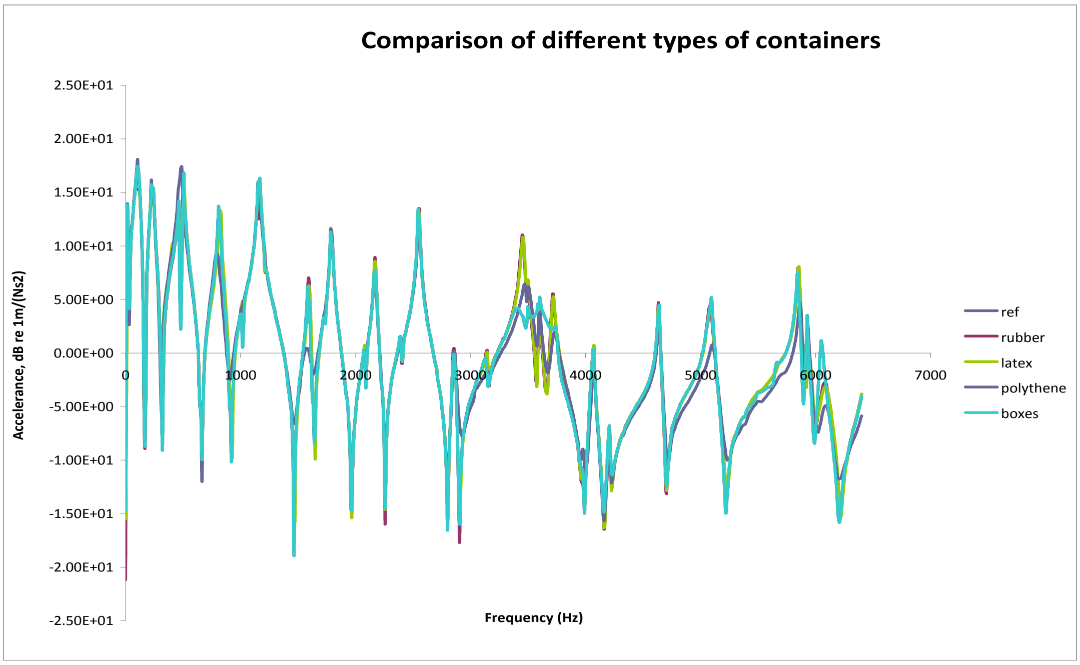

Figure 6: Effect of different types of containers on vibration response of a plate.

3.5 Investigation into using powders instead of particles

The smallest particles are found in powders. These are irregular in shape and size, but are much smaller than the particles previously used in this work, being measured on a micron scale. They also behave a little like liquids when in a container. They can be poured and flow from one container to another. With regards to damping, it would be expected that the powders provide more damping than the larger particles. This is because there are many more particles and therefore more collisions. There are also less air gaps between the particles so a greater particle density or mass in the container. However, the particles have a lot less mass and therefore dissipate less energy with each collision.

In the experiments, the containers with copper particles of 4 mm in diameter were used initially. The containers were attached in positions either side of the accelerometer using super glue. The plate vibrations were then measured. The same containers were then filled with copper powder. They were attached in the same places and again the vibrations were measured.

The results are shown in Figure 7. As expected, the results show that the copper powder does damp the vibrations a little more. This is most evident below 1000 Hz, and between 2500 and 4500 Hz. Therefore, powders could be used successfully for vibration damping purposes.

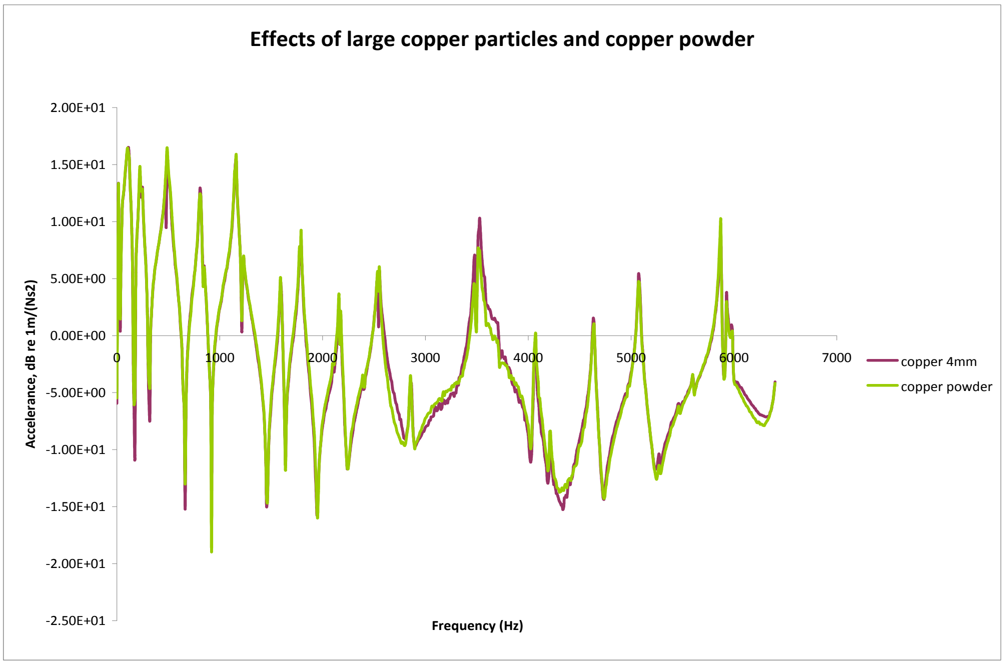

Figure 7: Effects of powders and particles on vibration response of a plate.

3.6 Effect of irregularly shaped particles

In what follows we describe the experiments to investigate the effect of irregular particles compared to spherical ones. This has been briefly investigated in the earlier paper [6]. However, the observed results were inconclusive. While powders described in the previous sub-section are irregular as well, they are much smaller than ordinary particles used. Therefore, the main aim of the present test was to look at particles of irregular shapes that are of a similar size to the ordinary spherical particles. The test was performed by placing 5 mm steel balls in Aluminium boxes attached to the plate with glue. The boxes were then filled with the same amount of irregular particles and attached in the same place. In both instances the frequency response function (accelerance) was measured.

Two types of irregular particles were tested. Firstly, large solid particles of irregular shapes were used. Secondly, machine swarf (off cuts) was investigated. The latter were small pieces of steel left behind as scrap from milling. Whilst the particles left over from the machine are smaller than the other particles, they are also lighter as they are curled up and have lots of empty space around them.

The results are shown in Figure 8. It can be seen that using irregular particles gave rather unusual results. In some instances, such as just under 1000 Hz, the large irregular particles perform in a similar way to the large regular particles, whereas the light particles (machine swarf) show little damping. However, at around 1500 Hz the light particles show a very similar amount of damping to the larger and heavier particles. At higher frequencies very little damping is seen. The large particles show very little damping compared to those of the irregular shaped particles, even though they are of a similar number and mass. Therefore, in practical applications, it would be more beneficial to use regular particles. However, at around 1500 Hz, the damping of the light particles is similar to that of the large particles.

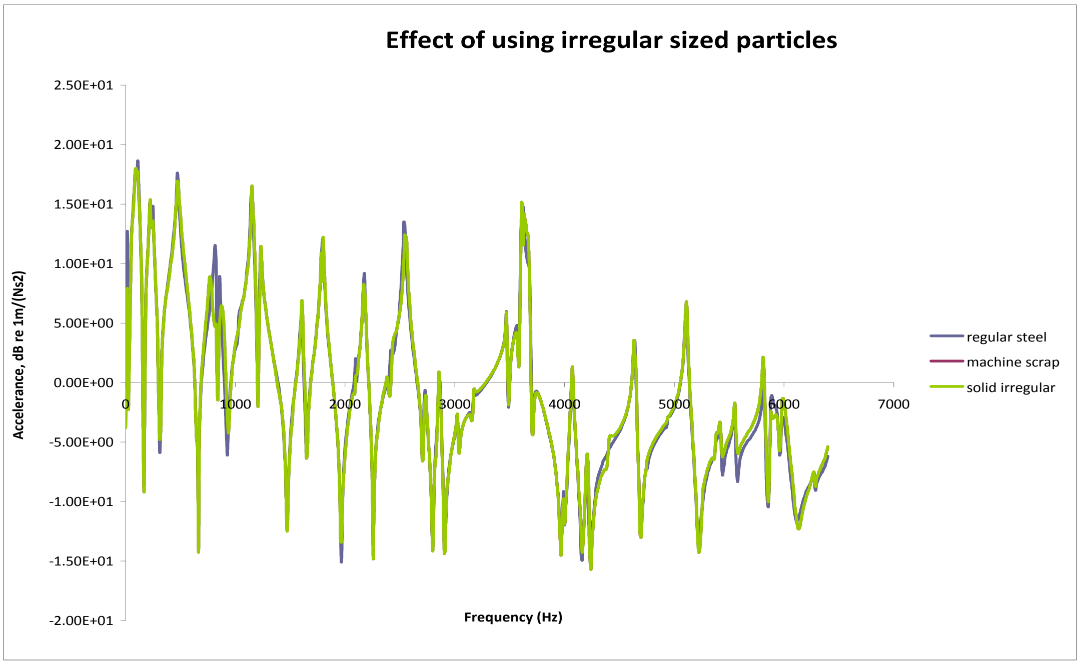

Figure 8: Effect of irregularly shaped particles on vibration response of a plate.

4 Comparisons with other methods of vibration damping

Following the above-mentioned investigations into the parameters most likely to affect the damping achieved, it was instructive to look at how the method of particle impact damping compares to some other methods of damping structural vibrations.

4.1 Viscoelastic damping layers

A widely used traditional method of damping involves viscoelastic damping layers covering the structures to be damped [13, 14]. The test was done by sticking the foam layer onto the plate. Two separate attachments of layers were used. In the first case a layer was applied in the same surface area and positions as the containers of particles. In the second case layer was applied to the entire top surface of the plate.

The results are shown in Figure 9. It can be seen that at higher frequencies, above 3000 Hz, the viscoelastic layer is more effective. However, at medium and low frequencies the particle dampers provide a lot more damping than viscoelastic layers. The small squares of viscoelastic layers (placed in the locations of particle containers) do not provide any damping even at higher frequencies. This would suggest that whilst covering vibrating structures by viscoelastic layers is a good method of damping where an entire surface can be covered, particle dampers are more useful if it is undesirable to cover a whole structure yet added mass is less important. Note that particle dampers are also unaffected by changes in temperature.

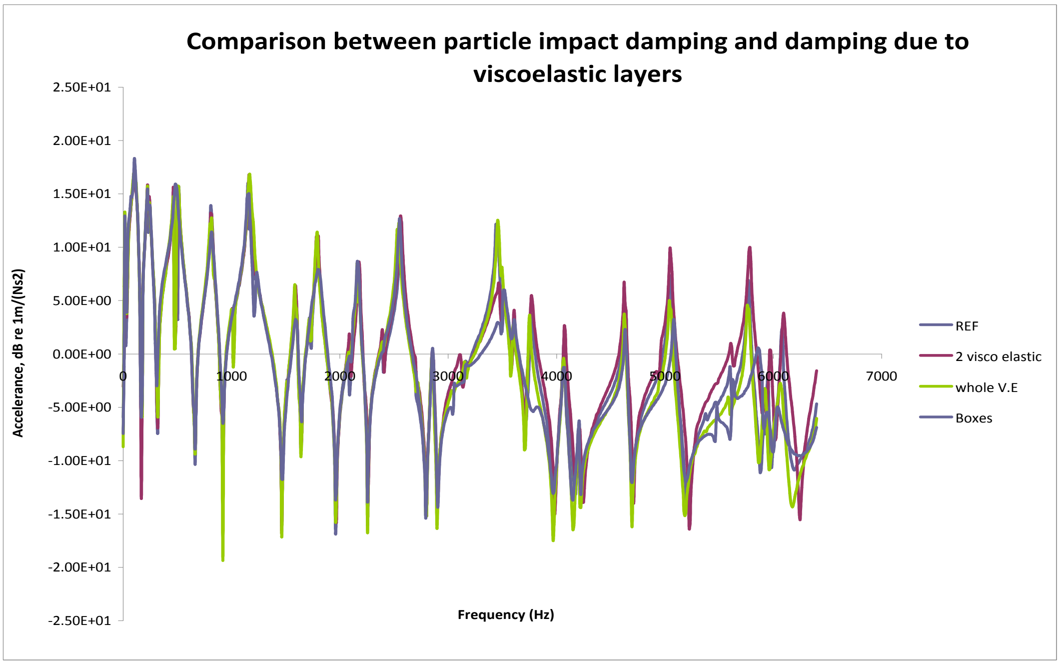

Figure 9: Comparison between particle damping and damping due to viscoelastic layers.

4.2 Comparison with acoustic black holes

Tests were carried out also to compare particle damping to the relatively new method of damping structural vibrations based on the 'acoustic black hole effect' [15-17]. To do this a vibration response of a plate with two boxes filled with 2.5 mm steel particles was measured. This response was compared to the response of a plate of the same dimensions having two two-dimensional acoustic black holes in the same positions as the boxes (Figure 10).

Figure 10: A steel plate containing two-dimensional acoustic black holes.

The centres of the holes were covered with small pieces of thin viscoelastic layer, as required [15-17]. It was expected that the acoustic black holes would perform best at higher frequencies. The results are shown in Figure 11.

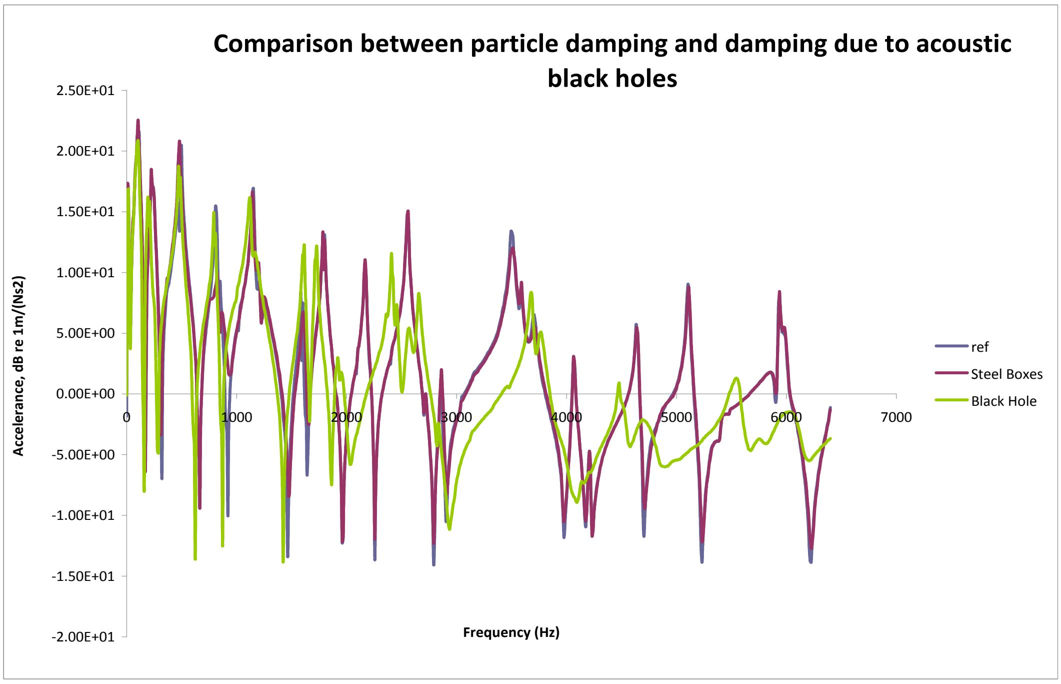

Figure 11: Comparison of particle damping with damping due to acoustic black holes.

As expected, at higher frequencies acoustic black holes vastly outperform particle dampers. However, at lower frequencies, there is little difference in the damping achieved. In some cases particle damping achieves better damping. Whilst it may seem obvious to use the acoustic black hole effect to damp vibrations in the majority of applications, the particle damping may be more practically suitable in many cases. The advantage of particle damping is that it does not take away mass, and it can easily be removed when not required, whereas black holes directly change the geometry of a structure.

5 Conclusions

In the present paper, the experimental investigations of the effects of main parameters of particles that influence Particle Impact Damping (PID) have been carried out initially. In particular, the experiments into material type and particle size have confirmed the previous results. Namely, smaller particles and particles made of a more dense material damp more.

Once the effects of main parameters of particles had been confirmed, further investigations were carried out. These were done to try to further exploit the qualities of the particle impact dampers. Firstly, powders were investigated. It was found that powders do improve the damping properties of granular materials, albeit not significantly.

Following this experiment, it was decided to look at the effects of geometrical forms of different particles to be used in PID devices, which could extend the range of possible applications. These included investigating the use of larger irregular particles and small machine swarf particles. It was found that the swarf was not good at damping as the odd, curled shape made the particles lock together with lots of air gaps. This meant that there were no collisions between particles. However, the larger irregular particles did make a successful damper. One should note in this connection that the use of irregular particles could dramatically reduce the cost in real life applications.

In addition to the above, different container methods were investigated. In particular, a 'bean bag' scenario was tested instead of the rigid metal containers. If successful, this would mean that the dampers could be applied into irregular of changing areas of free space, broadening their application possibilities. However, the bags did not show such great damping as the metal containers did.

Finally, direct comparisons have been made between some traditional damping methods and PID. It was found that compared to viscoelastic materials, PID performed better at very low frequencies, but it was superseded at higher frequencies. Secondly, PID was compared to the relatively new method of damping using 'acoustic black holes'. It was shown that the method of acoustic black holes is far superior at higher frequencies, however it has the disadvantage that it involves significant changing of the primary structure.

The limitations of PID are mostly due to the high mass of the damper compared to other methods of damping. This would be a disadvantage in many aeronautical applications where weight is a premium. However, as temperature does not affect damping performance of PID, this could be an advantage in many practical situations.

The most likely practical applications of PID could be in a 'post construction' situation, where a machine or structure has already been installed and vibrations become an issue. This is due to the advantage of PID, which is that it is easy to apply. It also does not affect the primary structure, unlike viscoelastic materials or the acoustic black holes. Conversely, it can be removed easily if not needed. PID is low cost and robust, and it can be very successful when using very dense and closely packed granular materials.

References

[1] H.V. Panossian, *Structural damping enhancement via non-obstructive particle damping technique,* Journal of Vibration and Acoustics, Vol. 114, No. 1, American Society of Mechanical Engineers (1992), pp. 101-105.

[2] R.D. Friend, V.K. Kinra, *Particle impact damping*, Journal of Sound and Vibration, Vol. 233, No. 1, Elsevier (2000), pp. 93-118.

[3] M. Saeki, *Impact damping with granular materials in a horizontally vibrating system*, Journal of Sound and Vibration, Vol. 251, No. 1, Elsevier (2002), pp. 153–161.

[4] Z. Xu, M.Y. Wang, T. Chen, *Particle damping for passive vibration suppression: numerical modelling and experimental investigation*, Journal of Sound and Vibration, Vol. 279, No. 3-5, Elsevier (2005), pp. 1097–1120.

[5] K. Mao, M.Y. Wang, Z. Xu, T. Chen, *Simulation and characterization of particle damping in transient vibrations*, Journal of Vibration and Acoustics, Vol 126, No. 2, American Society of Mechanical Engineers (2004), pp. 202-211.

[6] Z. Xu, M.Y. Wang, T. Chen, *An experimental study of particle damping for beams and plates*, Journal of Vibration and Acoustics, Vol. 126, No. 1, American Society of Mechanical Engineers (2004), pp. 141-148.

[7] G.R. Tomlinson, D. Pritchard, R. Wareing, *Damping characteristics of particle dampers—some preliminary results*, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 215, No. 3, SAGE (2001), pp. 253-257.

[8] K.S. Marhadi, V.K. Kinra, *Particle impact damping: effect of mass ratio, material, and shape*, Journal of Sound and Vibration, Vol. 283, No. 1-2, Elsevier (2005), pp. 433–448.

[9] S.E. Olson, *An analytical particle damping model*, Journal of Sound and Vibration, Vol. 264, No. 5, Elsevier (2003), pp. 1155–1166.

[10] M. Saeki, *Analytical study of multi-particle damping*, Journal of Sound and Vibration, Vol. 281, No. 3-5, Elsevier (2005), pp. 1133–1144.

[11] L. Hu, Q. Huang, Z. Liu, *A non-obstructive particle damping model of DEM*, International Journal of Mechanics and Materials in Design, Vol. 4, No. 1, Springer-Verlag (2008), pp. 45-51.

[12] Z. Xia, X. Liu, Y. Shan, *Application of particle damping for vibration attenuation in brake drum*, International Journal of Vehicle Noise and Vibration, Vol. 7, No. 2, Interscience (2011), pp. 178-194.

[13] M. Heckl, L. Cremer, E. Ungar, *Structure Borne Sound*, 2nd Edition, Springer-Verlag, Berlin (1988).

[14] D.J. Mead, *Passive Vibration Control*, Wiley, Chichester (1998).

[15] V.V. Krylov, *New type of vibration dampers utilising the effect of acoustic 'black holes'*, Acta Acustica united with Acustica, Vol. 90, S. Hirzel Verlag (2004), pp. 830-837.

[16] V.V. Krylov, R.E.T.B. Winward, *Experimental investigation of the acoustic black hole effect for flexural waves in tapered plates*, Journal of Sound and Vibration, Vol. 300, Elsevier (2007), pp. 43-49.

[17] E.P. Bowyer, D.J. O'Boy, V.V. Krylov, F. Gautier, *Experimental investigation of damping flexural vibrations in plates containing tapered indentations of power-law profile*, Applied Acoustics, Vol. 74, Elsevier (2013), pp. 553-560.