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Low Frequency Absorption of Additively Manufactured Cylinders

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ABSTRACT

Attenuating low frequencies is often problematic, due to the large space required for common absorptive materials to mitigate such noise. However, natural hollow reeds are known to effectively attenuate low frequencies while occupying relatively little space compared to traditional absorptive materials. This paper discusses the effect of varied outer diameter, outer spacing, and wall thickness on the 100-1600 Hz acoustic absorption of additively manufactured arrays of hollow cylinders. Samples were tested in a large normal incidence impedance tube such that cylinder length was oriented perpendicular to the incoming plane wave. By varying only one geometric element of each array, the absorption due to any particular parameter can be assessed individually. The tests confirmed the hypothesis that minimizing cylinder spacing and maximizing cylinder diameter resulted in increased overall absorption and produced more focused absorption peaks at specific low frequencies. Wider cylinder spacing produced a broader absorptive frequency range, despite shifting upward in frequency. Thus, manipulating these variables can specifically target absorption for low frequency noise that would otherwise disturb listeners.

Keywords: Absorption, Absorptive materials
I-INCE Classification of Subject Number: 35

1. INTRODUCTION

Low frequency noise is prevalent throughout the world due to large vehicles and other man-made machines. Sound emitted by objects such as vehicles, airplanes, air conditioning units,

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and many others give off excess amounts of low frequency noise, which cause excessive levels of environmental noise pollution. These noises can be mitigated by common absorbers such as melamine or bass traps, but the volume requirement is very large. To ensure the comfort of residents in environments near such high low frequency noise, a more effective acoustic absorber is required.

Recent studies into the absorptive properties of natural reeds reveal that the low frequency absorption can be more effective than that of melamine, the most common acoustic absorber. Orienting the natural reeds normal to the incident sound creates significantly more low frequency absorption, which can be implemented to attenuate this obnoxious environmental noise. The properties that drive this attenuation, however, are not as well understood.

In order to gain a better understanding of what causes such effective absorption, samples of cylinder patterns were modeled using a computer-aided design software and printed using MakerBot 3D printers. Only one aspect of the geometry was manipulated for each sample and the material was kept the same in order to pinpoint the driving factor behind the low frequency absorption. In this study, the outer diameter and outer spacing between each of the cylinders will be varied, to discern the direct impact of each parameter on acoustic absorption. In addition to these two variables, the effect of wall thickness will also be investigated.

There has currently been little research on the topic of patterns of additively manufactured cylinders, although the effects of natural reeds and reed orientations have been studied. One of the first studies by Pennec et. al [1] analyzed the ability to effectively tune a narrow band pass filter by modifying the internal radius of hollow cylinders, along with the effect that immersing the cylinders in different liquids had on the filter. It was concluded that these phononic crystals can be tuned to selectively attenuate the desired frequencies. This was achieved by changing the inner radius of the cylinders, as well as modifying the liquid in which the reeds are immersed.

Egan et. al [2] compared two theoretical models to experimental data in order to analyze how reed orientation impacts sound absorption. The three reed orientations tested were parallel to the incident sound, perpendicular to the incident sound, and a cross pattern, in which the reeds were alternately layered vertically and horizontally. Each sample was also modeled theoretically using the Brannen and To model, along with the Attenborough model. The results indicated that the perpendicular and cross methods had very similar responses, showing a very high absorptivity around 300 Hz, while the parallel orientation was well below this mark.

Oldham et. al [3] analyzed naturally occurring biomass as acoustic absorbers. When looking at the biomass, the study found that collections of reeds had a significant impact on low frequency noise. Materials such as cotton, jute, and wool fiber showed significant absorption in frequencies below 1000 Hz, although testing involving sisal fibers appeared to be less effective than the remainder of the samples. In addition to analyzing the ideal material, it was evident that sound absorbers with relatively small and compacted average diameters had the greatest effect on low frequency sound.

Putra et. al [4] conducted a study on a similar topic that investigated natural materials as sound absorbers. However, it focused on non-fibrous-type acoustic absorbers, since most of the research done prior to this study focused on fibrous materials. Collections of hollow bamboo reeds were oriented in many different directions, to determine the optimum configuration for low frequency absorption. Tightly packed samples of reeds along with reed samples with some introduced space were studied, along with the impact of adding a front surface to the absorber. The study by Putra et. al showed that a peak absorption of 0.8 can be achieved in all arrangements, with the air gap forcing the peaks towards the lower frequencies. Adding the front surface caused the response with axial arrangements to be more broadband and span a wider range of frequency absorption.

A study by D'Alessandro et. al [5] also looked at the effect of reed size and orientation, by creating samples of reeds packed close together, of various thicknesses and orientations. Reed lengths of 3 cm, 5 cm, and 7 cm were used in a vertical, horizontal, and crossed patterns, to create overall sample thicknesses of those same dimensions. Tests performed on the vertical orientation showed that larger thicknesses resulted in a greater absorption coefficient, especially in low frequencies. A similar effect was seen in the horizontal reed orientation. However, the response shifted to lower frequencies as the thickness increased. The peak absorption coefficient did decrease, but only a minimal amount. Finally, crossed orientation exemplified the same effect, where the absorption peak shifts into lower frequencies while decreasing slightly.

Finally, this paper is a continuation of a study performed by Lepak et. al [6] that investigated the effect of orientation, fill, and reed diameter on acoustic absorption. Two inch cubic arrays of cylinders were printed and tested in a 10 cm diameter impedance tube with a wooden frame to hold them in place. The conclusions drawn state that the absorption was greater when the sample was placed normal to the incident sound, with the frequency absorption range shifted lower. The diameter study showed that a larger diameter performs better in low frequency absorption. The final parameter compared the effect of hollow versus solid cylinders on low frequency absorption. Generally, hollow cylinders had both a higher absorptivity and a lower peak, which make them more ideal for low frequency absorption. With this information in mind, the samples of this study were oriented normal to the incident plane wave during testing and the arrays were printed with hollow cylinders.

This paper presents a parametric study of outer diameter, outer spacing, and wall thickness on the 100-1600 Hz acoustic absorption of additively manufactured arrays of hollow cylinders. The samples were tested in a 10 cm normal incidence impedance tube such that cylinder length was oriented perpendicular to the incoming plane wave.

2. METHODOLOGY

2.1 Sample Design

In the previous work by Lepak et al. [6], a 2" by 2" square tube was used, and the samples were all printed as square arrays. However, the impedance tube in which all the data was collected for this study was 10 cm in diameter, which presented a few design challenges. All samples had to be designed as a circular array in order to occupy the entire surface area of the circular tube section. This posed an extra challenge regarding the variable cylinder lengths following the circular tube section which was not an issue with previously printed cubic arrays. Furthermore, 3D prints often require support material that is broken off after printing. Overhangs and steep angles in the model need the support material to prevent deformation during the printing process. Samples had to be modeled so that no support material would be between the cylinders, as any extra material would affect the absorptivity. The final design consideration was maintaining a constant face towards the plane wave source in the impedance tube.

In order to accommodate all necessary design stipulations, a two part, slide together casing was developed as shown in Fig 1.

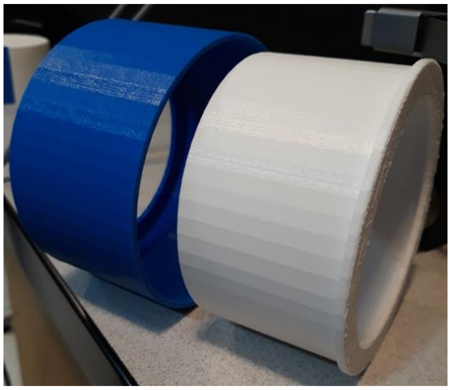

Figure 1. Two part slide-together casing for sample holding.

This casing held all samples securely, along with providing a constant 8 cm diameter test face. The printed cylinders were attached at the base, but open at the top. This created the potential for a cantilever cylinder vibration, which was prevented with a semicircular cap that held the cylinders tightly against the casing. Figure 2 shows a sample with this half-circle component, shown in blue, that thwarts the cylinder vibration. The overall sample dimensions, including the casing, were 100 mm in diameter, with 50 mm in depth. The face exposed to the plane wave source at the front was 80 mm in diameter. The final construction of a sample held in the casing is shown in Fig. 2.

Samples for this study were designed in SolidWorks to have a diagonal pattern, such that the incident sound would have no direct path through the sample, as this was theorized to have the greatest effect on low frequency absorption. The samples were printed out of PLA plastic using the MakerBot Replicator Plus and MakerBot Replicator 3D printers. A set of nine samples were designed and printed to test the effect of the outer spacing between cylinders and the outer diameter of said cylinders. Diameters of 10 mm, 7.5 mm, and 5 mm were used, while the outer spacing was varied between 1 mm, 2.5 mm, and 5 mm. All samples maintained a constant thickness and infill of 1.25 mm and 10%, respectively.

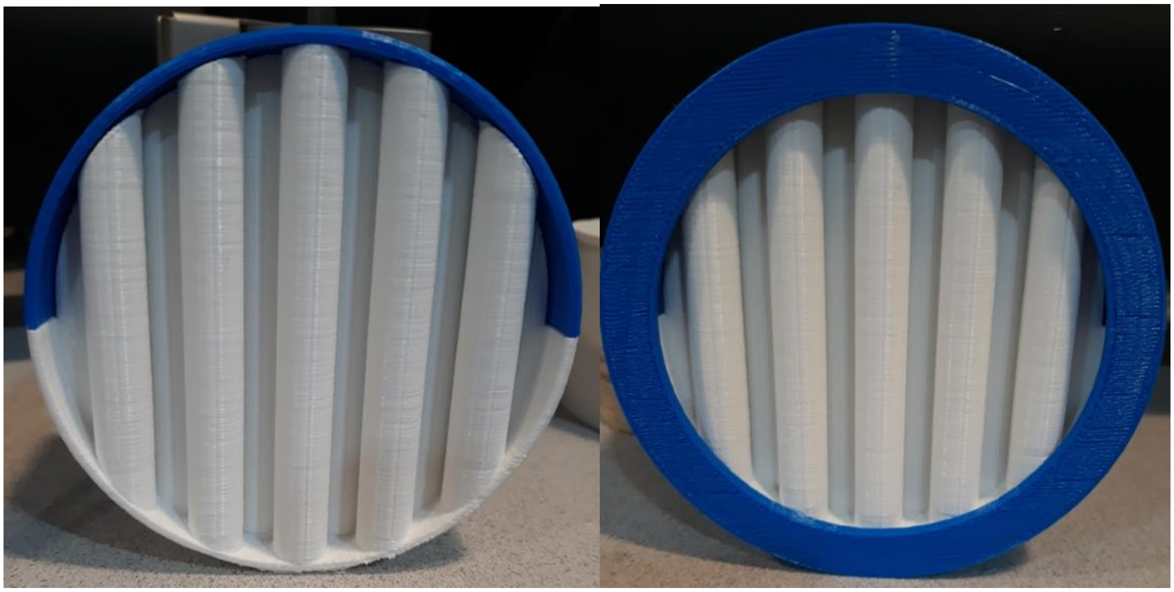

Figure 2. Printed sample with semicircular cap and complete assembly of sample.

In addition to studying the outer spacing and outer diameter of the cylinders, samples were also made to test the effect of cylinder wall thickness on low frequency absorption. For this study, all cylinders had a constant 10 mm diameter as well as a constant outer spacing of 5 mm. Thicknesses of 0.5 mm, 1.25 mm, and 2.5 mm were printed for testing.

2.2 Test Procedure

All testing was conducted using the Brüel & Kjær Type 4206 Normal Incidence Impedance Tube in the two microphone configuration as shown in Fig. 3. This hardware was coupled with the PULSE LabShop data acquisition software for absorption analysis. All test samples fitted snugly inside the casing were inserted into the tube oriented with the cylinder length perpendicular to the incident plane wave. The samples were placed opposite the white noise sound source, which generated equal sound intensity at all frequencies up to 1600 Hz in order to create standing waves inside the tube. The signal-to-noise ratio was evaluated to ensure that the microphones were only detecting the desired source noise. Once this ratio was deemed satisfactory, the transfer function was calculated based on the sound pressure level measured at the two fixed locations. The PULSE FFT used this transfer function to calculate absorption.

The entire sample and casing assembly was removed and replaced after each test, repeating the whole process three times for each sample. The absorption data from each trial was nearly identical as shown in Fig. 4**.** Therefore, this process was deemed repeatable and thus the collected absorption data was deemed reliable**.** Each trial was averaged in PULSE post-processing, and this average was plotted for data analysis. Three trials of a melamine foam disk inside the same sliding case assembly used for the 3-D printed cylinder arrays were tested and averaged for control comparison as melamine is known to be the industry standard for lightweight and effective low frequency attenuation.

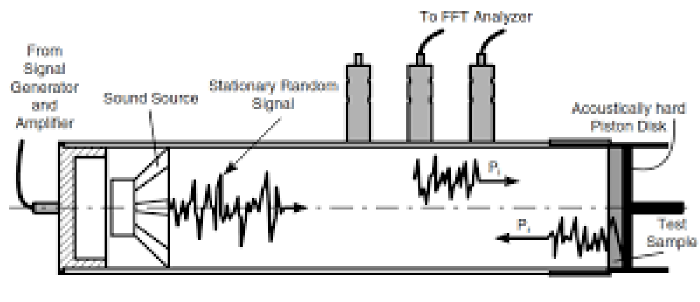

Figure 3. Impedance tube two microphone configuration section view

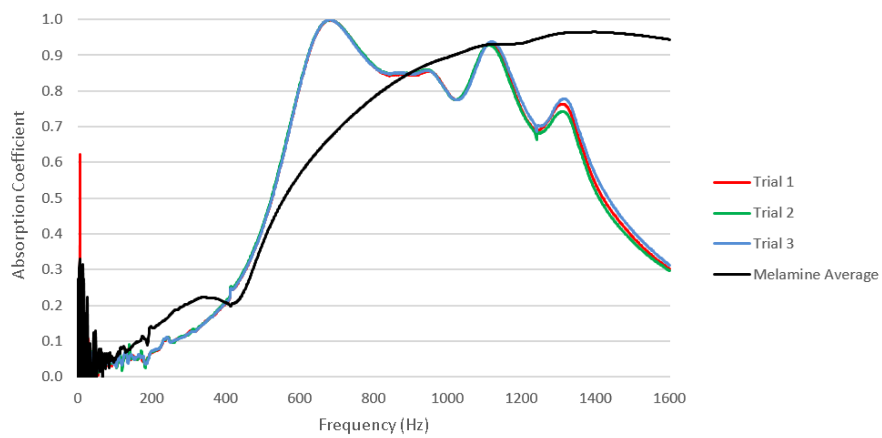

Figure 4. 10 mm diameter 1 mm spacing average absorption coefficient

3. ANALYSIS AND DISCUSSION

3.1 Wall Thickness

Before testing, it was hypothesized that wall thickness should have no significant impact on absorption. The theory was that as all samples should be equally solid with identical surfaces, and thus structurally equivalent as long as the cylinder diameter and spacing was kept constant. Figure 5 disproves this theory as the three curves are not line-on-line. Part of this variation in results could certainly have been due to the fact that the 0.5 mm thickness sample had visible holes in some cylinders as the 3-D printer resolution was not able to accommodate such fine precision. This, however, does not explain the low absorption, particularly from 600-800 Hz in the 2.5 mm thickness sample. The unexpected absorption variation between the samples could also be due to the fact that although the outer diameter and cylinder spacing was kept constant for all three arrays, the inner diameter was different for each one. Identifying and subsequently quantifying the impact of the inner diameter to outer diameter ratio should be a topic of future investigation as a potential cause for this deviation.

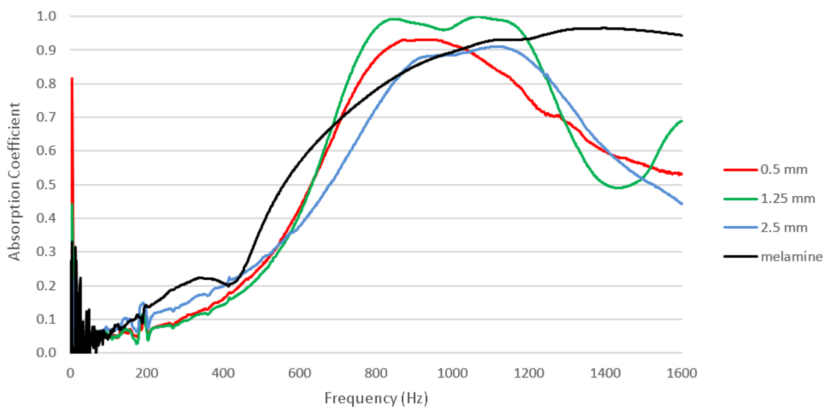

Figure 5. Average absorption coefficient vs. wall thickness

3.2 Cylinder Spacing

As shown in Fig. 6, all three curves seem to be scaled versions of each other, as expected due to the acoustic effect of cylinder spacing. The smaller the spacing, the more absorptive, as hypothesized, as the densely packed cylinders yield less room for the source noise to transmit through. This is demonstrated by the 1 mm spacing array absorptive peak near 1, compared to the 5 mm spacing array peak near 0.5. Smaller spacing proved to be particularly effective at lower frequencies, evidenced by the 1 mm sample absorptive peak around 600 Hz vs the 5 mm sample peak near 800 Hz. However, larger spacing is somewhat advantageous as it yields a broader frequency range of attenuation. As illustrated in Fig. 6**,** the sample remains near its peak from 900 Hz though the entire test frequency range with no decline, whereas the 1 mm sample peak sustains only from 800-1200 Hz before steeply dropping off by about 0.1 per 100 Hz. Moreover, the 2.5 mm sample maintains its peak from 900-1400 Hz before its respective steep decline of a similar slope. This absorptive decline is not seen in the melamine control at all up to 1600 Hz. However, the 1 mm spacing sample performs better than melamine through its 800-1200 Hz absorptive peak.

As displayed in Fig. 7**,** the 2.5 mm and 5 mm spacing results behave as expected with the same trends as the previously analyzed 5 mm diameter samples in Fig. 6**.** That is, a clear scaling factor between the two samples, with larger spacing proving to be significantly less absorptive, and causing higher frequency absorptive peaks with the 2.5 mm spacing sample peaking near 0.95 at approximately 800 Hz compared to the 5 mm spacing sample peak of about 0.55 near 900 Hz. Furthermore, the 5 mm sample peak is maintained from 900 Hz on with no drop off, but the 2.5 mm sample peaks only from 800-1200 Hz before declining to 0.65.

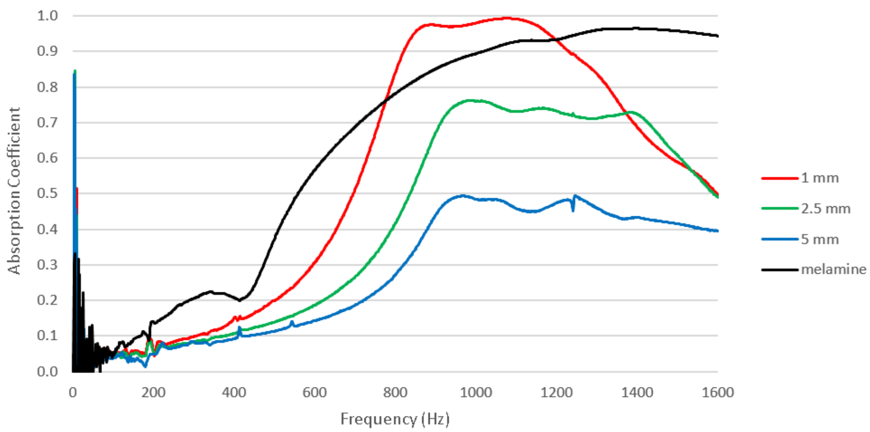

Figure 6. 5 mm diameter average absorption coefficient vs. cylinder spacing

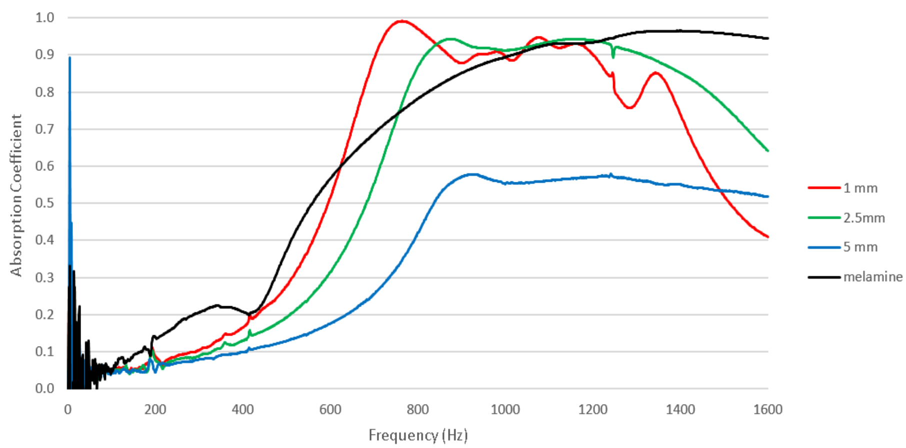

Figure 7. 7.5 mm diameter average absorption coefficient vs. cylinder spacing

However, the 1 mm spacing sample displays sharper absorptive peaks and valleys from 600-1400 Hz not seen in any other 3-D printed cylinder array so far, nor in the melamine control. This artifact might be due to an acoustic or mechanical resonance in the cylinders themselves, as they are technically cantilevered from the bottom of the assembly, although every effort was made to close off these tubes and prevent them from vibrating laterally. Despite this difference, a few previous trends are in fact met with the 1 mm sample. The highest absorptive peak occurs at a lower frequency than the larger two spacings of 7.5 mm diameter cylinders, at around 600 Hz, and the peak itself is highest, nearing 1. Additionally, the absorptive drop off manifests earlier and steeper than the other two 7.5 mm diameter samples. This decline is approximately twice as steep in the 1mm sample, at about 0.2 per 100 Hz, than the 0.1 per 100 Hz decline in the 2.5 mm sample. Both 1 mm and 2.5 mm spacing array peaks outperform the melamine control from about 600-1000 Hz. Thus, smaller spacing is desirable for low frequency attenuation.

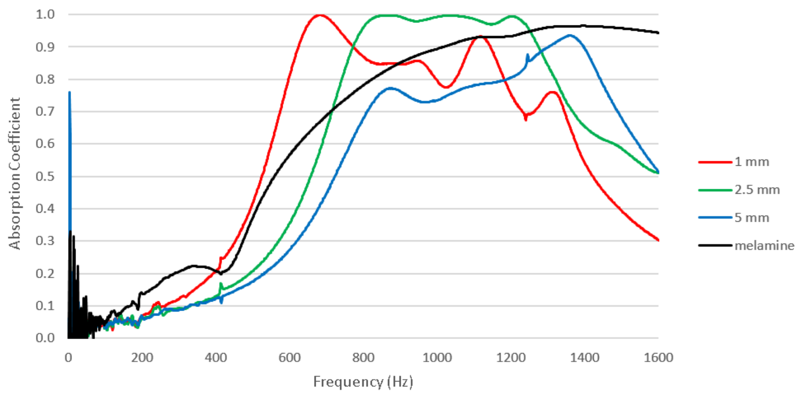

Figure 8. 10 mm diameter average absorption coefficient vs. cylinder spacing

The 1 mm spacing array result in Fig. 8 looks similar to the 1 mm spacing array result from the 7.5 mm diameter sample in Fig. 7, which did not meet some of the expected trends. The particular similarity of note is the several sharp peaks and valleys from 600-1400 Hz rather than one smooth curve, like the melamine control. Interestingly, the 5 mm spacing sample seems to be the mirror image of the 1 mm spacing curve with opposite absorptive peaks and troughs.

The 2.5 mm spacing sample behaves as expected, with a peak around 1 lasting from about 700-1200 Hz before steeply dropping off. The peaks in general in Fig. 8 are tuned as expected, occurring at higher frequencies as the spacing increases, at 600, 700, and 1400 Hz respectively. The 1 mm spacing array outperforms melamine from 400-800 Hz, whereas the 2.5 mm spacing array outperforms melamine from 700-1200 Hz. This further proves that smaller spacing is more effective at low frequency attenuation.

3.4 Cylinder Diameter

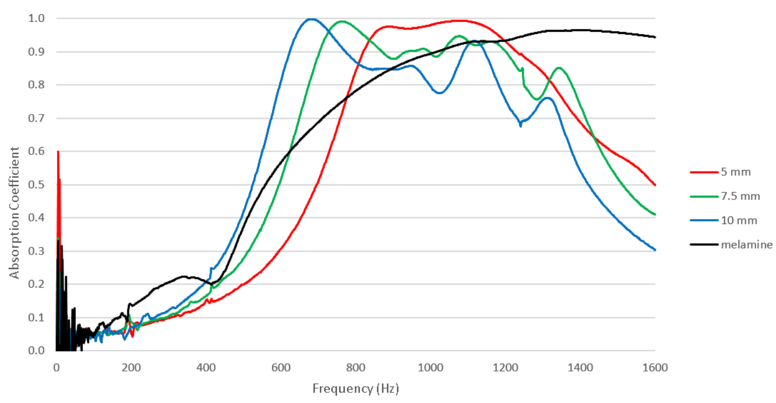

Figure 9. 1 mm spacing average absorption coefficient vs. diameter

In general, larger diameter yields lower frequency attenuation. This effect is demonstrated by the fact that all samples in Fig. 9 achieve a peak near 1, although the 10 mm diameter sample reaches this peak around 600 Hz whereas the 5 mm diameter sample reaches this peak near 800 Hz. Thus the diameter of the cylinder tunes the absorptive peak, with a larger diameter corresponding to lower frequency absorption. Furthermore, all samples perform better than melamine for about a 400 Hz range. The 10 mm diameter array performs well at 400-800 Hz, the 7.5 mm diameter array performed best from 600-1000 Hz, and the 5 mm diameter array performed best at 800-1200 Hz. Absorption of all samples begins dropping off after 1100 Hz, with the larger diameters having secondary and tertiary peaks at higher frequencies, although neither secondary nor tertiary peaks are as significant as melamine's absorptive performance above 1100 Hz.

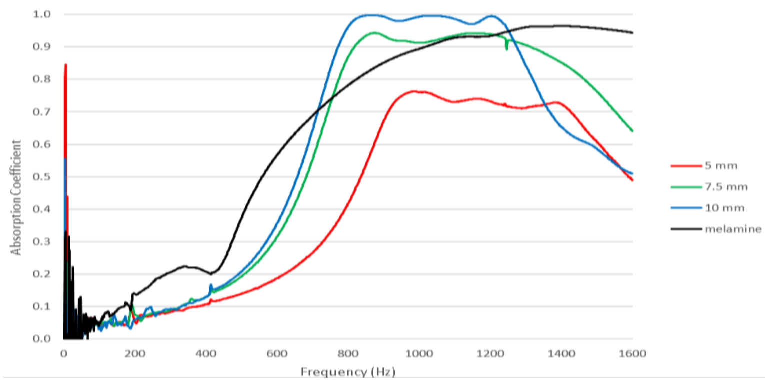

Figure 10. 2.5 mm spacing average absorption coefficient vs. diameter

In Fig. 10**,** is is clear that the absorptive peak decreases as diameter decreases. This peak decreases from near 1 with the 10 mm diameter sample, to near 0.7 with the 5 mm diameter sample. The 10 mm diameter array absorbs more than melamine for its entire 700-1200 Hz peak, but the 7.5 mm diameter array absorbs more than melamine only near 800 Hz. The 5 mm diameter sample is inferior to melamine at all frequencies. Thus larger diameter is desirable for low frequency attenuation. All samples display a distinct absorption drop off. This decline begins at a lower frequency as diameter increases, starting at 1200 Hz with the 10 mm diameter array, and at 1400 Hz with the 5 mm diameter array.

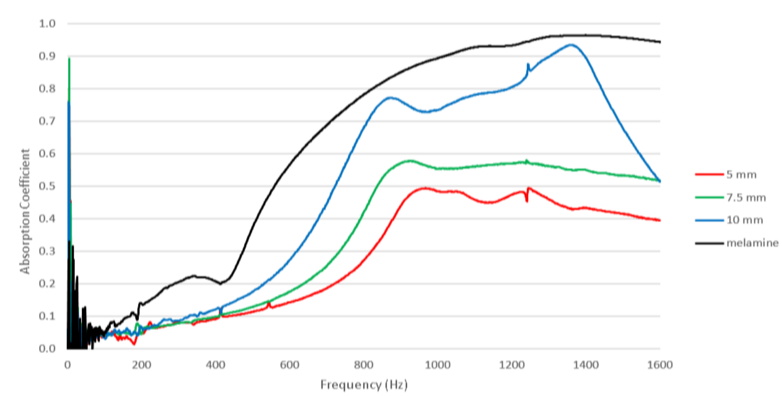

Figure 11. 5 mm spacing average absorption coefficient vs. diameter

No 5 mm diameter sample in Fig. 11 performs better than melamine at any frequency, as expected. This is the smallest diameter sample series, and thus has the poorest low frequency absorption. All sample's initial absorptive peaks are also tuned as expected, with the 5 mm diameter array peaking at the highest frequency.

3.4 Filling Fraction vs. Bandgap Width

Many studies have been conducted which investigate the effect of the filling fraction on sound attenuation [7-10]. Zendehnam et. al [7] define the air-filling fraction of phononic crystals as the ratio of d/Λ where d is the outer cylinder diameter, and Λ is the center to center distance between cylinders. All researchers agree that as a general rule, a larger filling fraction results in a wider effective frequency range of attenuation, often referred to as the bandgap. This expected trend is particularly evidenced in the work of Kushwaha [10]. Sánchez-Pérez et. al [9] were interested in developing tunable filter based on the filling ratio, and were able to identify 0.41 as the optimal value to produce an effective broadband attenuator in the entire audible frequency range for arrays with square symmetry. However, their data measured attenuation in dB therefore the bandgap width was easily ascertained using the frequency limits of positive attenuation values. As this data in this study measured absorption, a unique method of quantifying the bandgap width had to be established.

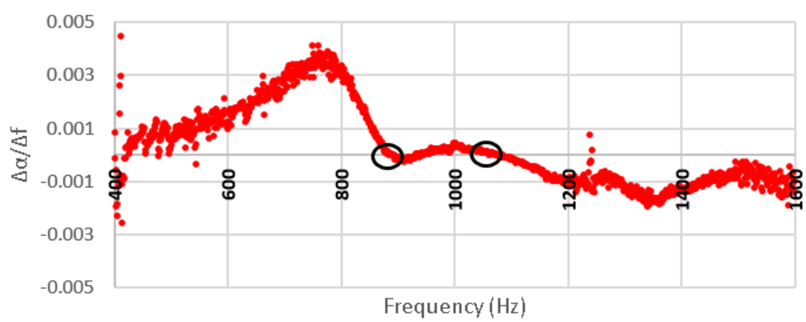

Figure 12. 5 mm diameter 1 mm spacing absorption coefficient first derivative curve

The bandwidth criteria for this study was determined to be the frequency range between the first and third inflection points on the absorption curve, located using the zeros from the first derivative curve. Figure 12 illustrates one such example for the 5 mm diameter 1 mm spacing array. Every sample had a slight dip in absorption soon after the original peak, which is why the second inflection point was ignored. That phenomenon was perhaps due to an artifact created by the impedance tube.

Employing said bandwidth criterion, the filling fraction of each array was plotted against the bandgap width as shown in Fig. 13. The data does in fact meet the expected trend of a linear relationship between the filling fraction and the effective frequency range of attenuation. This is confirmed by the coefficient of determination of above 90%. The array with the widest bandgap, and therefore the most effective attenuator, was the 10 mm diameter, 1 mm spacing sample. Conversely, the least effective attenuator with the most narrow bandgap, was the 5 mm diameter, 5 mm spacing sample. Therefore, the filling fraction investigation is consistent with the findings of both the diameter and spacing comparisons, with the largest diameter and smallest spacing performing best, and vice versa.

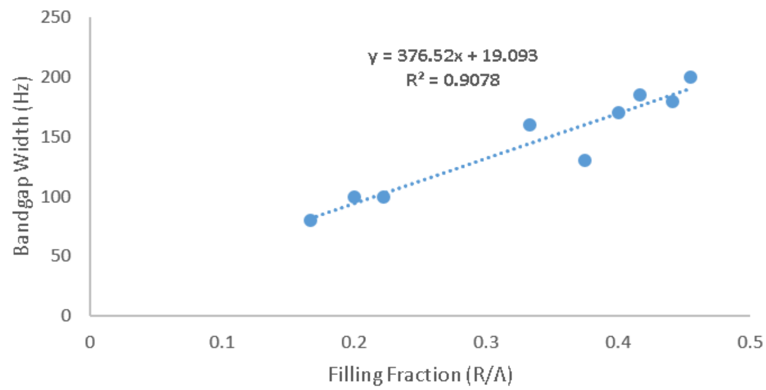

Figure 13. Filling fraction vs. bandgap width

4. CONCLUSIONS

Of all the samples tested, the 10 mm diameter, 1 mm spacing performed best overall for low frequency absorption as it had the largest diameter and smallest spacing. This sample performed better than melamine from 400-800 Hz, which is the lowest range of all of the arrays when compared to melamine. Smaller cylinder spacing causes a steeper drop off in absorption after its maximized effective low frequency range. Larger cylinder spacing yields a wider effective frequency range of absorptivity. Moreover, larger cylinder diameter and smaller cylinder spacing yields a higher filling fraction which results in a wider range of effective absorption. Larger cylinder diameter tunes the absorptive peak to a lower frequency. Cylinder wall thickness does in fact have an impact on absorption, although it might be a result of the inner diameter change among the arrays tested as well. This is an intriguing subject for future research.

Additionally, the absorption of natural reeds found on campus will be tested in the 3-D printed casing to determine the performance of irregular, natural reed shapes. This will be particularly important information in the application of our research to develop an engine liner, as the 3-D printed plastic would not withstand the extreme temperature demands of an engine interior. Thus our results determining general trends is useful, but the absolute absorption values cannot not directly be taken at face value. After all the analysis is complete, we will design, print, and test a new sample that combines the current engine liner honeycomb design known for high frequency attenuation, with the best performing low frequency attenuating array of cylinders to hopefully create broadband noise absorber.

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