Tomography Systems and Sound Manipulation Using Acoustic

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Abstract

Conventional materials in noise reduction such as concretes, woods, foams and glasses is widely used in building to reduce noise in our surroundings. However, these materials exhibit very low capability in reducing low frequency noise. Metamaterials are introduced to provide better sound reduction in low frequency replacing the conventional bulky materials with less weight and cost. Hence, this study performed to investigate the feasibility of acoustic metamaterials in sound reduction. Five samples of acoustic enclosures are fabricated using different materials with dimension of 100 mm^3. Wood acoustic enclosure are fabricated manually while acrylonitrile butadiene styrene (ABS), poly lactic acid (PLA), PLA with metamaterial (1 mm thickness of w_{cavity}) and PLA with metamaterial (5 mm thickness of w_{cavity}) acoustic enclosures are fabricated digitally using three-dimensional (3D) printing method. Performance analysis for acoustic enclosure samples was measure based on decibel drop, *d* to show the difference in sound pressure level before and after acoustic enclosure is placed on the sound source. PLA acoustic enclosure with metamaterial of 5 mm thickness is able to reduce sound level better than the rest of acoustic enclosures samples with the highest reduction of sound pressure level, 26.1 dB occurred on 800 Hz and proved that a greater thickness of metamaterial exhibit better sound reduction.

Keywords: Sound Reduction, Noise Reduction, Acoustic Metamaterials, Metamaterials, Acoustic Enclosure.

1. Introduction

Noise pollution is common in big city such as Japan, Sydney and London. Heavy road traffic is marked as significant source of noise in these cities whereas in developing countries such as Malaysia, construction noise is the most common source of noise pollutant [1]. The sources of noise pollution consist of noise with both high frequency and low frequency.

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Noise reducing material had been placed in buildings, bridges, cooling towers and heavy industrial area [2] as one of the alternative ways to control noise Conventional materials use in noise reduction such as concretes, woods, foams and glasses is widely used in building to reduce noise in our surroundings. However, these conventional materials exhibit very low capability to reduce the problem of reducing low frequency noise [3] due to long wavelength [4] exist in this wave. Sound reducing materials for low frequency such as concrete or wood are heavy and more costly [5].

Advancement of technology has grown in acoustic engineering where metamaterials are introduced to provide better sound reduction in low frequency [6], replacing the conventional bulky materials with less weight and cost. Hence, this study performed to investigate the feasibility of acoustic metamaterials in sound reduction.

Acoustic wave is a longitudinal wave where pressure and particle velocity are the essential parameters used to describe the wave [8]. Metamaterials responsible to replace molecules of conventional materials with man-made structures on a scale much less than the required wavelength to be used [9].

1.1 Acoustic Metamaterial Properties

Acoustic metamaterials utilized the acoustic motion of its scrupulous designed small-scale structure to create a material with extraordinary acoustic properties, which absent in conventional material made from natural sources.

Porous acoustic metamaterials consisted of a stack of perforated plates made of an acoustically hard material separated by a sound-supporting fluid such as air to allow sound waves propagate towards metamaterials. Basically, this design use hole array as its main component, having transmission properties of sub-wavelength control over sound waves. Porous metamaterial designed do not rely on diffraction to achieve negative refraction, in contrast to sonic crystals [7].

In resonant structure acoustic metamaterial, the limited frequency range was established using repeated equal distribution of small metals in air called sonic crystals. Sonic crystals are capable to work as an ordinary sound absorber by themselves with varying arrangement and design to build structures with extreme acoustic properties [7]. The peak of sound absorption coefficient decreases in frequency as the thickness of the air layer is increased.

Porous [7] and resonant [10] [11] structure were implemented together in acoustic metamaterial for a better sound absorber in low frequency [12] [13]. The combination of porous [14] and HR geometrical characteristics was to provide resonating cavity so the sound passing through the metamaterials will go through the propagation slowly [15]. This metamaterials are able to control and manipulate sound waves in almost independent of the incident angle upon the surface.

1.2 Unit Cell Metamaterial Design

A unit cell of the metamaterial was designed using wavelength equation and concept of Helmholtz resonator (HR) to obtain suitable measurement and design. The only requirement of this configuration is the presence of resonance condition [17]. The basic wavelength equation is shown in (1.1) where λ is the wavelength of sound waves, v is the speed of sound waves travel in air and f is the frequency of sound waves. Thickness of a material must follow the value of wavelength for perfect absorption using f of interest for sound manipulation. Frequency of HR, f_H, obtained from equation (1.2) where c is the speed of sound, A_{neck} is the area of the neck, V_{cavity} is the volume of cavity and h_{eq} is the equivalent height of neck.

$$\lambda = v / f (m) \tag{1.1}$$

$$f_H = \frac{c}{2\pi} \times \sqrt{\frac{A_{neck}}{V_{cavity} h_{eq}}} \tag{1.2}$$

Based on (1.3), (1.4), and (1.5) V_{neck} is the volume of neck, h_{neck} is the height of neck, D is the diameter of neck, $lneck$ is length of neck and w_{neck} is the width of neck. By assuming (1.6), (1.7), and (1.8) where l_{cavity} is length of cavity, h_{cavity} is the height of cavity and w_{cavity} is the width of cavity. Therefore, A_{neck} and V_{cavity} are deriving as (1.9) and (1.10) respectively.

$$A_{neck} = \frac{V_{neck}}{h_{eq}} \tag{1.3}$$

$$h_{eq} = h_{neck} + 0.3D \tag{1.4}$$

$$D = \frac{2l_{neck} w_{neck}}{l_{neck} + w_{neck}} \tag{1.5}$$

$$l_{neck} = \frac{1}{3} l_{cavity} \tag{1.6}$$

$$h_{neck} = \frac{1}{6} h_{cavity} \tag{1.7}$$

$$w_{neck} = \frac{1}{2} w_{cavity} \tag{1.8}$$

$$A_{neck} = l_{neck} \times h_{neck} \tag{1.9}$$

$$V_{cavity} = l_{cavity} \times w_{cavity} \times h_{cavity} \tag{1.10}$$

1.3 Performance Analysis

The performance analysis for acoustic enclosure samples was measure based on decibel drop, *d* to show the difference in sound pressure level before and after acoustic enclosure is placed on the sound source. Decibel drop can be calculated using equation (1.11) where dB_{source} is the pressure level before acoustic enclosure is place and $dB_{materials}$ is the pressure level after acoustic enclosure is place.

$$d = dB_{source} - dB_{materials} \tag{1.11}$$

2. Methodology

The development of acoustic metamaterials consisted of four stages, which are parametric study of acoustic metamaterials unit cell design, acoustic metamaterial simulation, fabrication of acoustic enclosure samples, and experimental testing in sound reduction.

2.1 Metamaterial Unit Cell Design

The designation of acoustic metamaterials was carried out using frequency range from 200 Hz to 1000Hz. Firstly; wavelength of both minimum and maximum frequency must be determined using basic wavelength equation (1.1). In room temperature, speed of sound is equal to 343.2 ms^{-1} and wavelength obtained at frequency of 200 Hz (λ_{200}) and 1000 Hz (λ_{1000}) are 1.7160 m and 0.3432 m respectively. Wavelength is longer at frequency of 200Hz due to low frequency behavior.

Determination of subwavelength thickness based on the waves propagated through it is the most important criteria in metamaterial designing. Considering that metamaterial should possess thickness much less than the wavelength of sound waves they influenced. Hence, metamaterial thickness must be much less than 1.716 m which is the maximum thickness [17] [16]. For the ease of fabrication and testing of acoustic metamaterial, mm was chosen as the unit of dimensions. One-quarter wavelength, $\lambda_{resonant}$ of incident sound was said to be the resonant frequency, $f_{resonant}$ which peak absorption will take place and was calculated as (1.12) and (1.13) respectively.

$$\lambda_{resonant} = \frac{1}{4} \times Thickness\max = \frac{1}{4} \times 1.716 = 0.429m \tag{1.12}$$

$$f_{resonant} = \frac{v}{\lambda_{resonant}} = \frac{343.2}{0.429} = 800Hz \tag{1.13}$$

The dimension of area and volume of the HR calculated as explained in section 1.2.2. The obtained parametric was tabulated in Table 1.1 and the unit cell was designed using 3D design TinkerCAD software. The most important part to provide a resonance condition in this design was the presence of opening on the neck, area of neck and volume of cavity.

Table 1.1 Parameter Scale in Metamaterial Design with HR

Parameter	Scale
Length of cavity, l_{cavity}	3mm
Height of cavity, h_{cavity}	6cm
Width of cavity, w_{cavity}	20mm
Length of neck, l_{neck}	1mm
Height of neck, h_{neck}	1cm
Width of neck, w_{neck}	10mm
Diameter of neck, D	$1.8182x10^{-3}$
Equivalent height of neck, h_{eq}	0.01055m
Area of neck, A_{neck}	$1x10^{-5}m^2$
Volume of cavity, V_{cavity}	$3.6x10^{-6}m^2$
Frequency of HR, f_H	886.32Hz

According to design, unit cells placed side by side with 0.5 mm distance from each other and grouped together in a line of six unit cells. A 100 mm^3 cube box is then built as the base for acoustic enclosure with thickness, t of each surface is 5 mm as shown in Figure 1.2. The group of unit cells was placed on each inner wall. The number of unit cells placed on each wall is not restricted to a certain number but more unit cells require higher accuracy of fabrication technology. Parametric study carried out to obtain the optimal number of unit cells to be fabricated on each wall.

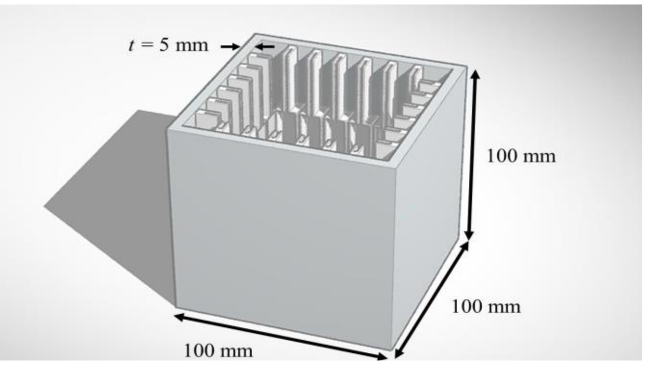


Figure 1.2 3D Acoustic Metamaterial Designed

2.2 Unit Cell Design Simulation

This unit cell was simulated in COMSOL Multiphysics through eigenfrequency module with boundaries assumed hard and rigid. Studies conducted towards the model are acoustic pressure (AP) and sound pressure level (SPL) of frequency below 1000 Hz. The main purpose of this simulation is to obtain eigen frequency of the unit cell and ensure that the resulting frequency is not in the range of 200 to 1000 Hz frequency to avoid the vibrating effect of sound propagated towards unit cell metamaterial. If the eigen frequency is in the range of interest frequency of 200 to 1000 Hz, the design of unit cell need to be changed until it is below the stated range.

Before start, make sure that the simulation module is in .acpr file by selecting pressure acoustics in frequency domain. Place the geometry on work plane and set the surrounding of geometry as air. Material contents of the study are set with density of 1.25kg and speed of sound of $343ms^{-1}$. Then, build mesh on the geometry to ensure that boundaries and domains of the geometry is valid for eigenfrequency study. Simulate the eigenfrequency study by setting frequency to 1000 Hz so that the resulting eigenfrequencies obtained are in the vicinity of 1000 Hz.

2.3 Fabrication of Acoustic Enclosure

Five samples of acoustic enclosures are fabricated using different materials with dimension of 100 mm^3. Wood acoustic enclosure are fabricated manually while acrylonitrile butadiene styrene (ABS), poly lactic acid (PLA), PLA with metamaterial (1 mm thickness of w_{cavity}) and PLA with metamaterial (5 mm thickness of w_{cavity}) acoustic enclosures are fabricated digitally using three-dimensional (3D) printing method.

The wood acoustic enclosure shown in Figure 1.3 was manually fabricated where five parts of wood with area of 100 mm^2 were cut and assembled using acoustic sealant. The outer wood surface was smoothened using sand paper for safety handling while conducting experiment. Safety measures include the use of hand gloves, goggles, and mask was taken into consideration along fabrication process.

Figure 1.3 Wood Acoustic Enclosure with Dimension of 100 mm^3

Meanwhile, the 3D design of acoustic enclosure printing setup in digital fabrication is as shown in Figure 1.4. First, the acoustic enclosure design in *.stl* file was imported from 3D design software before fabricated using 3D printing. This study used FlashForge Dreamer 3D printer. Before printing, filament must be loaded to its correct extruder, pre-heat filaments and platform as well as cleaning the platform. During printing, the printer cover must be placed tightly on top of the platform to ensure surrounding temperature not disturb the temperature inside the printer to avoid distortion on the sample. After printing process ended, pre-heat the platform again and slowly unattached printed sample from it. The printed design of acoustic enclosure and acoustic enclosure with metamaterial are shown in Figure 1.5 (a) and (b) respectively.

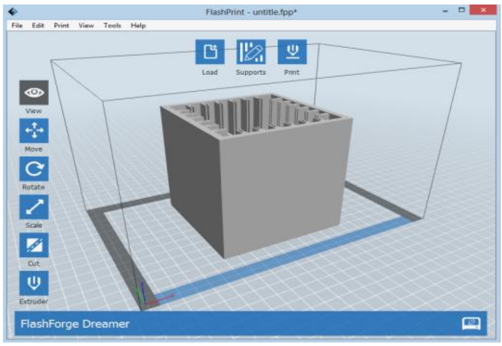
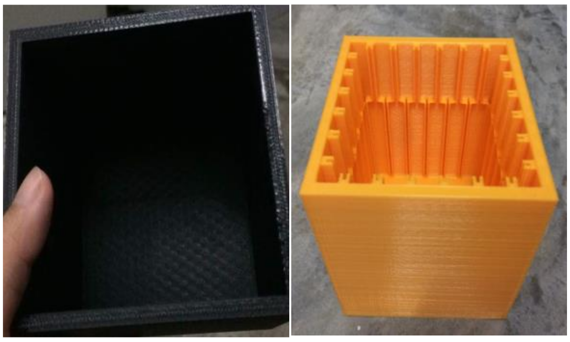


Figure 1.4 3D Design of Acoustic Enclosure Printing Setup



(a) (b)

Figure 1.5 3D Printed of (a) Acoustic Enclosure and (b) Acoustic Enclosure with Metamaterial

2.4 Sound Reduction Experiment

Acoustic enclosures samples undergo testing of sound reduction towards frequency varied from 200 to 1000 Hz. Sound reduction experiment performed to determine the performance of acoustic enclosure in sound reduction.

The equipment setup is as shown in Figure 1.6. The sound level meter needed to measure SPL in a room condition. A wireless speaker (sound source) provides a pure tone of 200 to 1000 Hz. Throughout the experiment, these variables must be kept constant; the distance of sound level meter to sound source is 10 cm, duration of each sample is 30 seconds, and loudness of each pure tone coming from wireless speaker is in level 20 out of 100. While conducting experiment, the use of headphone is advisable to protect hearing due to continuous expose to loud noise.

Figure 1.6 Sound Reductions Experimental Setup consists of Sound Level Meter, Wireless Speaker, and Acoustic Enclose Sample

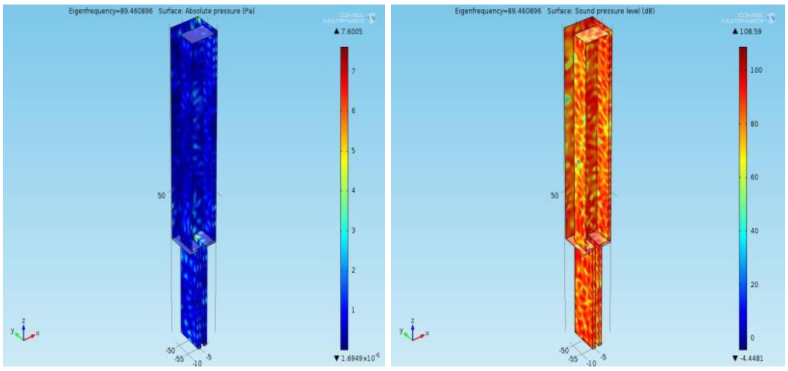
In order to determine the accuracy of this experiment, each level of pure tone was verified with the correct frequency before experiment was conducted. First, wood acoustic enclosure was placed on top, enclosing the speaker, and sound level meter were turned on simultaneously for 30 seconds to record the equivalent SPL. This step was repeated with different acoustic enclosure samples. After completing these steps using pure tone of 200 Hz, the whole experiment was repeated using 300 Hz until 1000 Hz.

3. Results and Discussions

This section discussed on the results and findings obtained from the simulation of unit cell metamaterial design, acoustic enclosure samples fabrication and sound reduction experiment of different acoustic enclosures.

3.1 Simulation Result

Results of this simulation only applied to structure that have rigid walls and hard boundaries. Based on Figure 1.7, AP on volume of unit cell geometry is concentrated in the opening between neck and cavity, proving the theory of mass spring system in HR. This opening area is where volume of air accumulated from the neck area and oscillates as it passes volume of cavity. While AP on surface of unit cell geometry is concentrated in the walls of cavity that explained the oscillating phenomena in the structure while sound waves going around in the area and attenuated.



(a) (b)

Figure 1.7 AP on (a) Volume and (b) Surface of Unit Cell Geometry

The result of eigenfrequency on the volume of unit cell structure is 89.46 Hz while eigenfrequency for surface of the unit cell structure is 90.12 Hz. These eigenfrequencies are lower than the range of frequency interest to be influenced in sound reduction. Therefore, this structure and its parameters were approved to be propagated with such sound without having to consider the vibrating effect. SPL of the unit cell was determined in this study to obtain the resonant frequency of the structure to be compared with calculation and experimental result. Based on Figure 1.8, the highest SPL was in 773 Hz, which means sound wave with frequency higher than this can be reduced by the unit cell while sound waves with frequency lower than this will not be reduced.

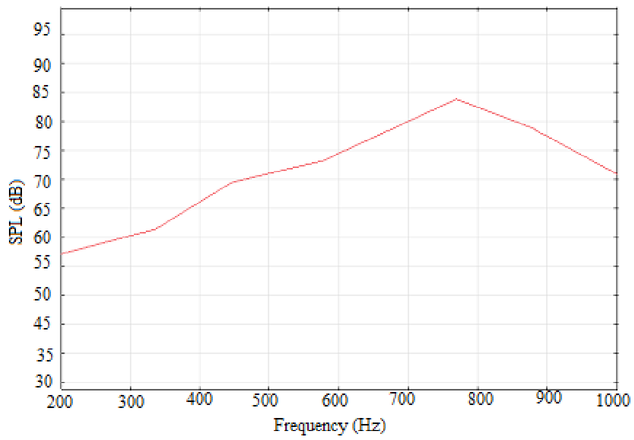


Figure 1.8 Graph of SPL versus Frequency

3.2 Comparison on Fabrication Process

Performance comparisons in term of fabrication process for each acoustic enclosure sample are shown in Table 1.2. In terms of difficulties, fabrication of wood acoustic enclosure was the most difficult which requires more tasks such as estimating, marking, cutting, smoothing and assembling. Moreover, it involved manual measurement and estimation, which lead to more failures due to human error while there is almost no error in 3D printing technology as it based on machinery work.

In term of duration, digital fabrication required longer time compared to manual fabrication. However, only 10 to 15 minutes are required to prepare file and set the printer in digital fabrication. The rest duration was for printing process, which can be left and allows user to multitask. In contrast, manual fabricating required full concentration handwork until finished. 3D printed sample can be tested immediately after fabricated while wood sample needed to wait for acoustic sealant used to be completely dry. Meanwhile, longer time required in printing samples with metamaterial due to the presence of more surfaces being printed. Printing duration for ABS was shorter than PLA because ABS melting point was lower than PLA. Therefore, lower temperature needed to continuously heat the filament and platform of printer, resulting to shorter duration of printing process.

In terms of fabrication cost, PLA and ABS sample required the lowest cost because the materials used is abundantly available in the market with wide range of choices and prices. Cost of fabricating samples using 3D printing method include only the filaments used which a spool of ABS and PLA filament cost up to RM80.00 and able to cover the fabrication of all four samples of 100 mm^3 cube box using the same spool. However, the cost of fabricating wood samples includes of material and the acoustic sealant used for assembling purpose.

Table 1.2 Fabrications of Acoustic Enclosure Samples

Sample	Fabrication method	Difficulties	Duration in hours (h) and minutes (min)	Cost (RM)
Wood	Manual handwork	Designing & developing	8 h	40.00
ABS	3D printing	Designing	24 h 12 min	20.00
PLA	3D printing	Designing	23 h 28 min	20.00
PLA Metamaterial (1mm)	3D printing	Designing	23 h37 min	20.00
PLA Metamaterial (5mm)	3D printing	Designing	23 h 54 min	20.00

3.3 Performance of Acoustic Enclosure

The performance of each acoustic enclosure sample in reducing sound was observed based on the SPL reading shown in Table 1.3. PLA with metamaterial of 5 mm thickness reduced all sound source from 200 Hz to 1000 Hz. PLA with metamaterial of 5 mm thickness is the best sound reducing material followed by PLA with metamaterial of 1 mm thickness, PLA, ABS, and wood. The lowest SPL recorded was 52.6 dB (in the range of acceptable limit) from PLA with metamaterial of 5 mm thickness during 800 Hz frequency.

Table 1.3 SPL of Different Acoustic Enclosure

	f, Hz	200	300	400	500	600	700	800	900	1000
SPL (dB)	Source	59.4	72.3	76.2	76.2	76.7	76.0	78.7	78.6	78.6
	Wood	61.8	75.2	5.9	76.0	75.6	73.4	66.2	66.4	66.9
	ABS	61.2	74.8	75.2	75.2	73..7	73.0	66.2	61.5	65.9
	PLA	60.7	73.4	74.7	74.5	71.6	69.5	64.9	55.1	60.6
	PLA MM (1mm)	61.3	74.1	74.7	74.5	71.5	69.1	63.6	54.5	57.8
	PLA MM (5mm)	58.4	70.9	74.3	73.9	70.7	68.3	52.6	56.6	57.3

Based on Table 1.4, pattern of decibel drop, *d* increased from wood sample to PLA with metamaterial of 5 mm thickness. *d* started on 400 Hz for wood, ABS, PLA and PLA with metamaterial of 1 mm thickness while PLA with metamaterial of 5 mm thickness have *d* starting on 200 Hz due to more resonant cavity present. Based on HR, increasing thickness of unit cell structures means v_{cavity} of the resonance system also increases, giving space for more sound to be attenuated. The other four samples caused increment in SPL when propagated with frequency from 200 to 300 Hz, hence required more thickness to influence such low frequency and reducing the SPL. Frequency more than 500 Hz shows significant decrease in *d* as this range of frequency is easier to be reduced due to its wavelength.

The highest *d* for PLA with 5 mm metamaterial sample, take place at 800 Hz frequency while the highest *d* for the other four samples takes place at 900 Hz frequency. PLA with metamaterial shows the best result in reducing sound due to the presence of metamaterial and resonant structure in the system. Multiple structures of resonant systems in the acoustic enclosure enable reduction of sound significantly by more than 20 dB to an acceptable SPL that is less damaging towards human hearing.

Table 1.4 Decibel Drop of Different Acoustic Enclosures

f, Hz		200	300	400	500	600	700	800	900	1000
d, dB	Wood	-	-	0.3	0.2	1.1	2.6	12.5	16.2	11.7
	ABS	-	-	1.0	1.0	3.0	3.0	12.5	17.1	12.7
	PLA	-	-	1.5	1.7	5.1	6.5	13.8	23.5	18.0
	PLA MM (1mm)	-	-	1.5	1.7	5.2	6.9	15.1	24.1	20.8
	PLA MM (5mm)	1.0	1.4	1.9	2.3	6.0	7.7	26.1	22.0	21.3

Wood sample showed the least of *d* throughout 400 to 1000 Hz frequency of sound source because of the presence of uncertainty in air gaps between walls and acoustic properties of the acoustic sealant resulting to sound waves able to escape from the acoustic enclosure instead of attenuated in it. If air was able to pass through the material, then sound also should be able to escape through them. Digital fabrication allowed fabrication of sample as a whole and reduced the source of uncertainty.

The existence noise barriers technology required at least 3x3 meter of concrete for 20 dB reduction of sound. Meanwhile, 20 dB of sound reduction can be achieved by applied PLA with 5 mm metamaterial. Based on Table 1.5, the cost to build acoustic metamaterial was less than half of cost to build noise barriers. Therefore, acoustic metamaterial should be able to replace conventional material for noise barriers application as metamaterial can reduce sound with much less development cost.

Table 1.5 Developments Costing of Noise Barrier

Material	Unit	Price per unit	Price per meter sq
Concrete	1x1 m	800-1000	800-1000
Metamaterial	100x100 mm	10-20	100-200

4. Conclusion

In this study, PLA acoustic enclosure with metamaterial of 5 mm thickness is able to reduce sound level better than the rest of acoustic enclosures samples with the highest reduction of sound pressure level, 26.1 dB occurred on 800 Hz. Based on this study, acoustic enclosure with metamaterial has been successfully developed for noise control application in sound reduction. The use of 3D printing technology improves the ease of fabrication time and cost.

This study found that acoustic enclosure of PLA with metamaterial thickness of 5 mm is able to reduce sound better compared to acoustic enclosure of PLA with metamaterial thickness of 1 mm. Hence, it can be conclude that a greater thickness of metamaterial exhibit better sound reduction.

This study can be further improved by employing different dimensions, number and arrangement of Helmholtz resonator in acoustic enclosure. Further study should provide observation of different patterns of unit cell metamaterial on sound reduction.

The liquid/gas two-phase flow interface and its void fraction were experimentally investigated using conductive type wire-mesh tomography sensor. The circular type wire-mesh sensor was designed for a circular cross-sectional area test section of 7178.0366 mm^2. Wire-mesh tomography technique provides reliable measurement of liquid/gas two-phase flows interface and its void fraction. In order to accurately estimate the gas-liquid interface using the wire-mesh tomography technique, more efforts need to be invested in developing algorithms for it.

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References

[1] Luxon, L. M., & Prasher, D. (2007). *Noise and its effects*. Wiley.

[2] Wise, S., & Leventhall, G. (2010). *Active noise control as a solution to low frequency noise problems*. Low Frequency Noise, Vibration and Active Control, 29(2), 129-138.

[3] Guenneau, S., & Craster, R. V. (2013). *Fundamentals of Acoustic Metamaterials.* Acoustic Metamaterials Springer Series in Materials Science. 1-42.

[4] Wang, Q. (2008). *Studies On The Relationship Between Sound Absorption.* Acta Polymerica Sinica, 008(6), 517-521.

[5] Takahashi, Y. (2009). *Vibratory sensation induced by low-frequency noise: A pilot study on the threshold level.* Low Frequency Noise, Vibration and Active Control, 28(4), 245-253.

[6] Simon, F. (2013). *Low frequency sound absorption of resonators with flexible tubes.* The Journal of the Acoustical Society of America, 133(5), 3265.

[7] Sanchez-Dehesa, J., Chocano, V. M., & Guild, M. D. (2014). *Recent results on sonic crystals for sound guiding and acoustic absorption.* The Journal of the Acoustical Society of America, 136(4), 2076-2076.

[8] Zhang, S. (2010). *Acoustic metamaterial design and applications.* Unpublished doctoral dissertation, University of Illinois.

[9] Active Standard ASTM C423. (2017). *Standard Test method for sound absorption and sound absorption coefficients by the reverberation room method.* ASTM International,West Conshocken, PA.

[10] Herrero-Durá, I., Picó, R., Sánchez-Morcillo, V., Garcia-Raffi, L. M., & Romero-García, V. (2015). *Vibroacoustic effects of resonant sonic crystals in sound absorption*. European Acoustics Association Journal.

[11] Mast, T. Dougles. (2014). *Helmholtz resonator.* AccessScience. McGraw-Hill Education.

[12] Liang, Z., Feng, T., Lok, S., Liu, F., Ng, K. B., Chan, C. H., Li, J. (2013).*Space-coiling metamaterials with double negativity and conical dipersion*. Scientific Reports, 3, 1614.

[13] Jiménez, N., Huang, W., Romero-García, V., Pagneux, V., & Groby, J. P. (2016). *Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption*. Applied Physics Letters, (109), 121902nd ser.

[14] Sandberg U. (2001). *Plenary paper published in the Proceedings of the 2001* International Congress and Exhibition on Noise Control Engineering, Hague, Netherlands.

[15] Sood, D., & Tripathi, C. C. (2015). *A Wideband Wide-Angle Ultra-Thin Metamaterial Microwave Absorber*. Progress In Electromagnetics Research M, 44, 39-46.

[16] Claeys, C. C., Pluymers, B. & Desmet, W. (2014). *Design of a resonant metamaterial based acoustic enclosure* Leuven, Flanders. 3351-3358.

[17] Araque, J. L., & Baena, J. D. (2014). *Duality for 3D metamaterial resonators.* International Congress on Advanced Electromagnetic Materials in Microwaves and Optics.