Experimental Investigation on the Sound Reduction Performance of Frequency Controlled Acoustic Interference Cavities

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ABSTRACT

The European directives on noise reduction associated with buildings, rail, road and aviation clearly depicts the need for high efficiency sound attenuating structures for targeted noise reduction. Accordingly, this paper presents key observations from Phase 1 of the UK Department of Transport (DfT) funded research to investigate the targeted creation of acoustic interference to develop high-efficiency noise reducing structures. Geometrical cavities inspired from existing theories around the Herschel-Quincke concept is experimentally investigated for the creation of frequency dependent acoustic interference. The interference cavity within a global structure was digitally conceived and prototyped using the Selective Laser Sintering (SLS) process in a Nylon 12 material. A modified impedance tube method was then used to measure the frequency dependent Sound Reduction Index (R) for a frequency range of 250 to 1600 Hz. The results showed that depending on the frequency of interest, acoustic interference can be recreated by controlling the cavity length. In addition peak R values of 72.47 dB was observed at 900 Hz confirming the potential of the technology for high efficiency noise reducing structures. The observations presented in this paper establishes a new viewpoint in the use of acoustic interference for targeted noise abatement.

Keywords: Sound, Insulation, interference, I-INCE Classification of Subjects Number(s): 38.5.1, 51.4

1. INTRODUCTION

The European Union's Green Paper on Future Noise policy (1) estimates 80 million people suffering from unacceptable noise levels that cause sleep disturbance and an additional 170 million having annoyance during the daytime due to inadequate acoustic insulation. The growing demand for air and ground travel means that more people are being exposed to high levels of noise on a regular basis which is recognised as an important environmental and public health issue (2).

Sound transmission and its interaction with structures is an active area of research where various solutions for sound reduction are constantly being analysed by researchers across the globe. The traditional concepts of mass insulation have been recently superseded by the adoption of multi-panel structures such as double-leaf walls, layered windows etc. Attempts to utilize the resonance behaviour to further improve the performance of these structures are also being studies. Mason and Fahy (3) suggested that adding Helmholtz resonators to the perimeter of the air layer of the partition can improve its sound reduction performance. This was further confirmed by Mao and Pietrzko (4) through experimental investigations and reported progress on sound insulation.

Strategies coupling the sound absorptive property of the materials have also been investigated; Idrisi *et al.* (5) studied the effect of absorptive materials with additional mass and suggested possible improvements. Lin *et al.* (6) attached a vibration absorber to one side of the panel and discussed its effects by means of a simple one-degree of freedom model. Mu *et al.* (7) studied the effect of applying micro-perforation to the transmission side of the panel and confirmed possible improvements for sound reduction.

For most plate like building structures such as walls, doors and windows the assessment criteria have been widely studied and various recommendations put forward (8-16). Overall, the literature shows that the acoustic insulation of such structures is highly dependent on the material, number of layers, mass and stiffness (13). However, this work attempts a new method of passive sound reduction using the principle of acoustic interference which is recreated through frequency controlled

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geometrical cavities.

Acoustic interference is well known and is widely used for noise cancelling applications in an active form (17). The active technology employs a microphone to pick up the incoming acoustic wave and uses an electronic circuit and speaker to create a similar wave that is in 180° phase difference to cancel/reduce the ambient noise. However, the investigations in this paper is relating to changing the phase of an acoustic wave as a function of cavity geometry without using any active components.

The idea was inspired from existing theories around acoustic interference such as the Herschel-Quincke (HQ) wave guide concept (18) that is usually employed in the presence of a directional and active fluid flow such as in duct noise (19). The concept was first introduced in 1833 by Herschel who theorised that under unidirectional fluid flow, if the sound of a given pitch is divided into two branches in one dimension, then potential noise reduction may occur when the branched wave meets the source wave due to interference. Herschel's one dimensional theory was experimentally confirmed by Quincke in 1866 (20). Outside of this one-dimensional theory, there is no published literature around this concept investigating it for noise reduction in the absence of a directional flow.

The presented study investigates the targeted creation of destructive interference as a function of geometry in the absence of a unidirectional fluid flow to establish proof of concept. This was done to validate the potential of the proposed concept to create high efficiency and customizable noise barriers. As a first step complex geometrical cavities to exploit the acoustic interference are digitally conceived and prototyped using the Selective Laser Sintering (SLS) (21) process in a Nylon 12 material. A modified impedance tube method (22) is then used for the measurement of the frequency dependent Sound Reduction Index (R) to characterise the sound reduction potential as a function of the incident sound frequency.

2. METHEDOLOGY

2.1 Geometrical Creation of Acoustic Interference

The theoretical principle behind the proposed concept to create destructive interference is shown in Figure 1. When the sound wave from a common source enters the geometrical cavity of a different but connected length, the sound waves meet with a phase difference to create destructive interference at a certain point. The amount of phase shift between the two waves depends on the relative length of the cavity and the wavelength of the incident acoustic wave. When the difference in wavelength is half the incident wavelength, the phase difference is 180° and can be used to cancel the noise.

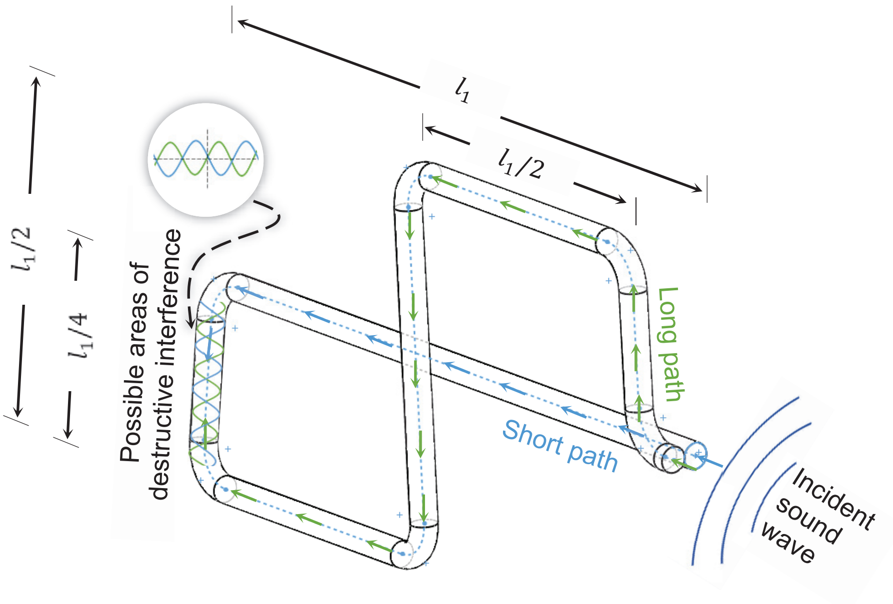

Figure 1 - Proposed concept to create destructive interference

Considering a case shown in Figure 1; when sound waves simultaneously enter through both sides of a cavity of total length l at a constant sonic velocity c. The frequency can be roughly related using a one dimensional Eqn. (1):

$$f = \frac{(2n-1)c}{2\delta l} \tag{1}$$

Where n is a positive integer and δl is the transmission length difference or interference length (referring to the location where interference will occur). Consequently, the length of the short path (l_1) and long path (l_2) can be related as:

$$\delta l = l_2 - l_1 \tag{2}$$

For a one-dimensional linear system based on a Herschel-Quincke theory, interference boundary can be expected to between 1/4th and the total length of the air cavity (18,20).

2.2 Design Generation

The design of the interference cavity started with calculations following Eqn. (1). Using a sonic velocity of 343 m/s and assuming an interference boundary as shown in Eqn. (3):

$$\frac{l}{\delta l} = 1 \tag{3}$$

Using the above assumption, destructive interference can be expected to occur at the mouth of the cavities. Using this relation, δl was predicted to be 17.15 cm for a frequency of 1000 Hz. A minimum wall thickness (t) of 1cm was considered to minimise vibro-acoustic transmission through the cavity boundary. However, it is acknowledged that studying the effectiveness of wall thickness for further characterization was outside of the scope of this study.

Table 1 - Specimen design parameters

Shape	δl (cm)	$d1$ (cm)	$d2$ (cm)	$d3$ (cm)	$d4$ (cm)	t (cm)	h (cm)	D (cm)
U	17.5	3 (3BU)	2.5 (2.5BU)	2 (2BU)	1.5 (1.5BU)	1	10	10

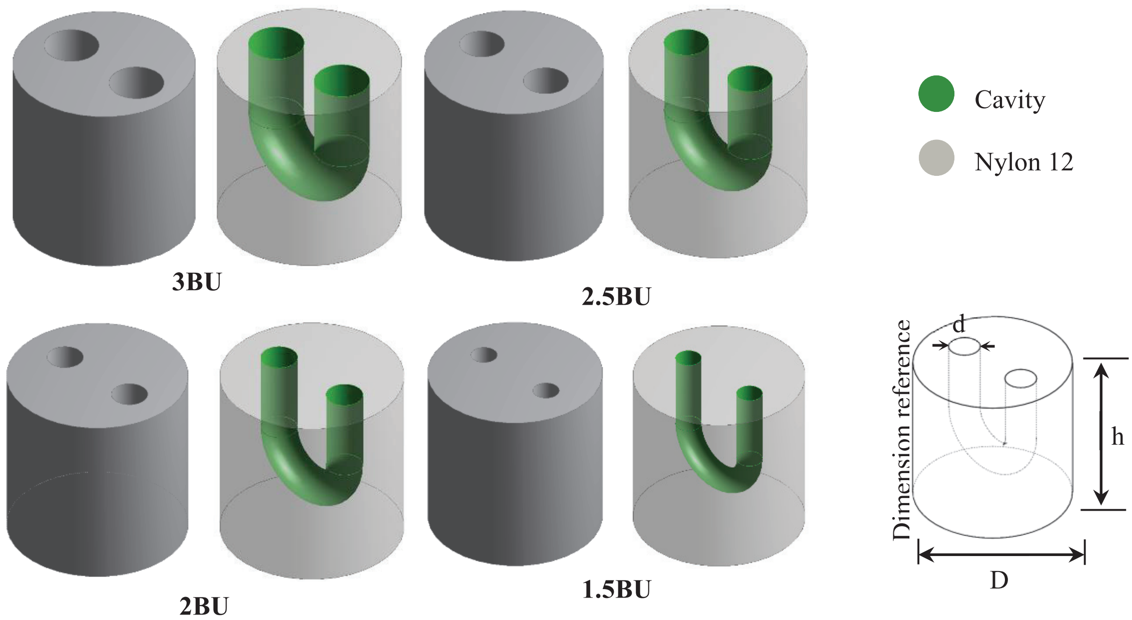

Figure 2 - Designs of the test specimen considered

A total of four designs featuring cavity diameters (d) of 1.5, 2, 2.5 and 3 cm were conceived with further parameters presented in Table 1. The global diameter (D) and height (h) were prescribed by the dimensions of the impedance tube required to conduct the analysis at a frequency range of 250 to 1600 Hz. In order to effectively consider a δl value of 17.15 cm within a global diameter and height of 10 cm, various cavity shapes were consulted. Finally, a U shape as shown in Figure 2 was used because of its scalable simplicity.

The U shape also assisted in easy powder removal from the cavities after the SLS process used for Rapid Prototyping (RP) (21). The conceptual designs were then digitally produced using the SolidWorks 2015 Computer Aided Design (CAD) package. SolidWorks is an industry standard, general purpose computer CAD software developed by Dassault Systèmes.

2.3 Rapid Prototyping

Using the CAD files generated, rapid prototyping of the test specimens were carried out using the SLS process categorised under the Additive Layer Manufacturing (ALM) technique. ALM is an emerging technique that provides an alternative solution to traditional, subtractive manufacturing in many situations where fast and 'cost-efficient' fabrications are required (23). SLS is a popular technique which enables fast, flexible and cost-effective fabrication of highly complex polymer parts. The quick set-up and build time enable the fastest route from design generation to prototyping.

Before the sintering process, the CAD files were sent to a proprietary software called 'Magics' to generate layer-by-layer data for the SLS process. Magics is a data preparation software for the ALM process, it is also used to orient and assemble the parts on the SLS build platform. The self-supporting capabilities of the technique allowed the fabrication of geometrically complex interference cavities with relative ease compared to traditional and other ALM techniques.

The SLS machine brand named 'Sinterstation 2500' developed by 3D Systems owned by the University of Wolverhampton, School of Engineering at Telford Innovation Campus was used for manufacture of the test parts. Powdered Nylon 12 was the material used with properties listed in Table 2.

Table 2 – Material properties of Nylon 12 sintering powder (24)

Density of Laser Sintered Part	0.9 to 0.95 g/cm³
Tensile Modulus	1700 ± 150 MPa
Tensile Strength	45 ± 3 MPa
Elongation at Break	20 ± 5%
Flexural Modulus	1240 ± 130 MPa
Melting Point	172 to 180°C
Coefficient of Thermal Expansion	1.09×10^{-4} K^{-1}

The manufacturing process began with the conversion of 3D CAD files into a sliced STL file format using the Magics software. The STL file is then sent to the SLS machine for processing. On receiving the process command, the machine warms up with the material heated to just below melting point prior to the feed bed rise and the levelling roller pushes fresh powder across the build platform.

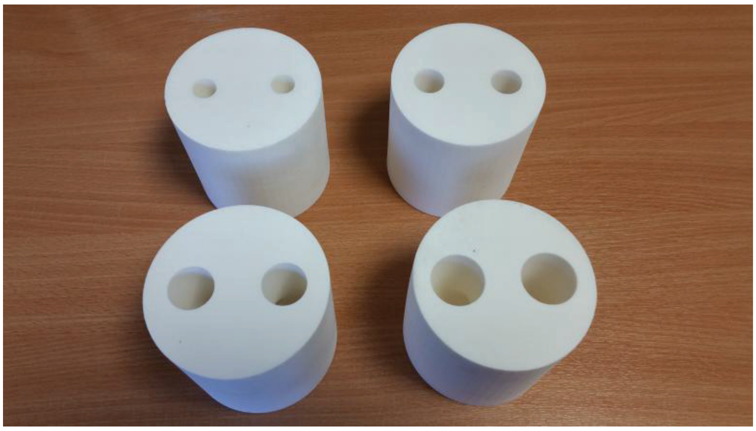

Figure 3 - Sintered Nylon 12 geometries

The first layer is then traced out by a CO2 laser which melts and fuses the material upon contact. After the completion of the first layer the build platform drops by a set amount, and a new layer of powdered material is added. The next layer is then traced out and the process repeats layer by layer until the model part is fully developed. Once the sintering process is complete, the model is allowed to cool and then it is removed from the build platform. The un-sintered powder in the interference cavity is removed using compressed air. The finished prototypes of the test parts each having a unique interference cavity is shown in Figure 3.

2.4 Acoustic Testing

The measurement of the sound reduction indices were carried out using an impedance tube measurement setup using the transfer function method. This method can accurately measure sound absorption coefficients and impedance in accordance with ISO10534-2 (25). The method separates the incident and reflected energy from the measured transfer function, and then estimates the acoustic properties of the tested sample installed in the tube.

The schematic of the test setup is shown in Figure 4. Four MPA416 1/4'' Class 1 microphones, with a frequency response 20 ~ 12.5k (Hz) designed for impedance applications were used. The sound source is an in-tube loudspeaker connected to a PA50 power amplifier. The microphones and the power amplifier were directly connected to a 4-channel MC3242 data acquisition hardware. The MC3242 was then connected to a PC running the VA-Lab software.

Using the four microphone setup the R values were measured for a frequency range of 250 Hz to 1600 Hz. A tube diameter of 10 cm was used to allow a snug fit for the test specimens. Before commencing the measurement all microphones were calibrated taking into consideration the background noise. The calibrated microphones were then placed in the microphone cavity and sealed to avoid any leakage.

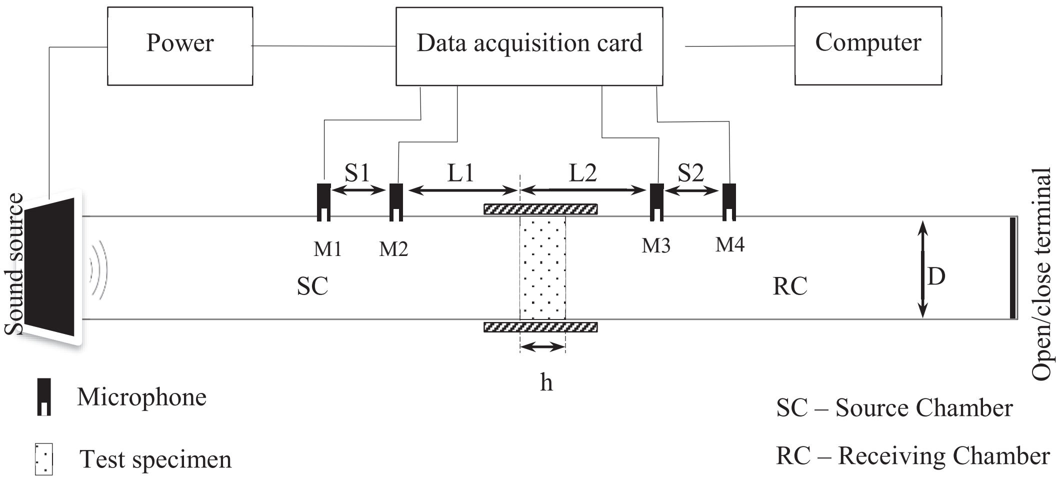

Figure 4 - Experimental setup to measure the sound reduction indices

Before testing the prototypes, a validation study was carried out using a foam specimen of known R values and the measured results compared. During the measurements, the temperature and relative humidity in the test lab was measured to be 21℃ and 64% respectively.

After the validation study, the test specimens were fitted snugly into the specimen holder, with care taken to avoid undue compression. Any gaps around the edges of the samples were sealed with Vaseline after making sure that the front surface of the specimens was normal to the tube axis. The microphone spacing S1 and S2 were measured to be 8 cm and the distance from the sample to the nearest microphone L1 was measured to be 4.8 cm, the furthest distance L2 was measured to be 15 cm. Finally, the specimen height h and diameter D was measured to be 10 cm.

A total of four specimens were analysed and the R values measured. For each specimen, a total of six measurements were taken at 1/12 octave band range, three measurements with the receiving chamber open and three with the receiving chamber closed. The measurements were then averaged to obtain the final R value representing the frequency dependent sound reduction indices for the prototypes.

3. Results and Discussion

3.1 Validation

Before commencing the test on the interference cavities, a validation study was conducted using a Polyurethane foam of density of 6 Kg/m^3 to evaluate the effectiveness of the modified impedance tube test set-up used for the study. The thickness and diameter of the foam sample used were 2.5 cm and 10 cm respectively.

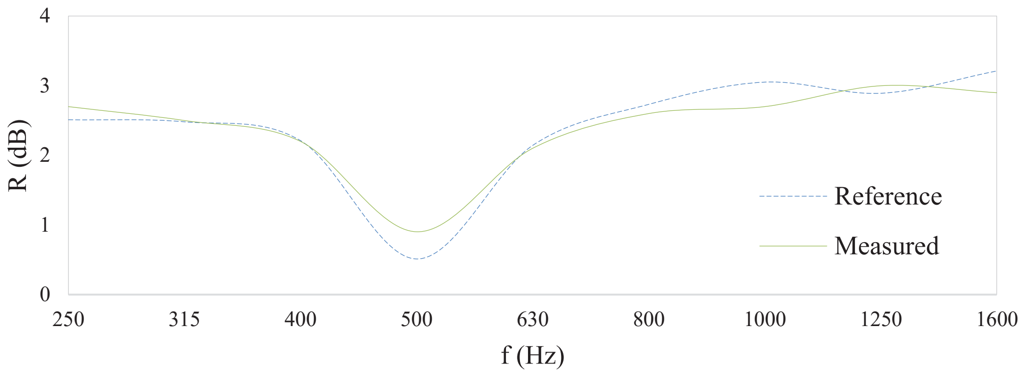

Figure 5 - Comparison of reference and measured R values for validation of the test set-up

Comparison of the measured values with respect to existing reference data is presented in Figure 5. Analysing the results, a highest difference of 0.39 dB was observed at a frequency of 500 Hz. This is well below the ISO specified measurement uncertainty of ± 1.2 dB at the same frequency. The difference in results with respect to ISO10140 (26) measurement uncertainty is listed in Table 3. It can be seen that a good agreement is obtained as all experimental data is well within the standard measurement uncertainty expected.

Table 3 - Experimental test measurement uncertainty

Frequency, Hz	Measurement Uncertainty	
	Standard (dB)	Experimental (dB)
250	± 1.5	$-$ 0.19
315	± 1.5	$-$ 0.02
400	± 1.2	$+$ 0.01
500	± 1.2	$-$ 0.39
630	± 1.2	$+$ 0.04
800	± 1.0	$+$ 0.13
1000	± 1.0	$+$ 0.35
1250	± 1.0	$-$ 0.11
1600	± 1.0	$+$ 0.31

3.2 Interference Cavities

Based on the validated test method, the acoustic performances of the interference cavities were analysed. The first step was to evaluate whether the geometries based on the proposed theory were able to recreate destructive interference to cancel/reduce the sound that is transmitted through the structure.

Since $\delta l/l = 1$ and the cavity length is 17.15 cm; theoretically destructive interference can be expected to occur around a frequency of 1000 Hz. Looking at the results presented in Figure 6, destructive interference can be clearly observed around 900 Hz validating the interference can be created as a function of geometry. The peak sound reduction of 72.47 dB during interference is substantially higher than the linear value clearly making a case for high performance noise abatement devices.

Even though, the results validated the creation of destructive interference, a variation in the frequency from the predicted 1000 Hz to 900 Hz can be observed. Consequently, continued parametric studies are required to improve the theoretical accuracy. The ratio of cavity length to diameter may have an influence in the frequency deviation, further strengthening the requirement of a multi-dimensional approach going forward.

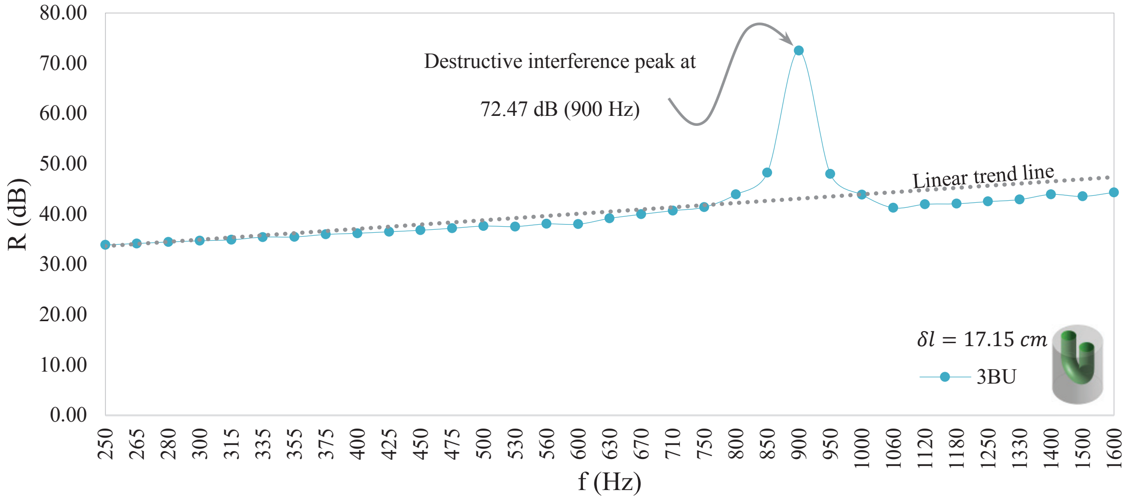

Figure 6 - Sound reduction indices measured for 3BU

In order to study this further, the four diameters considered were 1.5 cm, 2 cm, 2.5 cm and 3 cm named 1.5BU, 2BU, 2.5BU and 3BU respectively. The results for these geometries are presented in Fig. 7. Consistent with previous performances, all geometries featuring the same interference length recreated peak destructive interference at the same frequency of 900 Hz. However, the peak interference noise reduction values seems to vary according to the diameter cavity diameter.

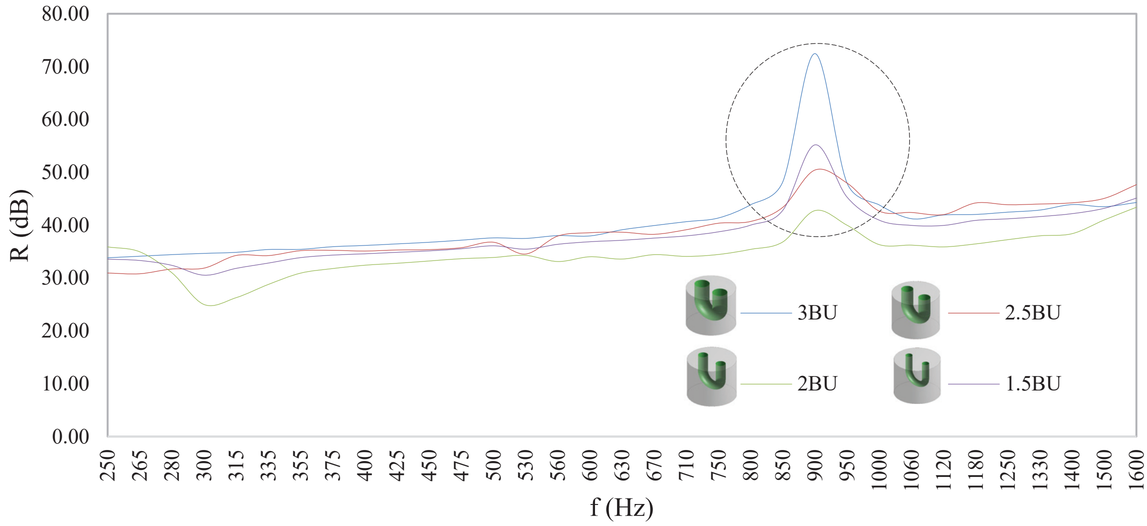

Figure 7 - Sound reduction indices for geometrical cavities with interference length of 17.15 cm

Peak sound reduction values were observed to be 55.22 dB, 42.73 dB, 50.47 dB and 72.42 dB for diameters of 1.5 cm, 2 cm, 2.5 cm and 3 cm respectively. The highest R values under this series of geometries with a δl of 17.15 was observed for a diameter of 3 cm (3BU).

The analysis showed that there is a shift of within $\pm 20\%$ of the predicted frequencies using for a δl of 17.5 cm between the proposed theory and experimental values. In order to incorporate this diversity into a design guideline, the targeted frequency for peak interference is proposed as $0.8f < f < 1.2f$ in conjunction with Eqn. (1). This added boundary represents the frequency where peak interference can be expected to occur. However, it is acknowledged that this study was limited to interference cavities with a ratio $\delta l / l = 1$, and more studies featuring designs where $\delta l / l \neq 1$ is required to further elaborate the suggested theoretical boundary.

Overall, the results are encouraging and establish the proof of concept that interference cavities can be used to develop high efficiency noise abatement devices. The study also helped relate the performance of interference cavities with respect to length and diameter. Additionally, comparative R values that can be expected through employing interference cavities as a function of frequency is also introduced.

3.3 Assumptions and Limitations

The study did not characterise the surface finish of the Nylon 12 geometries created using the SLS process. Consequently, it was assumed that the surface finishes of all the geometries are constant. It is also assumed that the SLS process has generated a homogenous structure for all the 13 prototypes with equivalent material properties.

The study is primarily limited to low frequencies between 250 Hz and 1600 Hz. In addition, only a single inference length is exploited in the samples tested. Consequently, for the research to be applied to potentially reduce broadband noise, further samples consisting of multiple cavities for a range of frequencies need to be designed and analysed.

Finally, the study only looked at interference cavities where the ratio of the interference length to the total cavity length is equal to one ($\delta l/l = 1$). This need to be expanded and cavities with ratios not equal to one need to be explored to create multiple destructive interference hitting more frequencies under a single δl.

4. CONCLUSIONS

This project validated and established the proof of concept regarding the potential of utilising acoustic interference to create noise insulation. Accordingly, strategies to implement inference cavities through design and manufacture of complex geometries combining digital design and SLS are presented. The principle of destructive interference was investigated and validated experimentally through measuring the Sound Reduction Index (R) for a frequency range of 250 to 1600 Hz at 1/12 octaves. It was found that sound reduction of up to 72.47 dB can be expected at 900 Hz. Further analysis found that samples with a diameter of 3 cm resulted in higher sound reduction in comparison with smaller diameters featuring a constant cavity length. A shift in the frequencies where interference peaks occur between theoretical and experimental frequency were observed during the study. In order to represent this as a design guideline the targeted frequency for peak interference theoretically is proposed as $0.8f < f < 1.2f$ in conjunction with Eqn. (1). The study establishes a new view point for the potentials of customizable structures for noise reduction. However, further studies in this area are required for parametric characterisation and to accurately identify the material dependence of the measured R values.

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REFERENCES

1. European Commission Green Paper, Future Noise Policy, Commission of the European communities, Brussels 1996; 540:1-34. 1996; 540.
2. Clark C, Stansfeld SA. The Effect of Transportation Noise on Health and Cognitive Development: A Review of Recent Evidence. International Journal of Comparative Psychology 2007; 20(2).
3. Mason JM, Fahy FJ. The use of acoustically tuned resonators to improve the sound transmission loss of double-panel partitions. J Sound Vibrat 1988 22 June 1988; 124(2):367-379.
4. Mao Q, Pietrzko S. Experimental study for control of sound transmission through double glazed window using optimally tuned Helmholtz resonators. Appl Acoust 2010 1; 71(1):32-38.
5. Idrisi K, Johnson ME, Toso A, Carneal JP. Increase in transmission loss of a double panel system by addition of mass inclusions to a poro-elastic layer: A comparison between theory and experiment. J Sound Vibrat 2009 6/5; 323(1–2):51-66.
6. Shuo-Yen L, Sohei T, Sakae Y, Shinichi S. Improvement of sound transmission loss of double-layer wall by using vibration absorber. Acoustical Science and Technology 2014; 35(2):119-121.
7. RL M, M T, D T. Improvement of sound insulation performance of double-panel structures by using damping materials. Noise Control Engineering Journal 2012; 60:473–480.
8. Arjunan A, Wang CJ, Yahiaoui K, Mynors DJ, Morgan T, English M. Finite element acoustic analysis of a steel stud based double-leaf wall. Build Environ 2013 9; 67:202-210.

9. Arjunan A, Wang CJ, Yahiaoui K, Mynors DJ, Morgan T, Nguyen VB, et al. Development of a 3D finite element acoustic model to predict the sound reduction index of stud based double-leaf walls. J Sound Vibrat 2014 11/24; 333(23):6140-6155.
10. Arjunan A, Wang C, English M, Stanford M, Lister P. A Computationally-Efficient Numerical Model to Characterize the Noise Behavior of Metal-Framed Walls. Metals 2015; 5(3):1414.
11. Arjunan A, Wang C, Yahiaoui K, Mynors M, Morgan T, Nguyen B, et al. Sound frequency dependent mesh modelling to simulate the acoustic insulation of stud based double-leaf walls. Proceedings of the 2014 Leuven Conference on Noise and Vibration Engineering (ISMA2014). 2014.
12. Finite Element Vibro-acoustic Simulation of Roll-formed Steel Studs in Partition Walls. Proceedings of the NAFEMS World Congress 2015; 21-24 June; San Diego, California, USA: NAFEMS; 2015.
13. Fahy FJ, Gardonio P. Sound and Structural Vibration: Radiation, Transmission and Response. : Elsevier Science; 2007.
14. Dijckmans A. Wave based modeling of structure-borne sound transmission in finite sized double walls. Proc.of Euronoise2015, Maastricht 2015.
15. Mak CM, Wang Z. Recent advances in building acoustics: An overview of prediction methods and their applications. Build Environ 2015 9; 91:118-126.
16. Takahashi D, Sawaki S, Mu R-. Improvement of sound insulation performance of double-glazed windows by using viscoelastic connectors. J Sound Vibrat 2016 6/9; 371:56-66.
17. Benoit B, Camastra C, Kenny M, Li K, Romanowski R, Kevin S. Engineering Silence: Active Noise Cancellation. North Carolina State University 2012.
18. James M. Fundamental studies of the Herschel-Quincke tube concept with mode measurements. Virginia Tech 2005(Blacksburg).
19. Poirier B, Maury C, Ville J. The use of Herschel–Quincke tubes to improve the efficiency of lined ducts. Appl Acoust 2011 2; 72(2–3):78-88.
20. Quincke G. Interference apparatus for sound waves (English translation). Ann. Phys. Chem. 1866; 128:177-192.
21. Yongnian Y, Shengjie L, Renji Z, Feng L, Rendong W, Qingping L, et al. Rapid Prototyping and Manufacturing Technology: Principle, Representative Technics, Applications, and Development Trends. Tsinghua Science & Technology 2009.
22. BSEN ISO 10534-2: 2001. Determination of sound absorption coefficient and impedance in impedance tubes, Part 2: Transfer-function method. 2001.
23. Guan G, Hirsch M, Lu ZH, Childs DTD, Matcher SJ, Goodridge R, et al. Evaluation of selective laser sintering processes by optical coherence tomography. Mater Des 2015 12/25; 88:837-846.
24. Material Specification Nylon 12. 2016; MD_NY12_01 Iss2.
25. BSEN ISO 10534-2: 2001. Determination of sound absorption coefficient and impedance in impedance tubes, Part 2: Transfer-function method. 2001.
26. BS EN ISO 10140-1: Acoustics. Laboratory Measurement of Sound Insulation of Building Elements. Application Rules for Specific Products. 2014.