PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Design of lightweight skeletal structures for noise mitigation

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ABSTRACT

Lightweight materials have often been used in transportation vehicles, giving rise to faster and more energy efficient vehicles. Apart from making the materials lighter and stronger, one consideration would be the improvement of the acoustic rating of the material. Effective use of sandwich panels can significantly increase the load bearing capacity and also reduce unwanted noise. This work aims at evaluating the acoustical performance of 3D printed skeletal sandwich panels. A finite element based simulation is performed to understand the acoustical properties of the structure, and the results obtained from simulation is in good agreement with the experimental results. The work reported here shows a great promise for the future applications.

Keywords: Sandwich panels, skeletal structure, sound transmission loss

1. INTRODUCTION

The sandwich panels have often been used for noise mitigation purpose in various applications like vehicles, buildings, rooms, airports, aircrafts, etc. A classical sandwich structure usually consists of a rigid core frame sandwiched between two stiff, robust, and thin facesheets. The sheets are bonded by various means. A variety of core frames such as honeycomb(1), cylindrical, square, corrugated core (2), pyramid lattice (3), etc. is used for the construction of sandwich structures. These structures exhibit some unique properties such as high flexural stiffness, low mass density, and high strength to volume ratio, excellent thermal and acoustic characteristics (2), etc. Acoustic analysis of sandwich panels was first pioneered by Kurtze and Watters (4) and later by Dym and Lang (5, 6). Following these works, a lot of progress has been made in designing of various types of sandwich panels with improved acoustical performance. Hansen (7) investigated the effect of panel size and damping on sound transmission loss of corrugated and fluted (orthotropic) panels. Xin et al. (8) studied the effect of core topology on Sound Insulation performance of lightweight metallic sandwich panels. Recently Meng et al. (2) designed the corrugated sandwich panels for low-frequency noise attenuation. Dannemann et al. (9) utilized a hybrid structure comprising of Helmholtz resonator liners and honeycomb sandwich panels for improved acoustical performance. Liu et al. (3) reported a pyramidal lattice sandwich structure (PLSS). The geometrical parameters were optimized to achieve the optimum sound transmission loss by the structure.

In this work, we presented a unique lightweight skeletal structure as a core frame of the sandwich panel and investigated its noise mitigation characteristics. A variety of structures with different sets of geometrical parameters have been experimentally investigated to improve the sound transmission loss.

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2. Experimental

2.1 Design and fabrication

Figure 1 (a-d) illustrates the design components of the proposed skeletal structure. The skeletal structure is comprised of three parts namely, the front facesheet, the skeletal core, and the rear facesheet. The geometrical parameters used in fabrication of structure is listed in **Table 1**. Samples were fabricated using the Flashforge Creator Pro 3D Printer in two different configurations namely circular shaped structure (diameter 100 mm and thickness 20 mm) and square-shaped structures (60 mm x 60 mm x 20 mm). Polylactic Acid (PLA) filament with a mass density of 1240 kg/m^3 was utilized in the printing of all samples.

2.2 Sound transmission loss measurements

Sound transmission loss was measured using the four microphone-based impedance tube (BSWA) which conforms to ISO 10534-2, ASTM E1050 – 12 and ASTM E2611 – 09 standards. Five consecutive measurements were performed and averaged to increase the signal-to-noise ratio (frequency range: 64-1600 Hz). All experiments were performed in a quiet environment to reduce the effect of unwanted noise. A steel holder as described in previously published article by Ang et al. (10) was used to mount the small square samples (60 mm*60 mm). The sample mounting process is pictorially described in Figure *2*(a-d). A thin layer of pressure sensitive adhesive (blue tack) was used to prevent possible air leakage through the gap between sample and holder (Figure *2*c).

2.3 Numerical simulation

A finite element-based numerical simulation was performed to validate the results. The finite element modelling was carried out using the acoustic-structure interaction module of COMSOL Multiphysics 5.4. The parameters used for air were mass density = 1.213 kg/m^3 and speed of sound = 343.3 m/s. The frequency domain in the acoustics module is governed by the Helmholtz equation (11),

$$Q_m = \nabla\left(-\frac{1}{\rho}(\nabla p_t - q_d)\right) - \frac{p_t k_{eq}^2}{\rho} \tag{1}$$

where, ρ is the mass density which is a complex function. Q_m, q_d are the monopole and dipole source terms (SI unit: 1/s^2 and N/m^3 respectively) k_{eq} is the wave number and p_t is the total pressure field. The maximum element size of the mesh was chosen to be 1/4th of the shortest incident wavelength.

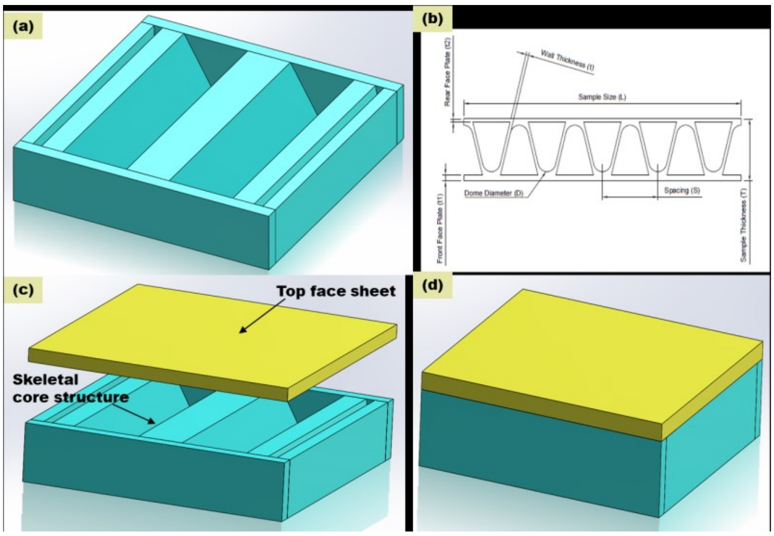

Figure 1 - (a) Schematic of three dimensional square shaped skeletal structure. (b) Nomenclature of the

skeletal structure. (c) Schematics of 3D sample in expanded form showing the skeletal structure sandwiched between face sheets. (d) Representations of 3D sample in assembled form.

Table 1.Parameters for design of modified corrugated structure.

Parameters	value
Sample size (square)	60 mm×60 mm
Sample size (circular)	100 mm dia.
Sample Thickness	20 mm
Wall thickness (t)	1 mm
Front face thickness (t1)	2 mm
Rear face thickness (t2)	1 mm

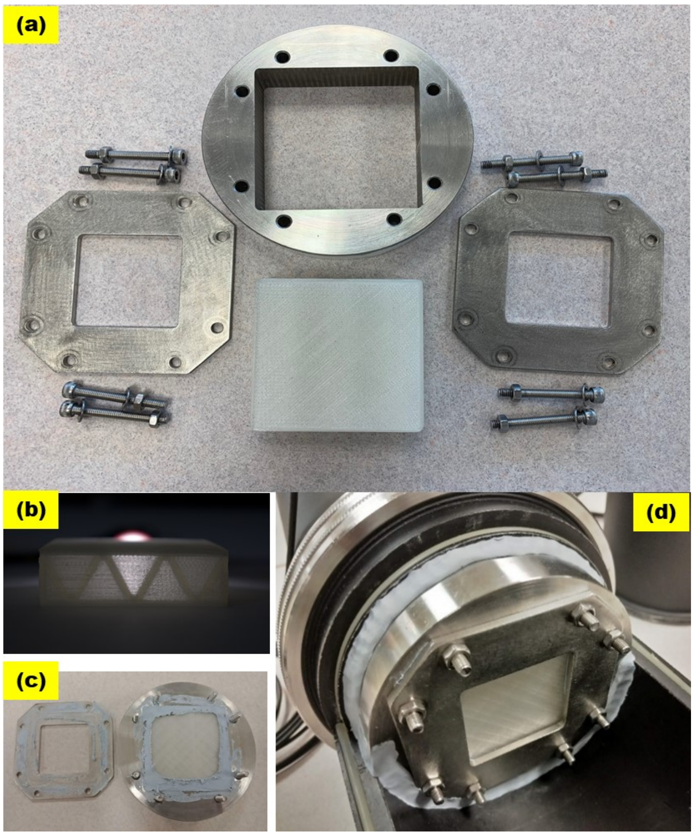

Figure 2 - (a) Photographs of a 3D printed square sample with the sample holder accessories. (b) Photograph of 3D printed sample displaying the skeletal structures. (c) Application of pressure-sensitive adhesive (Blu-Tack) in the gap between outer wall of PLA sample and cavity of stainless steel holder. (d) Sample mounted on the impedance tube for acoustic measurement.

3. RESULTS AND DISCUSSION

3.1 Acoustic properties of the skeletal structure

Figure *3* shows the transmission loss curve of the skeletal structure in the frequency range of 64-1600 Hz. The experimental result exhibits the high sound transmission loss (>45 dB) over a wide frequency range (64-510 Hz and 568 Hz-1370 Hz), while overall sound transmission loss was around 57 dB. The skeletal cavities have resulted in numerous prominent resonant dips at 338 Hz, 538 Hz, 742 Hz, 1016 Hz, 1212 Hz, and 1410 Hz.

In comparison with the experimental results, the simulated transmission loss spectra show similar trends under 800 Hz while there is some mismatch in resonant dip frequencies in higher range. The simulation results confirmed the multiple resonant frequencies resulted from the shape of skeletal structures. However, a slight discrepancy in sound transmission loss values is observed. The higher experimental STL values may be attributed to the surface roughness of 3D printed structure, which further enhances the sound energy dissipations.

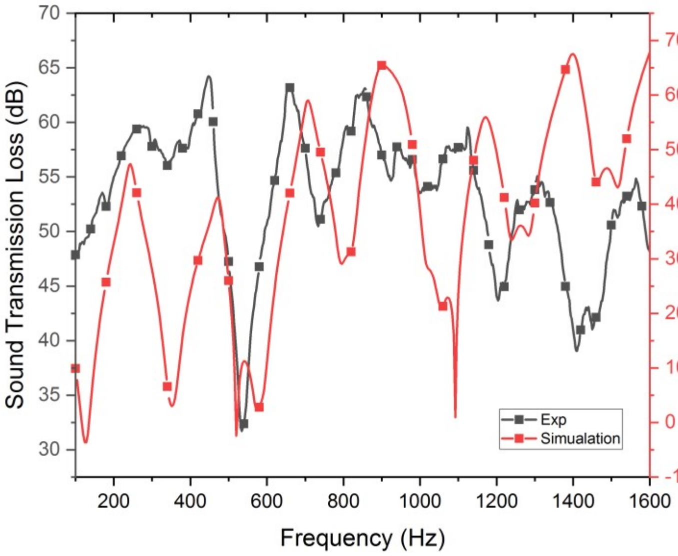

Figure 3 - Sound transmission loss curve of the skeletal structure.

3.2 Influence of geometrical parameters

The acoustic properties of the skeletal structures heavily rely on various factors such as size, shape, orientation, etc. We experimentally studied the effect on sound transmission loss characteristics of the structure by varying multiple parameters. Figure 4(a) shows the impact of sample sizes on the overall sound transmission loss. The trends of both the circular sample and a square sample are similar except a few mismatches in the STL magnitude. It is also worthy to note that the addition of the stainless-steel holder seems to amplify the transmission loss which can be observed at various peaks, while it has no significant impact on the transmission loss properties of the samples. So, it can be discerned that the sample size has not much influence on the acoustic performance of the given structure.

Figure 4(b) shows the effect of trimming of skeletal cavities and can be realized that an improvement in overall sound transmission loss when the corners of the corrugated sample are curved rather than made with an explicit edge. Furthermore, no major improvement in STL values is observed in cases of varying trimming diameters from 8.5 mm to 11 mm except that a slight increase in STL at 500 Hz and 700 Hz Figure 4(c). Figure 4(d) shows the schematic diagrams of skeletal structures with a varying trimming diameters.

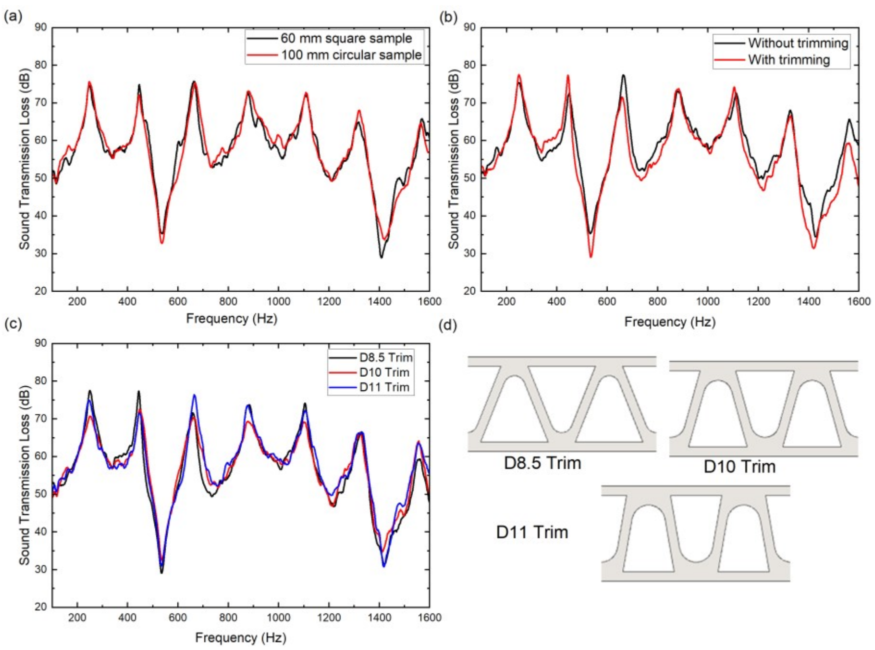

Figure 4 - Influence of experimental settings and geometrical parameters. (a) Effect of sample size, (b) Effect of trimming of samples, (c) Trimming size on overall sound transmission loss, and (d) Schematics of samples with different dome diameters.

4. CONCLUSIONS

In this study, the sound transmission properties of the skeletal sandwich panels are experimentally and numerically investigated. Simulation is performed using the finite element-based COMSOL Multiphysics models. The numerically calculated STL are compared with experimental results, and a good agreement is attained. However, still, there is a mismatch between these two results because of fabrication constraints and can be improved in future studies. Moreover, a variety of designs have been studied and realized a higher sound transmission loss with the lighter structure.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by the grant under the A*STAR IAF-PP (AME Domain) program work package 2 with Project number a1896a0034 on “Manufacturing of Lightweight Free-form Shell, Sandwich, and Hybrid Cellular Structures for Aerospace Component Manufacturing and Repair”.

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