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Heterogeneously perforated honeycomb-corrugation hybrid sandwich panel as sound absorber

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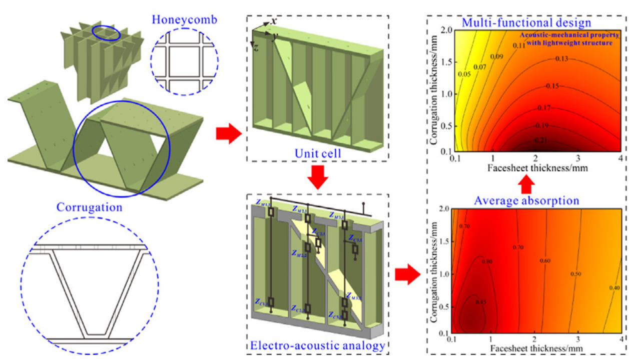
HIGHLIGHTS

- The sandwich panel with perforated honeycomb-corrugation hybrid core is found to be an excellent sound absorber.
- Small perforations on the top facesheet and the corrugation improve sound absorption at low frequencies.
- The structure with thinner honeycomb always performs better for sound absorption at low frequencies.
- The facesheet is more important to the acoustic-mechanical property than the corrugation.
- The Simulated annealing method is found to be effective for the sound absorption optimization of the sandwich structures.

GRAPHICAL ABSTRACT



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ABSTRACT

An ultra-lightweight sandwich panel with perforated honeycomb-corrugation hybrid (PHCH) core is innovated as a novel sound absorber, which demonstrates great sound absorption as well as excellent mechanical performance. Based on the hybrid-cored sandwich panel, small perforations of different diameters distributed heterogeneously on both the top facesheet and the corrugation are introduced to obtain perfect sound absorption at low frequencies with almost no deterioration in mechanical performance. Theoretical models for sound absorption coefficient and bending stiffness are established, then verified by numerical simulations. With specific mass taken into consideration, an integrated index is proposed to further evaluate the acoustic-mechanical property of the hybrid sandwich. It is found that the PHCH with thinner honeycomb always performs better at low frequencies, and the facesheet is more important to the acoustic-mechanical property than the corrugation. This new kind of lightweight sandwich constructions show promising engineering applications, capable of serving as multi-functional structures with great acoustic and mechanical properties at the same time.

1. Introduction

Honeycomb as sandwich core has been demonstrated to be one of the best candidates among lightweight materials and structures for load bearing and energy absorption, both in hexagonal [1,2] and square [3–6] forms. Being a prismatic lattice core as well, corrugation also has

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great specific stiffness and strength. However, the energy absorption capacity of corrugation is relatively low. As a novel kind of lightweight cellular material, sandwich construction with honeycomb-corrugation (H—C) hybrid core exhibits excellent compressive strength and energy absorption capacity, even greater than the sum of the two separated constituents alone.

In addition to mechanical performance, extensive acoustic researches have also been performed on honeycomb-cored sandwich structures. In particular, such structures are able to work well in high temperature and high humidity working environment, which is always the case in the field of aerospace. In 1957, Hickman et al. had studied the sound transmission properties of sandwich-type structure as acoustic windows [7]. Xin and Lu [8–14] demonstrated that honeycomb sandwich panels have great potential in sound isolation. Honeycomb sandwich with perforated facesheet has been widely applied in the engine intake liner to reduce fan noise [15–17], for its heterogenized design in perforation leads to varied Helmholtz resonators distributed over a wide frequency range. Arunkumar et al. [18] showed in a recent study that honeycomb sandwich panel with fiber-reinforced plastic facesheet exhibits enhanced vibro-acoustic and transmission loss characteristics because of high stiffness and inherent damping. Recently, a comprehensive review have been presented on the vibroacoustics of sandwich structures, which contains a great deal of models and experiments to access the excellent acoustic properties of various sandwich structures [19].

On account of its superiority in mechanics and potential in acoustics, the sound absorption behavior of honeycomb-cored sandwich with perforated facesheet also received much attention. In an early study by Wang and Lu [20], the effects of cell size, sample thickness and cavity depth were discussed to characterize the sound absorption property of cellular foams framed in a rigid hexagonal tube. This gives an innovative idea to investigate the absorption performance of micro-perforated panel (MPPs) with partitioning cavities, among which the best choice is honeycomb-cored sandwich with perforated facesheet. Honeycomb-backed MPP absorber was first proposed by Sakagami and coauthors [21], and their study showed that the honeycomb not only stiffened the MPP, but also improved its low-frequency sound absorption performance [22]. Subsequently, Toyoda et al. [23] theoretically analyzed the influence of honeycomb on the absorption peak value and the peak frequency. More recently, Yang and Cheng [24] found that honeycomb backing behaved better for broadband noise control compared with the volume-type MPP absorber, for the inner partitions of the honeycomb destroyed the lateral modes formed in the backing cavity. Besides, researchers also explored the sound absorption performance of parallel assembly of different materials [25] and MPP array with partitioned cavities [26,27], which are very similar to the idea of using honeycomb-backed cavity.

The construction of honeycomb-backed resonant absorbers originates from the traditional MPP proposed first by Maa [28]. Earlier, the MPP was widely used in architectural acoustics for controlling environmental noise, because its simple structure (thin perforated panel with a cavity behind) and the well-developed MPP theory enables relatively easy designs of the acoustic absorbers. However, such absorbers often suffer from narrow acoustic absorption bandwidth, which are insufficient for wide bandwidth noise control. As far as broadband absorption is concerned, further developments in MPPs have been made to extend the absorption frequency range by using series or parallel connection.

Series connection can be realized by installing multi-layer MPP absorbers. Using the electro-acoustic analogy, Zhang and Gu [29] investigated the impedance characteristics of double-layer MPP absorbers. Lee and Kwon [30] studied multi-layer MPP absorbers using the transfer matrix method and compared the theoretical predictions with experimental measurements, with close relation found between the absorption peak number and layer number in a particular frequency band. These studies showed that series connection was able to achieve better absorption over a wide range of frequencies.

An alternative approach toward enhanced broadband absorption is to arrange varied MPP absorbers in parallel or in array so as to combine different bands together. Researchers have explored the mechanism of resonance underlying such absorbers. Huang and coauthors [26] demonstrated that most of the acoustic energy was attracted toward and absorbed by resonant cells in the MPP array, while the non-resonating ones were unimportant. Moreover, the local resonances were in consistent with the resonances of the MPP array, though small shifts could be observed [31]. They made further investigation of the MPP array at oblique incidence and in diffuse field [32], finding a decrease of equivalent acoustic impedance with the increase of the incident angle. As a result, the absorption coefficient of MPP arrays was actually a function of the incident angle.

In this study, honeycomb-corrugation hybrid cored sandwich panel with heterogeneously perforated facesheet and perforated corrugation is proposed as a new kind of sound absorber, as well as lightweight load-bearing structure, which is shown schematically in Fig. 1. A theoretical model for sound absorption under normal incidence based on the acoustic impedance theory of ordinary MPP is established and then verified by full numerical simulations. Subsequently, the effects of key geometrical parameters on sound absorption, such as honeycomb thickness, facesheet thickness, corrugation thickness and total thickness of core, are quantified. Further analysis of facesheet thickness and corrugation thickness are investigated simultaneously by nephogram on average sound absorption in selected frequency range. Afterward, simulated annealing as the optimization algorithm is used to search for optimized average absorption coefficient and the corresponding sandwich configuration. Finally, an integrated index combining the sound absorption coefficient, the bending stiffness and the specific mass is proposed to evaluate the multifunctional potentials of the proposed structure.

2. Electro-acoustic analogy theory

The proposed new sound absorber is shown in Fig. 1(a), which is composed of a perforated top facesheet, a bottom facesheet (without perforation) and a honeycomb-corrugation hybrid core in between (the corrugated panel is perforated). Figs. 1(b) and (c) present separately the schematic diagrams of the perforated corrugation sandwich panel and the honeycomb blocks. Trapezoidal honeycomb blocks with inner length b_2 are precisely cut from a honeycomb panel, then inserted into the interstices of the corrugated plate, forming the H—C hybrid core. Fig. 1(d) presents the three-dimensional (3D) schematic illustration of one unit cell, the top facesheet has six perforations with different diameters $d_{1,1}$, $d_{2,1}$, …, $d_{6,1}$, and the corrugated panel has four perorations with different diameters $d_{2,2}$, $d_{3,2}$, $d_{5,2}$, $d_{6,2}$. Here, the second digit of the subscript refers to the layer number that the perforation belongs to. Note that the first perforation with diameter $d_{1,1}$ is perforated both on the facesheet and the corrugated plate. These small circular perforations on the top facesheet and the corrugated panel are located in the center of each honeycomb block, making them coaxial holes. The top and bottom facesheets have the same thickness t_f, the thickness of the corrugated plate is t_c. With H—C hybrid core thickness D and cell width b_1, the inclination of the corrugated plate can be calculated as $\theta \approx \arctan(D/2b_1)$.

When a plane sound wave is normally incident on the surface of the top facesheet with small perforations, part of the acoustic energy will be absorbed. The absorption coefficient α can thence be defined as the incident acoustic energy absorption ratio in a physical sense:

$$\alpha = 1 - \left| \frac{Z_s - Z_0}{Z_s + Z_0} \right|^2 \quad (1)$$

where Z_s is the total surface impedance and $Z_0 = \rho_0 c_0$ is the characteristic impedance of the air, ρ_0 being the density and c_0 the sound speed.