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Improvement of broadband low-frequency sound insulation of sandwich plates with negative Poisson's ratio butterfly-shaped auxetic cellular

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Abstract

The novel cellular cores auxetic metamaterials with negative Poisson's ratio (NPR) exhibit unique mechanical deformation characteristics compared to conventional cellular cores, which can be further exploited in modeling lightweight sandwich structures. The butterfly-shaped auxetic cellular is not only an improvement upon the traditional re-entrant auxetic cellular with NPR, but also a kind of bionic design, which possesses higher stiffness and thus offers greater potential for sound insulation. Based on this, the present article explores a study of the sound transmission characteristics exhibited by sandwich plates with butterfly-shaped auxetic cellular core layers. Firstly, the motion equation is derived based on the first-order shear deformation theory and Hamilton's principle, which is further solved analytically based on fluid-structure coupling conditions and combined with Navier method. Then, the sound transmission loss (STL) is analytically described. The correctness of the theoretical model is verified by comparing the theoretical solution with the calculation results of the commercial software COMSOL and the experimental results of impedance tube sound insulation tests. Based on the theoretical model, it is calculated that the sound insulation effect of butterfly-shaped auxetic cellular core is better than that of traditional re-entrant cellular with NPR. An analysis is subsequently conducted to explore the impact of key parameters on the STL of the butterfly-shaped cellular sandwich plates.

Introduction

Sandwich panel typically composed of thinner top/bottom panels and lighter sandwich layers. Compared to the traditional single-board structure, the sandwich structure boasts numerous advantages, including high specific strength, robust instability resistance, exceptional bearing capacity, and superior sound insulation performance, and it has found widespread application in various engineering fields such as aviation, high-speed rail, and shipbuilding [[1], [2], [3]]. Taking the high-speed train as an example, it generates various noises that impact passenger comfort during operation [4,5]. The acoustic environment in a high-speed train is an important index to evaluate its comfort, while noise control work is mainly concentrated in the broadband and low-frequency range of 100-2000Hz [6,7]. Given its pivotal role in the sound propagation path, the sandwich panel structure is highly susceptible to excitation by high-intensity broadband sound fields and the subsequent vibro-acoustic response often leads to notable issues related to sound transmission and noise within the vehicle carriage. Therefore, we can rationally design the sandwich plate structure to achieve superior sound insulation in the broadband low-frequency range, thus meeting the comfort requirements of passengers.

Generally speaking, the research on sandwich structure primarily focuses on the core layer because of its significant design flexibility, whereas honeycomb, lattice, ripple and other structures can be used as sandwich core layer. The core layer structure remains a pivotal factor that significantly impacts the acoustic performance of sandwich panels, and extensive research has been conducted on the influence of the sandwich structure in this regard. The sandwich structure with the foam core layer performs well in terms of sound absorption because the foam core has many holes of different sizes [[8], [9], [10], [11], [12], [13]]. Affected by the law of mass [14,15], the lightweight foam core sandwich structure has poor sound insulation performance, and the cellular core sandwich panel has many pores, so the foam as a filler can effectively improve its sound insulation performance. Boztoprak et al. [16] created structures with different densities and voids by filling porous materials in the cellular core layer, and studied their mechanical and STL properties. Apart from porous filling, Gai et al. [17], and Li et al. [18] also researched the STL of different types of cellular core sandwich structures. Li et al. [19] derived the sound transmission theoretical model of trapezoidal sandwich structure with corrugated core layer and its validity is verified by

FEM, then the influence of structural parameters on sound insulation property are studied based on theoretical model. The truss core can be regarded as an open-hole structure with fewer parts connected to the panel, which gives it a good potential for acoustic performance. The investigation carried out by Moosavimehr et al. [20] reveals that the acoustic transmission properties of the sandwich structure with truss core layer significantly surpass those of the traditional cellular core structure, despite having the same weight. Wang et al. [21,22] took the sandwich plate with a pyramid-shaped truss core as the research object, proposed a theoretical model for sound transmission, and verified its correctness through experiments. They also investigated the influence of related parameters on the STL of the sandwich structure. In addition, Li et al. [23] proposed a chessboard-designed Pyramid-core lattice sandwich structures to enhance its out-of-plane vibration isolation performance. Fu et al. [24,25] further researched the acoustic properties of sandwich plates featuring three distinct truss core designs: pyramidal core, tetrahedral coreand 3D-kagome core. Their investigation focused on acoustic radiation characteristics of sandwich under external excitation and their STL when subjected to external airflow.

Traditional cellular core materials exhibit a positive Poisson's ratio (PPR), meaning that when subjected to a transverse load, their axial size decreases. Conversely, cellular core metamaterials with a negative Poisson's ratio (NPR) possess unique mechanical properties; under transverse loading, they undergo an increase in their axial size, earning them the alternative name of 'auxetic materials' [26,27]. Compared with the conventional cellular core, the sandwich structure with NPR cellular core layer has better performance in shock resistance, energy absorption, shock absorption and sound insulation [[28], [29], [30], [31], [32]]. In recent years, scholars have designed and developed many different types of NPR cellular structures then analyzed their performance in various aspects. Jiang et al. [33] proposes a bio-inspired self-similar “concentric auxetic reentrant cellular” and studied its performance from the aspects of specific strength and energy-absorbing in detail. Han et al. [34] proposes an oblique cross structure with NPR effect in a specific direction, extrapolates its equivalent parameters and the relationship between the geometric structure and the equivalent parameters is analyzed. Xu et al. [35] devised three new enhanced star cells and the relationship between geometric parameters and Poisson's ratio is discussed in detail. Zhang et al [36]. devised a cosine type re-entrant NPR structure to improve the stress concentration problem in the deformation of traditional concave structures. Taking the re-entrant anti-trichiral cellular structure as the research object, Hu et al. [37] analyzed its NPR effect under large deformation through two mainstream methods: numerical and theoretical. Xu et al [35] proposed three types of star-enhanced cellular structures, analyzed their mechanical properties through experiments and simulations, and subsequently discussed in detail the relationship between geometric parameters and Poisson's ratio. Gao et al. [38] researched the deformation forms of the double-arrow cellular at different impact speeds and analyzed its energy absorption characteristics in detail. The studies conducted by Li et al. [39] reveal that cellular cores with NPR exhibit superior sound insulation compared to traditional cellular cores with PPR. Kong et al. [40] introduced a NPR arc curve Helmholtz resonator structure to overcome the challenge of achieving optimal low-frequency absorption in traditional absorbing structures at ultra-subwavelength scales for subaqueous low-frequency sound waves. Their research demonstrated that this structure exhibited remarkable sound absorption capabilities within the frequency range of 520-930 Hz. Li et al. [41] conducted a study on the vibro-acoustic response and STL of sandwich plates with a tunable Poisson's ratio (TPR) core under hygrothermal conditions. A review on the progress and application of metamaterials, including those with NPR, in acoustics has been presented by Ji et al. [42] in recent years. In addition, Zhong et al. [43] deliberated on the future development direction of the NPR structural mechanical metamaterials drawing from the current engineering requirements and fabrication techniques, offering profound insights into the potential applications and advancements of these innovative materials.

As evident from the brief literature review, the research of the sandwich panel with NPR cellular core layer mainly focuses on the mechanics aspects, and little attention is paid to its acoustic properties. However, the impact of noise on people's health has attracted more attention in recent years. Therefore, the present study employs the butterfly-shaped auxetic cellular metamaterial to model lightweight sandwich structures, and subsequently investigates its acoustic insulation capabilities. Firstly, the Hamilton's principle is employed to derive the equation of motion control, and the theoretical solution of STL for the butterfly-shaped cellular sandwich structure is formulated by incorporating the fluid-structure coupling condition and Navier's method. Subsequently, the correctness of the proposed model is verified by comparing it with the results obtained through FEM simulations and experiments. Based on the method proposed in this paper, it is calculated that the sound insulation performance of butterfly-shaped auxetic cellular core is superior to that of the traditional re-entrant cellular core with NPR. Finally, taking sandwich plate with butterfly-shaped auxetic cellular core layer as the research object, the influence of key structural parameters on the STL effect is analyzed in detail.

Section snippets

Sandwich plate structure with butterfly-shaped auxetic cellular core layer

Fig. 1 shows the sandwich plate structure with butterfly-shaped cellular core layer considered for the acoustic analysis. In particular, a parametric definition of the structure can be more convenient for the analysis below, h_f represents the height of the top and bottom skin layer, a and b representation the edge length of the structure in the x and y directions, respectively. The height of the cellular core layer is h_c. Additionally, a sound wave P^I, incident on the top surface of the…

Vibration theoretical model for sandwich plate structure

In this study, the displacement field of sandwich structures is defined by the first-order shear deformation theory [47]:

$$U(x, y, z, t) = u(x, y, t) + z\phi_x(x, y, t)$$
$$V(x, y, z, t) = v(x, y, t) + z\phi_y(x, y, t)$$
$$W(x, y, z, t) = w(x, y, t)$$

Where u, v and w denote the in-plane displacement of the middle surface with respect to the x, y and $z$axes, respectively. And the rotational displacement components around the x and $y$axes are represented by ϕ_y and ϕ_x.

The linear transverse and shear strain-displacement relationships of the…

The mathematical model of STL

As presented in Fig. 1, the upper surface of the sandwich plate is affected by plane harmonic sound wave, and the incident sound pressure can be represented as follows: $P^I(x, y, z, t) = P_0 e^{j(\omega t - k_x x - k_y y - k_z z)}$ where $j = \sqrt{-1}$. Considering the simply supported edges conditions, the incident sound pressure can also be represented by: $P^I(x, y, z, t) = P_0 e^{j(\omega t - k_x x - k_y y - k_z z)} = \sum_{m=1}^{M} \sum_{n=1}^{N} I_{mn} \varphi_{mn} e^{j(\omega t - k_z z)}$

Where$\varphi_{mn} = \sin(\alpha x)\sin(\beta x) = \sin(m\pi/a)\sin(n\pi/b)$, P_0 and I_{mn}signify the amplitude of the incident sound pressure. The…

Geometrical parameter and convergence

The goal of this section is to verify the correctness of the formula proposed in this article. In order to better close to engineering applications, the whole material of the sandwich plate is Aluminum 6063-T83, and its material parameters are: $E = 69Gpa$,$G = 26Gpa$,$\mu = 0.33$ and $\rho = 2700kg/m^3$. Besides, the geometric values of the sandwich plate structure are: $a = b =$

$0.5m$,h = $0.012m$ and h_f = $0.002m$. The geometrical dimensions for butterfly-shaped auxetic cellular with NPR are L_1 = L_2 = $0.008m$, L_3 = …

Effect of cellular core types

This section is dedicated to a comprehensive comparison of the acoustic performance exhibited by two distinct types of cellular cores: the traditional re-entrant and the butterfly-shaped. To ensure consistency in the structural parameters of the cellular cores, the structural dimensions of the re-entrant cellular core with NPR are specified as follows: L_{r1} = $2s$ = $0.036m$, $L_{r2} = d/r\cos\gamma = 0.017m$,$t_r$ = $t\sin\gamma$ = $t\cos\gamma_1$ = $0.0026m$and $\theta = \eta = 30°$. The frequency variation curves of STL for two different…

Conclusions

In this paper, the acoustic transmission characteristics of butterfly-shaped cellular core layer sandwich plate with NPR features are studied. Through the presented formulations and the detailed parameters research, some noteworthy conclusions can be summarized as follows:

a) In a broadband low-frequency range of 100-2040 Hz, it was observed that the average STL of the butterfly-shaped cellular core sandwich plate with NPR features increased by 5.71% compared to the re-entrant cellular core…

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CRediT authorship contribution statement

Xinxin Wang: Resources, Software, Conceptualization, Validation, Data curation, Formal analysis, Writing – original draft. **Tao Fu:** Methodology, Conceptualization, Supervision, Project administration, Funding acquisition, Writing – review & editing.…

Declaration of competing interest

The authors declare that there is no conflict of interests regarding the publication of this article.…

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