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Modal density and mode counts of sandwich panels in thermal environments

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ABSTRACT

A theoretical model for calculating the modal density and mode counts of sandwich panels with composite face sheets in thermal environments is presented. Governing equations are derived by applying the Hamilton's principle based on an improved ordinary sandwich panel theory. Modal density and mode counts are calculated using the wavenumber space integration with simply supported and clamped boundary conditions taken into consideration. The accuracy of the proposed model is verified by the finite element model. Thermal effects of both thermal stresses and temperature-dependent material properties on modal density and mode counts are investigated for an aluminum honeycomb sandwich panel with simply supported and clamped boundary conditions. Results indicate that the modal density and mode counts increase with the increment of the temperature. Both of the two effects should be considered in the calculation of the modal density and mode counts of sandwich panels in thermal environments. The proposed model has a wider application scope and can contribute to the prediction of vibration response of sandwich panels in the high frequency range.

1. Introduction

Sandwich panels have been extensively applied in the aircrafts, space vehicles and other industries where the thermal environment is of paramount importance factor to the structures. The evaluation of vibro-acoustic characteristics of sandwich panels is imperative in most applications, especially in thermal environments.

Statistical energy analysis (SEA), a representative energy-based method, is the main theory for the prediction of vibro-acoustic characteristics of structures in the high frequency range [1]. The prediction precision of the method is strongly dependent on the accuracy of the parameters. One of the most important parameters is the modal density of structures, which is defined as the average number of modes per unit frequency.

Research on modal density of sandwich panels can date back to the last century [2–4]. Clarkson and Ranky [2] derived a simple formulation of honeycomb sandwich panels based on a simplified fourth-order governing equation. Experimental research was also conducted by the authors. Renji et al. [5] studied the modal density of honeycomb sandwich panels with composite face sheet used Mindlin's theory in order to include the effects of transverse shear. Effects of shear and orthotropic behavior on modal density are investigated. Soon afterwards, Renji [6] determined the modal density of sandwich panels experimentally, in which both real and imaginary parts of the measured admittance were taken into consideration simultaneously. It is worth noting that the modal density formula of sandwich panels presented by Clarkson [2] and Renji [5] both were derived based on fourth-order governing equations, which neglect the rigidity of face sheets. Recently, Zhou and Crocker [7] investigated the effect of face sheet rigidity on the modal density of sandwich panels based on a sixth-order governing equation, and indicated that the face sheets rigidity was of vital importance for the case of sandwich panels with relative thick face sheets in the high frequency range. However, it was restricted for sandwich panels with isotropic face sheets. Ghinet and Atalla [8] presented a theoretical approach to model the vibro-acoustic behavior of sandwich composite panels, which was developed in wave approach context. Numerical computation of modal density was studied using the dispersion relation solved by the theoretical approach. Chronpoulos et al. [9] calculated the modal density of two dimensional composite orthotropic structures using the dispersion characteristic which was predicted by a wave finite element method. Guillaumie [10] studied the modal density of honeycomb sandwich panels with composite faces based on the formula derived by Clarkson [2] and Renji [5]. Cherif and Atalla [11] investigated the modal density of sandwich composite panels

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experimentally. Results indicated that combining the input mobility method at low frequency and the wavenumber method at mid and high frequency could obtain better results.

Additionally, the effects of boundary conditions on the computation of modal density and mode counts have received comparatively little attention. Bogomolny and Hugues [12] studied the mode counts of a rectangular plate under free, simply supported and clamped boundary conditions. Xie et al. [13] investigated the effects of boundary conditions on modal density and mode counts of one- and two-dimensional structures by applying the wavenumber integration method based on the phase-closure principle [14]. Farshidianfar et al. [15] proposed a new method to obtain mode count and modal density of circular cylindrical shells based on the wavenumber space integration by applying a more accurate equation and taking the effects of boundary conditions into account. Recently, Han et al. [16] proposed a model to calculate the modal density and mode count of sandwich panels based on an improved ordinary sandwich panel theory, which taken account of both the in-plane rigidity of the core and the inconsistent between the principal axes of the orthotropic materials and the axes of the coordinate system. A detailed parametric analysis including the effects of ply angles of face sheets and core, the in-plane rigidity of the core, transverse shear rigidity and boundary conditions on modal density were carried out.

The research on the dynamic behavior and vibro-acoustic characteristics of structures in thermal environments has received increasing attention in recent years. Thermal stresses and temperature-dependent material properties are the two main effects induced by thermal environments. Shiau and Kuo [17] developed a precision triangular plate element to analyze the free vibration of thermally buckled composite sandwich plates. Results showed that natural frequencies of the plate altered due to the change of buckle pattern. Sinha et al. [18] discussed the vibration characteristics of thermally stressed composite skew plate in pre- and post-buckling states. Matsunaga [19] proposed a two-dimensional global higher-order deformation theory to investigate the natural frequencies and critical temperatures of angle-ply laminated composite and sandwich plate under thermal environments. Jeyaraj et al. [20–22] studied the vibration and acoustic response characteristics of an isotropic rectangular plate, a fiber-reinforced composite plate and a multilayered viscoelastic sandwich plate in a thermal environment by numerical simulations combining the finite element with the boundary element method (FEM-BEM). Geng et al. [23,24] analyzed the vibration and acoustic response characteristics of a clamped rectangular plate in thermal environments theoretically, experimentally and numerically. It was indicated that natural frequencies decrease with the increment of temperature. Liu [25] and Li [26] studied the vibration and acoustic response of a rectangular sandwich plate which was subjected to a concentrated harmonic force under thermal environment based on equivalent non-classical theory and simplified piecewise low order shear deformation theory, respectively. The accuracy of the theoretical method was verified by FEM/BEM simulations. Hu et al. [27] proposed a unified kinematic formulation for various sandwich panel theory. They [28] developed a novel finite element for the buckling analysis of sandwich beams. Chen et al. [29] studied the vibration and stability of laminated composite plates. Zhang et al. [30] investigated the thermal effects on high-frequency vibration of beams by applying energy flow analysis. Results of both Chen [29] and Zhang [30] suggested that temperature-dependent material properties should be considered in the vibration analysis of structures in thermal environments.

From the above review, it is found that, lots of literatures have concentrated on the calculation of modal density of sandwich panels. Meanwhile, amounts of studies have been carried out on vibration and acoustic response characteristics of structures in thermal environments. However, few publications are available on the modal density and mode counts of sandwich panels in thermal environments. The aim of the paper is to propose a theoretical model which is able to calculate the modal density and mode counts of sandwich panels in thermal environments considering boundary conditions.

This article is organized as follows: In Section 2, the governing equations of sandwich panels under thermal environments are developed by applying the Hamilton's principle based on an improved ordinary sandwich panel theory, which was used by Han [16]. In Section 3, modal density and mode counts formula of sandwich panels are derived by wavenumber space integration with effects of simply supported and clamped boundary conditions taken into consideration. In Section 4, numerical simulations are performed. The accuracy of the present model is evaluated by comparing with FEM models. After establishing the efficacy of the presented model, thermal effects of both thermal stresses and temperature-dependent material properties are carried out. Summary and conclusions are presented in the sequel.

2. Governing differential equation

The research object of this article is symmetric sandwich panels. Considering a sandwich panel with dimension $a \times b$, which the x -direction is set along the a side of the panel. The thickness of the face sheet and core are d and c, respectively, as depicted in Fig. 1. The material parameters of the face sheet include elasticity modulus E_{f11}, E_{f22}, Poisson's ratio μ_{f12}, shear modulus G_{f12}, thermal expansion coefficient $\alpha_{f11}, \alpha_{f22}$ and mass density ρ_f, respectively. The elasticity modulus, Poisson's ratio, shear modulus, thermal expansion coefficient and mass density of the core are denoted as $E_{c11}, E_{c22}, \mu_{c12}, G_{c23}, G_{c31}, G_{c12}, \alpha_{c11}, \alpha_{c22}, \rho_c$, respectively. It is worth noting that transverse shear in the core is taken into account.

The improved ordinary sandwich panel theory [16] is employed to investigate the modal density and mode counts of sandwich panels under thermal environments. Assuming that the rotation angles of the straight lines which connect the corresponding point at the mid-plane of the top and bottom face sheets in xoz and yoz planes are denoted as $\psi_x(x,y,t)$, $\psi_y(x,y,t)$, and the transverse displacement of any point is $w(x,y,t)$.

According to the linear hypothesis, the displacements of any point in x and y directions in the top $(z<0)$ and bottom $(z>0)$ face sheets can be written as:

$$\begin{aligned} u_{t(b)}(x,y,z,t) &= \pm\frac{c+d}{2}\psi_x - \left(z \pm \frac{c+d}{2}\right)\frac{\partial w}{\partial x}; \\ v_{t(b)}(x,y,z,t) &= \pm\frac{c+d}{2}\psi_y - \left(z \pm \frac{c+d}{2}\right)\frac{\partial w}{\partial y}; \end{aligned} \tag{1}$$

where subscripts t and b represent the top and the bottom face sheet, respectively. The displacements of any point at the interfaces between the face and the core $(z = \pm c/2)$ in x and y directions can be shown as:

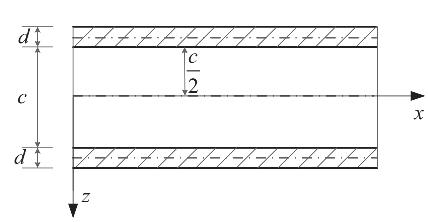

Fig. 1. A symmetric sandwich panel.