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Vibro-acoustic response of a clamped rectangular sandwich panel in thermal environment

Xiangyang Li, Kaiping Yu*, Rui Zhao

Department of Astronautic Science and Mechanics, Harbin Institute of Technology, No. 92 West Dazhi Street, Harbin 150001, People's Republic of China

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ABSTRACT

Composite sandwich structures are extensively applied in the automotive, marine and aircraft industries owing to their superior stiffness-to-weight ratio. This paper is concentrated on the vibro-acoustic characteristics of a clamped rectangular sandwich panel in high temperature environments. The analytical solution of vibration and acoustic responses for the fully clamped boundary condition is derived. Firstly, natural frequencies and corresponding modes in thermal environment are derived using the piecewise shear deformation theory. Thermal buckling temperatures and corresponding modes are obtained to investigate the buckling characteristics of the sandwich panel. The vibration response is acquired by applying the mode superposition method. The sound pressure distribution is derived by applying the Rayleigh integral, and the sound radiation efficiency is obtained in sequence. Sound transmission loss (STL) of the sandwich panel is also obtained in theory. Next, numerical simulations and experimental result are carried out to verify the accuracy of the analytical solutions. Finally, focus is placed on the influence of several key parameters including temperature, boundary condition, thickness of the core and dimension of the sandwich on vibro-acoustic characteristics of sandwich panel.

1. Introduction

Sandwich panels are multi-layered structures which result from the assembly of two face sheets and a core [1], where the face sheet is relatively thin and has high strength and stiffness while the core is comparatively thick and has a low density. Sandwich structures are widely used in automotive, marine and aircraft industries due to their superior stiffness-to-weight ratio and excellent thermal insulation properties. Hypersonic aircraft structure is not only subjected to various mechanical loads, but also exposed to the thermal and noise environment caused by aerodynamic heating and aerodynamics [2–5], and composite and sandwich structures have been widely applied in these aircraft structures. It is of significance for designers to understand the vibro-acoustic characteristics of the sandwich structures in thermal environment and suppress the noise to protect the aircraft systems.

Lots of literatures have been published to investigate the dynamic characteristics of laminated composite and sandwich panels in the thermal environment, including the analytical, experimental and numerical methods. Zhen et al. [6] proposed an efficient global local higher order model for thermoelastic analysis of a laminated composite and sandwich plate taking into account the contribution of the thermal expansion on the transverse displacement component. Matsunaga [7] presented a two-dimensional global higher-order deformation theory for free vibration and stability problems of angle-ply laminated composite and sandwich plates in thermal environment based on the power series expansions of displacement components. Ma and Lee [8] obtained an exact and closed-form solution for the nonlinear static responses of functionally graded beams subjected to a uniform in-plane thermal loading. Frostig and Thomsen [9,10] studied the influence of increasing temperature on the free vibration response of sandwich panels with temperature-dependent material properties by using the high order sandwich panel theory. Frostig and Thomsen [11] presented the geometrical non-linear response of unidirectional sandwich panels with a "soft" core subjected to thermally induced deformation type of loading. Mantari and Granados [12] addressed a thermoelastic bending analysis for functionally graded sandwich panel by applying a new quasi-3D hybrid type higher order shear deformation theory. Kulikov and Plotnikova [13] focused on the application of the method of sampling surfaces to three-dimensional steady-state thermoelasticity problems for composite plates subjected to thermal loading. Khalili and Mohammadi [14] applied an improved high-order sandwich plate theory for the free vibration of sandwich plates with functionally graded face sheets in thermal environment. Houari et al. [15] developed a new higher order shear and normal deformation theory by dividing the transverse displacement into bending, shear and thickness stretching parts to study the thermoelastic bending of a functionally

* Corresponding author.
E-mail addresses: lixiangyang@hit.edu.cn (X. Li), yukp@hit.edu.cn (K. Yu), ruizhao@hit.edu.cn (R. Zhao).

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graded material sandwich plate. Fazzolari and Carrera [16] carried out free vibration analysis of sandwich plates in thermal environment. Liu et al. [17] investigated the stochastic dynamic snap-through response of a thermally buckled composite panel based on the single-mode Fokker-Planck distribution. Pandeyand and Pradyumna [18] presented a layerwise finite element formulation for dynamic analysis of functionally graded material sandwich plates in thermal environment.

Meanwhile, many researchers have investigated the vibro-acoustic characteristics of the vibration structure. Täger et al. [19] presented an analytical model for the calculation of the vibro-acoustic modal frequency, modal damping and modal sound radiation level of composite structures. Petrone et al. [20] presented numerical and experimental investigates on the acoustic power radiated by aluminium foam sandwich panels. Guillaumie [21] studied the vibro-acoustic bending properties of a honeycomb sandwich panel with composite faces. Sahu and Tuhkuri [22] studied the active control of sound power transmission through a sandwich panel by using the volume velocity and weighted sum of spatial gradient method. Sadri and Younesian [23] presented an analytical model to study the vibro-acoustic response of a sandwich structure coupled to an acoustic cavity. Wang et al. [24] used the consistent higher-order approach and two-parameter foundation formulation to obtain STL in symmetric unidirectional sandwich panels with isotropic face sheets. Assaf and Guerich [25] studied the STL through viscoelastically damped sandwich plates based on finite element formulation for the sandwich plate coupled to a boundary element method to account for fluid loading. Wang et al. [26] presented a theoretical study on the STL of unbounded orthotropic sandwich panels considering the transverse shear deformation. Zhou and Crocker [27] presented the experimental and predicted STL obtained by statistical energy analysis for foam-filled honeycomb sandwich panels. They [28] investigated the STL of sandwich panel by using boundary element method. Kim and Han [29] addressed a hybrid analytical and finite element method to predict the STL of sandwich panel that used a finite element approximation in the thickness direction, while analytical solutions were assumed in the plane directions. Hwang et al. [30] studied the prediction model for sound reduction index of double sandwich panels. Cherif and Atalla [31] presented a detailed experimental validation of a general laminate model to predict the vibro-acoustic behavior of flat sandwich-composite panels. Yang et al. [32] addressed a glass fiber assembly-filled honeycomb sandwich panel to improve the acoustic properties.

However, until now, few works have been carried out to study the effects of thermal environment on the vibro-acoustic response of composite and sandwich structures. Jeyaraj et al. [33] presented numerical simulations on the vibro-acoustic characteristics of an isotropic panel in thermal environment using the commercial software *ANSYS* and *SYSNOISE*. It was observed that the displacement of the panel increases with the increment of temperature for all type of boundary conditions. Afterwards, they [34] presented numerical simulations on the vibro-acoustic characteristics of a viscoelastic sandwich panel in the thermal environment. Geng and Li [35] presented an analytical method to study the vibro-acoustic characteristics of a thin isotropic rectangular plate in thermal environment for a simply supported boundary condition. It is noted that the natural frequencies decrease with the increase of temperature and the first order natural frequency is much more sensitive to the temperature load than higher order frequencies. Geng and Li [36,37] studied the vibro-acoustic characteristics of a fully clamped rectangular isotropic plate in a thermal environment using analytical, experimental and numerical method. Liu and Li [38,39] researched the vibro-acoustic characteristics of an isotropic rectangular sandwich panel with a simple supported boundary condition in thermal environment. Li et al. [40,41] proposed a piecewise shear deformation theory and studied the vibro-acoustic characteristic of sandwich panels in thermal environment. Chronopoulos et al. [42] investigated the sound transmission loss and radiation efficiency of the honeycomb sandwich structure in different temperatures. Li [43] studied vibration and sound radiation characteristics of an asymmetric rectangular laminated thin plate by using the first order shear deformation theory. Yang et al. [44] studied the vibration and sound radiation characteristics of a functionally graded plate subjected to thermal environment analytically by utilizing the first order shear deformation theory.

Most of the above analytical, experimental and numerical methods focus on the simple structure with a simple supported boundary condition. For the fully clamped boundary condition, it is usually difficult to get the analytical solution especially for the complex structure such as a sandwich structure. Xing and Liu [45–47] presented a novel method of separation of variables for solving the analytical solution for free vibration of a thin plate with complex boundary conditions such as clamped and free boundary conditions. Li et al. [48] proposed an analytical method for a clamped composite laminated plate. Few analytical methods have been published for the complex structures.

This paper is concentrated on the vibro-acoustic responses of a fully clamped sandwich panel in thermal environment. The objective of this work is to obtain the analytical solution for the vibro-acoustic characteristics of the sandwich panel. The remainder of this paper is structured as follows. In Section 2, the governing equations of the sandwich panel are firstly introduced based on the piecewise shear deformation theory. Then thermal buckling temperatures and natural frequencies of the sandwich panel are obtained using governing equations. Thirdly, vibro-acoustic responses are calculated by applying the mode superposition method and Rayleigh integral. Finally, the STL of the sandwich panel is obtained analytically. In Section 3, the numerical simulations and experimental result are carried out to verify the accuracy of the analytical approach. In Section 4, the effects of temperature on structural and acoustic responses and STL are discussed in detail. Then the effects of boundary condition on structural and acoustic responses are demonstrated. Finally, the effects of thickness of the core and dimension of the sandwich panel on STL are studied, respectively. In Section 5, the final conclusions are presented.

2. Mathematic formulation

The dimension of the panel $a \times b$, and the thickness of the face sheet and the core is d and $2h$, respectively. The material properties of the face sheets are $E_{fx},E_{fy},G_{fxy},\mu_{12},\rho_f,\alpha_{fx},\alpha_{fy}$, and that of the core are $E_{cx},E_{cy},G_{cxy},G_{cxz},G_{cyz},\nu_{12},\rho_c,\alpha_{cx},\alpha_{cy}$. The structural dimensions of the panel and schematic of bending deformation are depicted as Fig. 1.

The linear small deformation hypothesis is employed to describe the elastic behavior of orthotropic face sheets and the core. In this paper, the symmetric sandwich structure is taken into consideration, only the antisymmetric deformation is studied, and neglecting the symmetric deformation of the thin panel. The deformations of the face sheets and the core are separated along the thick direction. Considering the fact that the face sheet is always much thinner than the core, thus the shear deformation of the face sheet can be neglected. The piecewise low order shear deformation theory [40,41] is employed to investigate the vibration characteristics of the sandwich panel.

2.1. Governing equations

Assume that the transverse displacement of any point in the midplane is given as $w = w(x,y,t)$; the rotation angles of the straight line connecting the midpoint of the upper and lower face sheet in *xoz* and *yoz* planes are denoted as ψ_1,ψ_2.

The displacement in x and y direction for any point in the upper ($z > 0$) and down ($z < 0$) face sheets can be easily written as

$$\begin{cases} u_f^{\pm}(x,y,z,t) = \mp\frac{2h+d}{2}\psi_1-\left(z \mp \frac{2h+d}{2}\right)\frac{\partial w}{\partial x} \\ v_f^{\pm}(x,y,z,t) = \mp\frac{2h+d}{2}\psi_2-\left(z \mp \frac{2h+d}{2}\right)\frac{\partial w}{\partial y} \end{cases} \tag{1}$$

The displacements of the core in x and y direction can be expressed as