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Vibration and acoustic responses of composite and sandwich panels under thermal environment

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ABSTRACT

The paper is focused on the vibration and acoustic responses of the sandwich panels constituted of orthotropic materials applied a concentrated harmonic force in a high temperature environment. The natural frequencies together with corresponding modes are obtained under the thermal stresses by applying the piecewise low order shear deformation theory. The critical temperature is derived to prevent the thermal load excess. And the sound pressure distribution is derived by applying the Rayleigh integral. The analytical solution is verified by the numerical simulations. It is observed that the natural frequencies of the sandwich panel decrease with the increment of the temperature. The interchanges of the mode shapes occur because of the material anisotropy. The peaks of vibration and acoustic responses float to the low frequency domain due to the decrement of the natural frequencies. The influences caused by the high temperature environment on the sandwich panels are deeply discussed.

1. Introduction

Hypersonic aircraft are always exposed to the thermal environment in their service life. The thermal environment is a key factor which changes the stiffness of the structural system and alters the dynamic characteristics of the system essentially.

The subject of sound radiation caused by the vibration structures is of great significance. It is imperative that designers understand the mechanism of sound radiation and take effective and economic measures to suppress or eliminate it so that they can improve the quality of the products and protect the facilities.

There are lots of literatures carried out on the structures to reveal the basic characteristics in the thermal environment including analytical and numerical work. At the same time, amounts of studies have contributed to the vibration and acoustic responses of the vibration structures. However, few studies have been done in the field of vibration and acoustic responses of the structures especially for the composite structures under thermal environment.

Jeyaraj et al. [1] utilize simulation methods combining the finite element with the boundary element method (FEM-BEM) to research the vibration and acoustic responses of the isotropic plates in thermal environment by applying the commercial software *ANSYS* and *SYNSOISE*. They find that the natural frequencies decrease while displacement response of the structure increases with the increment of the plate temperature. They also present numerical studies [2] on fiber-reinforced composite plate in a thermal environment using the classical laminate plate theory. It is observed that the resonant amplitudes decrease with the increment of the temperature due to the damping effect. Geng and Li [3] address analytical method to research the vibration and acoustic characters of an isotropic rectangular thin plate under the uniform thermal environment. They get the similar conclusions with Jeyaraj et al. [1]. Furthermore, they also find that the first natural frequency is more sensitive to the temperature changes. Zhao et al. [4] and Geng [3] apply the similar method to investigate the vibration and acoustic response characteristics of orthotropic composite plate with simple supported boundary conditions excited by a harmonic concentrated force in a hygroscopic environment which is similar to the thermal environment. It is observed that the dynamic and acoustic responses and the coincidence frequency increase with the reduced stiffness due to the increment of the moisture content. Geng and Li [5] present an investigation of vibration and acoustic response characters of a clamped rectangular isotropic thin plate in thermal environments. It is indicated that the response curves of plate vibration and radiated sound power shift toward lower frequency range, which is verified with the finite element and boundary element simulations by applying the commercial software *NASTRAN* and *VA one*. Geng et al. [6] demonstrate the experiment to investigate the vibration and

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acoustic response of a clamped rectangular aluminum plate in the thermal environment. They also employ the numerical simulation to study the experimental phenomena, which indicate that the initial deflection has a significant influence on the natural frequencies of the thermal plate.

The analytical, numerical and experimental methods above focus on the simple structural panels. Liu and Li [7,8] investigate the vibration and acoustic response of a rectangular isotropic sandwich plate which is subjected to a concentrated harmonic force or acoustic excitation under thermal environment. The equivalent non-classical theory [9] is employed to obtain the governing equation under thermal environment. However, their analytical solution will deviate from the true solution for the soft core and cannot be suitable for the composite materials. It is well known that sandwich panels are component of the two high strength face sheets and one soft-light core which aims to decrease the structural mass. The face sheets are typically made of metal or composite laminate and the core is consisted of lightweight materials such as foams.

Di Sciuva [10] develops the non-linear equations of motion for thick multilayered orthotropic plates based on a piecewise linear displacement field which is a linear zigzag displacement-based model. Furthermore, he applies this model to the linear problems of bending, free vibration and buckling load of multilayer composite plates. Later, Di Sciuva [11] addresses a third-order shear deformation plate model with continuous inter-laminar stresses. Di Sciuva proposes several finite element methods [12–14] on the basis of the linear and third-order zigzag models. However, C^1-continuous is required to approximate the deflection for these methods. Xiaohui and Wenji [15] address an improved C^0-continuous finite element for free vibration analysis of laminated composite and sandwich plates by applying a third-order zigzag model. Tessler et al. [16,17] propose a refined zigzag theory which includes the kinematics of first-order shear deformation theory as its baseline for composite beams and plates. One important benefit is that this improved zigzag theory adapts itself well to finite element approximations. It is suited for the development of computationally efficient, C^0-continuous finite elements [18,19]. Iurlaro et al. [20] present the derivation of the non-linear equations of motion and consistent boundary conditions for multilayered plates by applying the improved zigzag model. Subsequently, the equations are simplified and specialized to the linear boundary value problems of bending, free vibrations and buckling.

Brischetto et al. [21] address a high order sandwich panel theory by applying the zigzag function, which lies in the fact that it introduces a discontinuity in the first derivative of the displacements in the core–face interfaces. Frostig et al. [22] propose two types models for describing the governing equations of the core, which take the core's compressibility into consideration and enhance the accuracy of the theories. Noor et al. [23] present a review of sandwich structures and summarize various models including the advantages and problems.

Wu Zhen and Chen Wanji [24] address a global–local higher-order theory to investigate the free vibration of laminated composite and sandwich plates. This theory can satisfy the geometric and stress continuity conditions in interfaces, but the number of unknown variables is independent on the layer numbers of the laminate. Later, Wu Zhen et al. [25,26] develop a C^0-type higher-order theory for bending analysis and an accurate higher-order C^0 finite element theory for free vibration analysis of laminated composite and sandwich plates.

Additionally, the widely used methods also include the high and low order shear deformation theories proposed by Frostig [27–30] for the sandwich panels to make vibration analysis, which consider the compressibility of the core.

However, most of the theories above are complicated when the pre-stress is considered under thermal environment, let alone the analysis of the acoustic response.

Xiangyang et al. [31] present a piecewise shear deformation theory which has five unknown variables including the shear deformation of the face sheets. However, the face sheet is much thinner than the core in generality; thus, its shear deformation can be neglected. Therefore, the fundamental unknown variables can be degraded to three, namely, the transverse displacement of the mid-plane plane and the rotation angles of the straight line connecting the midpoint of the upper and lower skins in *xoz* and *yoz* planes. The simplification of the equations makes it probable to solve the equations under the thermal environment. Subsequently, the analysis of the vibration and acoustic responses of the sandwich panels can be expected to be completed.

Sandwich structures have been extensively used in aerospace, automobile and other industries because of its specific strength and stiffness and other advantages. Therefore, it is of great importance to make an intensive research on the vibration and acoustic characters of the sandwich structures component of composite material in high temperature environment.

The aim of the paper is focused on the vibration and acoustic responses of the sandwich panels constituted of orthotropic materials applied a concentrated harmonic force in a high temperature environment. Firstly, the free vibration of the sandwich panels with the in-plane forces induced by thermal effects is analyzed using the piecewise low order shear deformation theory, and the sound pressure distribution is derived by applying the Rayleigh integral. Secondly, the numerical simulation is employed to validate the accuracy of the analytical solution. Finally, the influences caused by the high temperature environment on the sandwich panels are deeply discussed.

2. Theoretical formulation

Consider the dimension of the panel $a \times b$, the thickness of each skin is d, whose material parameters are $E_{fx}, E_{fy}, G_{fxy}, G_{fxz}, G_{fyz}, \mu_{21}$, $\mu_{12}, \rho_f, \alpha_{fx}, \alpha_{fy}$. The material properties of the core, which has the thickness of $2h$, include the modulus, Poisson's ratio, density and thermal expansion coefficient $E_{cx}, E_{cy}, G_{cxy}, G_{cxz}, G_{cyz}, \nu_{21}, \nu_{12}$, $\rho_c, \alpha_{cx}, \alpha_{cy}$. The structural parameters of the sandwich panel are indicated as the Fig. 1.

2.1. Governing equations

The piecewise low order shear deformation theory [31] is employed to investigate the vibration characters of the sandwich panels. Assume that the transverse displacement of any point in

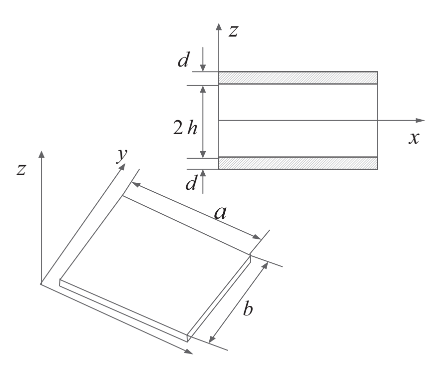

Fig. 1. Structural dimension of the sandwich panel [31].