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Original Research Article

Analytical and experimental investigation on the free vibration of a floating composite sandwich plate having viscoelastic core

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ABSTRACT

This paper focuses on the free vibration analytical solution of a composite sandwich plate consisting of woven carbon laminated faces and a viscoelastic foam core. In addition to the dry condition, a case of floating on bounded water is considered for the sandwich plate not only in analytical work but also in verification experiments. The equations of motion for the first-order shear-deformation plate in contact with the fluid are derived by using Hamilton's principle, and analytically solved using Navier's procedure. Bounded water boundary conditions and velocity potential function are used to describe the fluid motion. The viscoelastic properties of a marine PVC foam core are extracted from dynamic mechanical analysis. Frequency response function (FRF) method is applied in modal testing for measuring the natural frequencies of the dry and wet sandwich plates. Experimental results demonstrate the validity of the analytical results. The effects of the foam core behavior, core thickness, plate dimension ratio, and the fluid density on the natural frequencies are examined and discussed. The decrease of the fundamental mode natural frequency with the presence of the viscoelastic foam core is more prominent for the dry sandwich plate with respect to the wet one already damped by water.

1. Introduction

Lightweight composite sandwich panels are widely used as the main load-carrying body of aerospace, civil, and marine vessels. Composite sandwich plates consisting of two thin stiff composite faces and a thicker flexible core layer show proper behavior under bending due to an increased flexural stiffness. In addition, significant viscoelastic behavior of sandwich plates helps the damping of vibration and noise. The viscoelastic behavior of the sandwich plates is mainly due to their flexible core material. Several different materials used for sandwich core in marine applications like PVC foams are known to be viscoelastic materials having time- and frequency-dependent properties. The viscoelastic behavior of the core material decreases the natural frequencies of the sandwich plate in free vibration. On the other hand, the composite

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sandwich body of a marine structure may have different natural frequencies in and out of water, known as dry and wet natural frequencies. The decrease of the natural frequencies is attributed to the effect of the added mass of water.

The free vibration of composite sandwich plates has been studied in the previous works. Cupial and Niziol [1] numerically calculated the natural frequencies and loss factors for a plate assuming simplified viscoelastic properties for the core layer only in a dry condition. Kant and Swaminathan [2] derived an analytical solution to the natural frequency analysis of simply supported dry sandwich plates considering only elastic behavior for the face and core materials. A discrete layer annular finite element was employed to derive the equations of motion for a three-layered annular dry sandwich plate with a viscoelastic core layer by Wang and Chen [3]. Kim [4] examined the dynamic behavior of dry composite laminate plates undergoing moderately large deflection by considering the viscoelastic properties of the material. Xu et al. [5] presented a simplex optimization analysis method of dry metal structures with simple viscoelastic dampers. Chen [6] analyzed the non-axisymmetric vibration and stability problem of the rotating dry sandwich plate with a simple viscoelastic core layer by using the finite element method. Civalek [7] developed a discrete singular convolution method for the vibration analysis of moderately thick symmetrically dry composite laminate plates based on the first-order shear deformation theory.

The first-order shear deformation theory (FSDT) has been found to yield accurate results in the non-local problems of sandwich structures, such as buckling and free vibration [8]. A comparison between higher-order and first-order shear deformation theories for analyzing dry laminated composite stiffened plates was presented by Bhar et al. [9] using the finite element method. They clearly showed that the higher-order shear deformation theory tenders very close results with first-order shear deformation theory for un-stiffened even thick laminated composites. However, Bhar et al. [9] found significant differences between these two theories for stiffened composite laminates which was attributed to the realistic variation of transverse shear through the thickness due to the presence of the stiffeners. Several works have reasonably used the first-order shear deformation theory for polymeric laminated composites as well as functionally graded shells enhanced with composites, not only as flat plates [10] but also as annular ones [11].

Dynamic response of orthotropic viscoelastic laminated composite plates was investigated by Assie et al. [12] using an efficient numerical algorithm in time domain. Mahmoudkhani et al. [13] studied the free vibration and transverse response of dry sandwich plates with viscoelastic cores under wide-band random excitations. Kramer et al. [14] investigated the effects of material anisotropy and added mass on the free vibration response of elastic cantilevered composite laminate plates via combined analytical and numerical modeling. Yang et al. [15] experimentally investigated vibration and damping performances of composite pyramidal truss sandwich panels with viscoelastic layers embedded in the face layers. Khorshid and Farhadi [16] analyzed the vibration of an elastic composite laminate plate in contact with a bounded fluid.

Due to the lack of the analytical solution, the effect of the compressible flow on composite as well as functionally graded plates has been numerically examined [17]. The free vibration of isotropic viscoelastic plates on viscoelastic medium was analytically investigated by Kiasat et al. [18]. Avcar [19] examined separate and combined effects of rotary inertia, shear deformation and material non-homogeneity (MNH) on the values of natural frequencies of the simply supported beam. Yang et al. [20] provided a unified yet accurate solution for vibration and damping analysis of simple viscoelastic and functionally graded dry sandwich plates with arbitrary boundary conditions. Finally, Kahya and Turan [21] presented a finite element model based on the first-order shear deformation theory for free vibration and buckling of functionally graded beams.

In the present work, a composite sandwich plate consisting of woven carbon laminated faces and a low density PVC foam core is subjected to an experimental modal analysis. The measurements are done on a free-free square sandwich plate in both dry and wet conditions so that only one side of the plate is in contact with water. Frequency response function (FRF) method is applied to extract the natural frequencies of the sandwich plate. On the other hand, the equations of motion for the first-order shear-deformation plate coupled with the irrotational bounded water are analytically solved using Navier's solution to obtain the natural frequencies. The viscoelastic properties of the PVC foam core including master curves for the relaxation moduli are experimentally extracted using dynamic mechanical analysis as in our recent work on compound materials [22]. The analytical solution of the equations of motion introduces direct relations between the natural frequencies and the mechanical and physical properties of the sandwich and water, applicable in the modern sandwich marine vessels. Experimental results demonstrate the validity of the analytical results. The effects of the core viscoelastic properties and thickness, plate dimension ratio, and fluid density on the natural frequency are examined and discussed.

2. Equations of motion and analytical solution

The governing equations for the free vibration of a thick sandwich plate are derived using the first-order shear-deformation plate theory. The ratio of the thickness to the side length of sandwich plates is usually more than 1–15, and thus the shear deformation during bending causes a significant deviation from simple plate theory. On the other hand, no discontinuity is assumed to exist at the interfaces between the core and the laminate face layers. For small-amplitude vibration of symmetric sandwich plates considered in the present work, no interface failure or delamination, and no deviation of the neutral plane is expected. Furthermore, the core material is regarded to be viscoelastic having frequency-dependent storage and loss moduli which results in a significant damping behavior of the sandwich plate. Because of the presence of stiff fibers in the composite laminates, the faces show negligible viscoelastic behavior, and thus the laminates are assumed to be elastic.