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Effect of core thickness on wave number and damping properties in sandwich composites

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ABSTRACT

Due to their higher strength-to-weight and stiffness-to-weight ratios compared to metals, fiber reinforced composite materials are a great alternative for use in many structural applications. However these properties lead to poor acoustic performance as composite materials are excellent noise radiators. This is particularly true for sandwich composite structures. Therefore the focus of this study is to investigate the effect of a core thickness change on the vibrational properties of Rohacell foam/carbon-fiber face sheet sandwich composite beams. Four different foam core thicknesses were explored, using a combination of experimental and analytical methods to characterize sound and vibrational properties of the sandwich beams. First, the wave number responses of the beams were obtained, from which coincidence frequencies were identified. Second, from the frequency response functions the structural damping loss factor, η, was determined using the half-power bandwidth method. Experimental and analytical results show that the relationship between core thickness and coincidence frequency is non-linear. A drastic increase in coincidence frequency was observed for the sandwich beam with the thinnest core thickness due to the low bending stiffness. Moreover this low bending stiffness results in low damping values, and consequently high wave number amplitude responses at low frequency ranges (<1000 Hz).

1. Introduction

Conventional fiber reinforced polymer composite materials are widely used in various engineering applications, such as civil, aerospace, automotive and alternative energy due to their superior mechanical performance over metallic materials. However while composite structures combine high stiffness and strength at a low weight, they offer poor acoustic properties by radiating noise at low vibrational frequencies. This is especially the case in sandwich composite structures due to their high stiffness-to-weight ratios. Therefore a considerable interest has been taken in studying the acoustic properties of sandwich structures in order to improve their performance in the aforementioned engineering applications. The current state-of-the-art to improve acoustic performance involves adding additional sound absorbing material to the structures. However, this results in an increase in mass, defeating the purpose of using sandwich composites for their high stiffness-to-weight ratio. In many applications, such as aerospace and automotive, this increase in weight leads to an increase in cost, as well as fuel consumption, yielding in an increase in carbon emissions. Therefore there exists a technical challenge, which involves improving acoustic performance without sacrificing structural performance or weight.

Studies have been performed regarding the understanding of wave-speed characteristics and transmission loss for sandwich composites [1–11]. By analyzing the wave number characteristics, the coincidence frequency of a structure can be determined. The coincidence frequency defines a unique frequency where the vibrational waves become supersonic, and consequently above that frequency the structure will begin to radiate noise. Thus an increase in coincidence frequency can yield an improvement in acoustic performance by increasing the frequency range in which noise does not radiate. Existing analytical models can yield a fundamental understanding as to how the material properties of the face sheets and core affect the wave number characteristics. However these models do not provide an insight into the amplitudes of the wave numbers, which will be proportional to noise radiation level, nor identify the coincidence frequency for a sandwich beam. Although the wavenumber characteristics are important to understand the acoustic performance, only a few studies have been found in the area. He and Gmerek [7] have performed Statistical Energy Analysis (SEA) along with experiments to obtain wave number characteristics including the amplitudes and the coincidence frequencies for sandwich beams.

Besides obtaining the wave number characteristics of a beam from a vibrational response, one can also obtain information

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Table 1
Properties of core and face sheet materials.

Material	Longitudinal modulus (E_1, GPA)	Shear modulus (G_{13}, MPa)	Density (kg/m^3)
Carbon fiber–epoxy face sheet	100	N/A	1600
Rohacell 51–WF core	7.5E−2	24.6	52

Table 2
Dimensions of sandwich composite beams.

Beam type(face sheet, Core)	Length (mm)	Width (mm)	Face sheet thickness (mm)	Core thickness (mm)
Carbon fiber with Rohacell	505	25.4	0.381	5.9
Carbon fiber with Rohacell	505	25.4	0.381	8.5
Carbon fiber with Rohacell	505	25.4	0.381	10.7
Carbon fiber with Rohacell	505	25.4	0.381	18.4

regarding the structural damping properties. Improved damping properties may lead to reduction of vibratory loads, increased fatigue life of structural components, and diminished noise. For these reasons it is important to design sandwich composite structures with high levels of inherent damping for a variety of structural applications. Considerable effort has been made to investigate structural damping loss factors for sandwich beams [12–19]. Key findings from the earlier works include that loss factors are frequency dependent, as well as determined by the overall beam bending stiffness and core properties. Nilsson [8] reported that loss factors have either a minimum or maximum value depending upon the individual loss factors of the sandwich beam's face and core materials. The damping properties are often closely related to the acoustic performance of a structure. Although it would be important to understand these structure–property relationships, only little work has been done in addressing it.

Here, the focus of this work is to investigate the effect of a core thickness change on the wave number and damping properties as well as the relationship between the two vibrational responses via a combination of experiments and analytical modeling. Such an understanding of the structure–property relationship in sandwich composite materials can add promise for lightweight composite structures with both enhanced acoustic and damping performance, which still remains uncompromised in mechanical performance.

2. Experiments

2.1. Materials and fabrication

This study involves the use of sandwich composite beams with carbon fiber–epoxy tapes as the face sheets, and Rohacell 51 WF foam as the core. The carbon fiber–epoxy tape is a two-ply, 0–90° composite laminate, while Rohacell is an isotropic, polymethacrylimide foam. Both commercially available materials were provided by The Boeing Company, which are manufactured by the M.C. Gill Corporation, and are commonly used in sandwich composite fabrication. Note that fully cured carbon tapes were provided, and thus no further curing process was necessary in this study. More detailed information regarding the curing conditions of the carbon fiber–epoxy tape can be found from the M.C. Gill Corp [20]. Table 1 shows the properties of the Rohacell core and carbon fiber–epoxy tape, while Table 2 gives the dimensions of the beams which were used in this study. The longitudinal (along the length of the beam) modulus (E_1) shown in Table 1 is the effective laminate modulus. The dimensions of each beam were kept the same with the exception of the core's thickness, which had a value of 5.9 mm, 8.5 mm, 10.7 mm, or 18.4 mm. When bonding the face sheets with the core, a symmetric sandwich structure is fabricated (0–90°-core-90–0°).

Since the carbon fiber tapes were supplied fully-cured, the fabrication process required cutting the Rohacell and carbon fiber tapes to desirable dimensions, then using Loctite 1C-LV epoxy to bond the face sheets with the core. Since a properly and fully cured bond between the face sheets and core is important, the beam was kept under vacuum pressure in a vacuum bag while the adhesive epoxy was curing for at least 48 h. This ensured that adequate, uniform pressure was applied across the beam during the bonding process, until the Loctite epoxy was fully cured.

2.2. Wave number measurement

The wave number analysis involves taking the frequency response function of a random vibration, measured at 64 equidistant points along the beam, and transforming it into the wave number domain using a Fourier transform [7]. Once transformed using MATLAB, the data can be analyzed in a surface plot, which plots wavenumber (k) and frequency (ω) vs. amplitude (output acceleration in G's/input force in lbf). If one looks at the contour plot of the surface, a dispersion plot can also be obtained. Note that the relation between wavenumber (k), frequency (ω), and wave speed (c) are shown in Eq. (1).

$$k = \frac{\omega}{c} \tag{1}$$

In order to find the coincidence frequency, one must add the speed of sound in air with the dispersion plots. Data points above this line represent where the vibrational wave speeds are sub-sonic, while data points below are supersonic. Thus finding the frequency at which the speed of sound and the dispersion plot data intersects yields the coincidence frequency [7,11].

The experiment setup involves imposing a clamped–clamped condition on the beams; see Fig. 1 for a schematic. The clamps were placed upon silicone rubber pads, which are attached to a vibration isolation table to ensure outside, undesirable vibrations were mitigated. The electrodynamic shaker (Labworks LW126-25 System with PA141 Shaker) was also placed upon vibration isolation pads and securely fastened to the table. An impedance head is attached to the shaker to measure the input force, which was used to normalize the frequency response function. The shaker was excited with a random noise signal ranging from 20 to 4000 Hz. A micro-accelerometer, with a mass of 0.6 g, was used to measure the frequency response function at the equidistant points along the beams investigated in the study. The software of Vibration View (Vibration Research Corporation) was used to excite the shaker and record the data.

In order to verify the accuracy of the experiment setup, a 6061 aluminum beam was tested as a reference beam under random vibration. The dimensions of this aluminum beam were 482.6 mm in length, 25.4 mm in width, and 2.29 mm in thickness. The results almost identically match those found in literature [7] as well as Eq. (2), which calculates the coincidence frequency for an isotropic, homogenous material [11].

$$f_c = \frac{c^2}{2\pi\sqrt{K}} \tag{2}$$

$$\text{where } K = \frac{Eh^2}{12\rho(1-\nu^2)}$$