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VIBROACOUSTIC CONTROL OF HONEYCOMB SANDWICH PANELS USING MFC ACTUATORS

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Abstract

New all-composite aircraft fuselage designs are being developed with a flexible honeycomb core sandwiched between carbon fiber reinforced composite laminate face sheets. The honeycomb sandwich panels offer potential advantages for significant weight reduction, while maintaining strength and fatigue properties. However, the excessive levels of vibration and noise of honeycomb sandwich panels have been a major cause for concern. Thus, vibration suppression and noise reduction in honeycomb sandwich panels pose major challenges for future aircraft design.

In this research, vibroacoustic characteristics of honeycomb sandwich panels are experimentally examined in order to develop efficient and reliable vibroacoustic control mechanisms. The experimental measurements of vibroacoustic characteristics of honeycomb sandwich panels are validated using finite element model. Macro Fiber Composite (MFC), a newly developed piezoelectric actuator by the NASA LaRC, is typically directional or anisotropic, and more flexible and conformable as compared to a traditional monolithic isotropic piezoceramic actuator. The honeycomb sandwich panel is proposed as a test platform to demonstrate the effectiveness of MFC actuators in vibration suppression and noise reduction of honeycomb sandwich panel.

Analytical prediction as well as experimental investigation are implemented to evaluate the effectiveness of vibroacoustic control of honeycomb sandwich panel with MFC actuators. The velocity feedback controller are utilized to determine appropriate voltage of the MFC actuators. The experimental results show 43% and 45% attenuation of first and second vibration modes with 25V and 40V velocity feedback voltages, respectively. Moreover, the results also demonstrate 72% attenuation of first mode of radiating noises with velocity feedback. The study suggests that using the MFC actuators in vibroacoustic control of honeycomb sandwich panel has been highly effective.

1. INTRODUCTION

Honeycomb sandwich structures have high strength-to-weight and stiffness-to-weight ratios. They can withstand high service stresses and severe environmental conditions. Increasing numbers of aircraft and military structures are being replaced by honeycomb sandwich, for example, honeycomb materials have been used for noise damping applications in modern jet engines, and actively cooled honeycomb structures may be the basis of wing and fuselage design. Thus, in recent years, the vibration and noise control of honeycomb sandwich plates are draw much attention by many researchers. [1-9]

Two enhanced-performance piezoelectric actuators have received much attention in the literature. These two are the Macro-Fiber Composite actuator (MFC) developed by NASA Langley Research Center and the Active Fiber Composites actuator (AFC) introduced by Hagood and Bent, as shown in Figures (1) and (2). The new high-performance MFC/AFC actuators employ interdigitated electrodes and utilize the high d_{33} piezoelectric charge constant, which is normally two times greater than d_{31}; whereas, the traditional monolithic piezoceramic actuators utilize d_{31}. Moreover, the newly developed actuators are, particularly, directional or anisotropic as well as more flexible and conformable than traditional monolithic isotropic piezoceramic wafers. The MFC actuator is similar to its AFC counterpart because both consist of the same three primary components: active piezoceramic fibers aligned in a unidirectional manner, interdigitated electrodes, and an adhesive polymer matrix. However, the rectangular fibers, which are exclusive to the MFC actuator, have greatly enhanced the manufacturing process and the performance of the actuator.

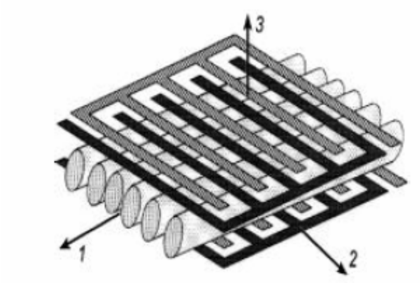


Figure (1) – AFC actuator

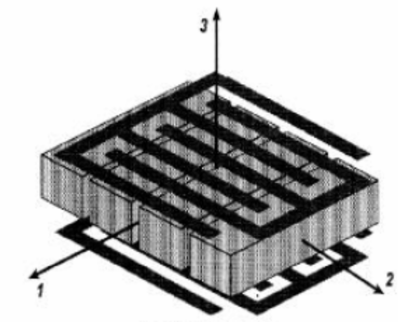


Figure (2) – MFC actuator

2. DYNAMIC ANALYSIS OF HONEYCOMB SANDWICH PLATES

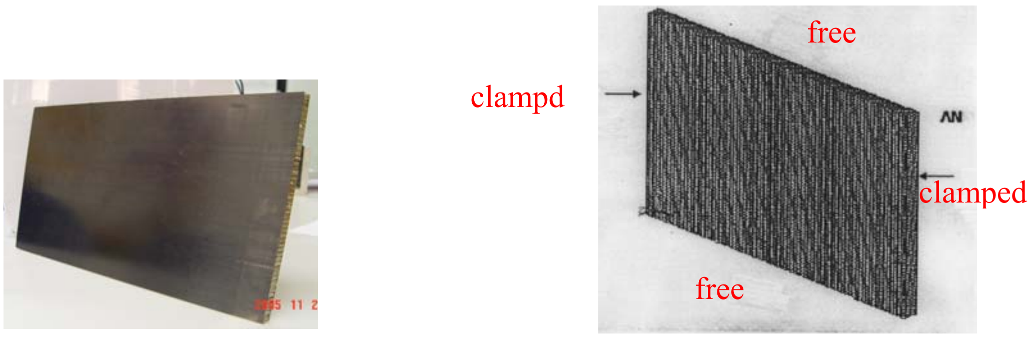
2.1 Overview

In order to theoretically and experimentally analyze the structural dynamic characteristics of the honeycomb sandwich plates, the finite element method and experimental modal analysis, are performed in this study. The dynamic characteristics of the honeycomb sandwich plates in question include the natural frequencies, modal damping and mode shapes.

2.2 Dynamic Characteristics of Honeycomb Sandwich Plates

The honeycomb sandwich plates as shown in Figure (3a) are constructed with a flexible honeycomb core sandwiched between carbon fiber reinforced composite laminate face sheets. The thickness of the core is 1.27cm. The face sheet is constructed by 3 carbon fiber layers with 0°/90°/0° oriented angle arrangement. The thickness of the face sheet is 0.51mm. The honeycomb sandwich plate is evaluated with a CFCF boundary condition. The geometry of the honeycomb sandwich plate after applying clamped boundary is 30cm x 30cm.

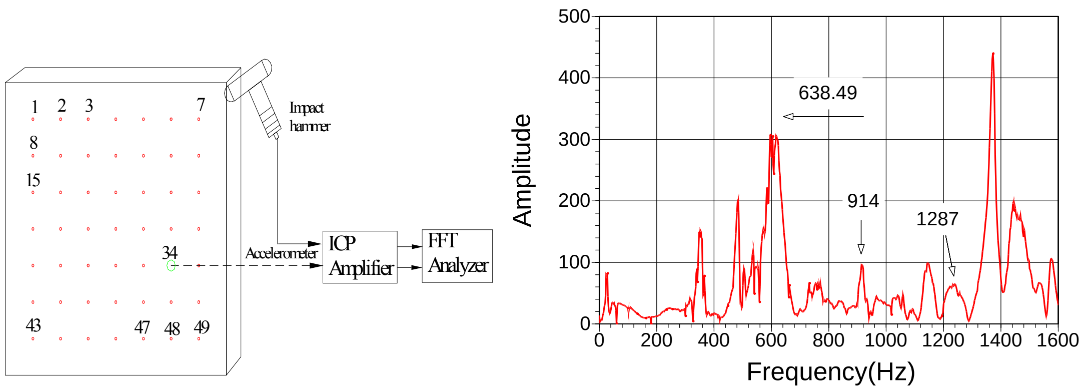
Figure (3b) shows the finite element modelling of the honeycomb sandwich plate using finite element software, ANSYS. The first three frequencies corresponding to flexural vibration of the FE model are 722.92Hz, 835.13 Hz and 1414.5 Hz.



(a) (b)

Figure (3) –honeycomb sandwich plate, (a) the picture and (b) the finite element model.

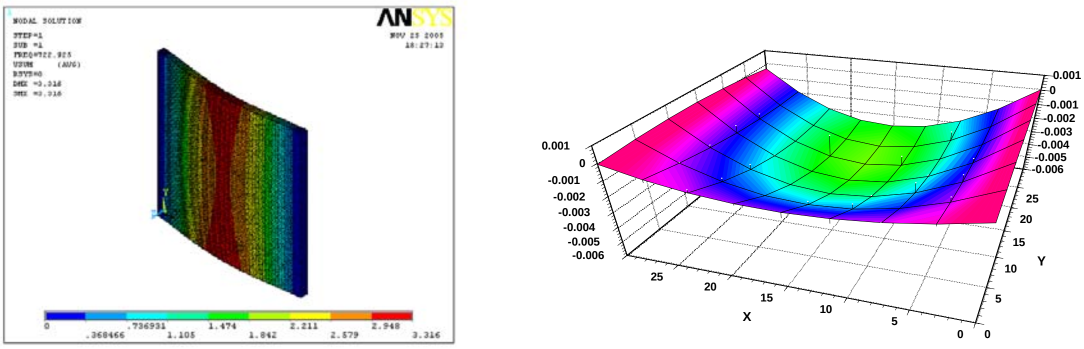
A drawing of the experimental setup is shown in Figure (4a) for the experimental verification. The honeycomb sandwich plate is evenly divided into 7x7 test locations in x and y directions, respectively. An impulse hammer (PCB 086D80) excites the structure while an accelerometer (PCB 352C65) measures responses at the node 34. The response node 34 is carefully selected to avoid at the nodal lines of first three mode shapes. Figure (4b) represents the frequency response of the acceleration signal at node 34. There are three distinct peaks, as shown in Figure (4b), corresponding to 638 Hz, 914Hz and 1287Hz, respectively. These three peaks imply the vibration modes of the structure in frequencies ranging from 0-1.6kHz. In frequency analysis, the differences between theoretical predictions and experimental results are 11.6%, 9.46% and 9.01%, respectively. A close agreement found between the theoretical and experimental results in the first three modes of vibration of the honeycomb sandwich plate.



(a) (b)

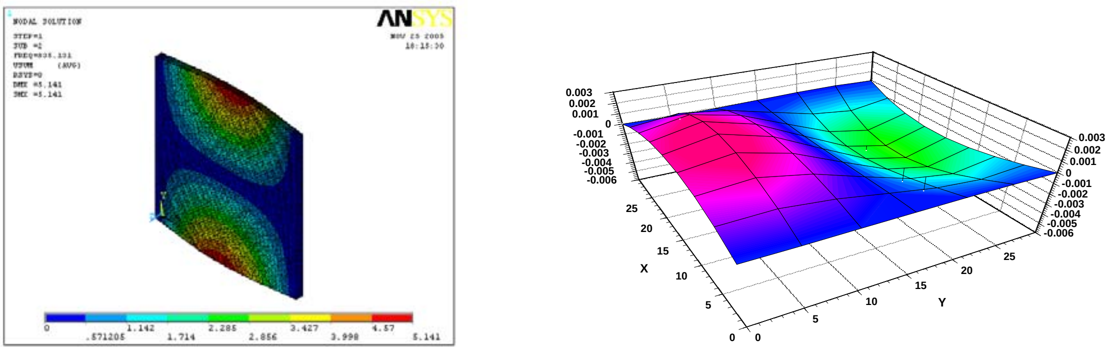
Figure (4) – (a) Experimental modal analysis setup and (b) frequency response at node 34.

Next, the mode shapes corresponding to these three vibration modes are carefully investigated using the experimental modal testing method [10]. Figures (5a-7a) show the first three mode shapes obtained from ANSYS FE model, respectively. Figures (5b-7b) are the first three mode shapes determined by experimental modal analysis, respectively. The obtained mode shape results indicate that there is a close agreement among numerical predictions and experiments in the current study. It is also worth mentioning that the first two modes of honeycomb sandwich plate are the targeted mode of vibration suppressed in this study.



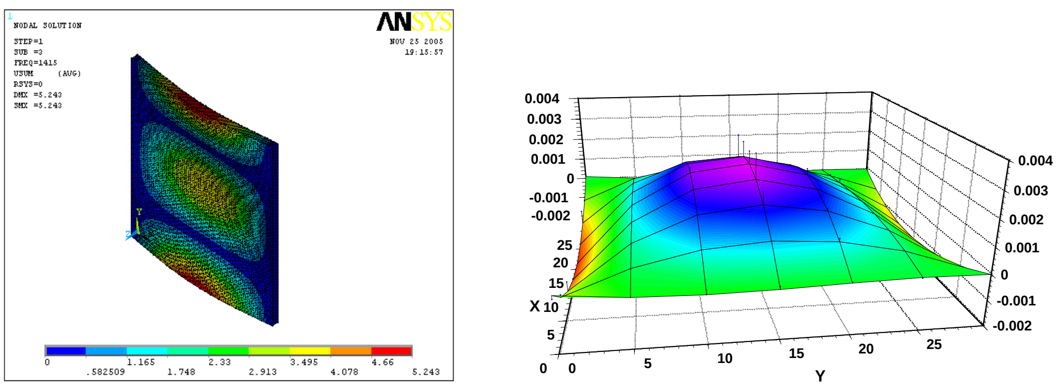
(a) (b)

Figure (5) – first vibrational shape determined by (a) ANSYS and (b) experimental measurement.



(a) (b)

Figure (6) – second vibrational shape determined by (a) ANSYS and (b) experimental measurement.



(a) (b)

Figure (7) – third vibrational shape determined by (a) ANSYS and (b) experimental measurement.

3. STATE-SPACE MODEL OF ACTUATED MFC/HONEYCONB PLATES

The strain energy U and kinetic energy T of the MFC/honeycomb plate can be presented by

$$\begin{aligned} U &= \frac{1}{2}\iint_{A,A_p} \begin{bmatrix} \varepsilon & \kappa \end{bmatrix} \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix} dxdy \\ &- \iint_{A_p} \begin{bmatrix} N_p & M_p \end{bmatrix} \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix} dxdy \end{aligned} \tag{1}$$

$$T = \frac{1}{2}\iint_{A,A_p} \rho(\dot{u} + \dot{v} + \dot{w})dxdy \tag{2}$$

where ε and κ are the midplane strain and curvature. A, B and D are extension, bending and extension-bending coupling stiffness matrices, respectively. A and A_P are the areas of plate and MFC, respectively. u, v and w are the deflections in the x, y and z directions. N_p and M_p are inplane piezo forces and moments. These are given by

$$N_p = \int Q_p\{\varepsilon_p\}dz \quad \text{and} \quad M_p = \int Q_p\{\varepsilon_p\}zdz \tag{3}$$

where Q_p is stiffness matrix of MFC and $\{\varepsilon_p\}$ is the piezo inplane actuation strain vector.

For the flexural vibration of honeycomb plate, the inplane deflections u and v can be neglected and the flexural deflection w is represented by

$$w(x,y,t) = \sum_{r=1}^{N} \Phi_r(x,y)q_r(t) \tag{4}$$

The displacement function $\Phi_r(x,y)$ are assumed to be product of polynomials in the x and y directions. The polynomials are determined by the boundary conditions. Using these displacement expressions, the strain energy and kinetic energy are written in matrix form

$$U = \frac{1}{2}\{q\}^T[K_s]\{q\} - [Q]_P\{q\} \tag{5}$$

$$T = \frac{1}{2}\{q\}^T[M_s]\{q\} \tag{6}$$

For the design of velocity feedback control, the following state space form can be obtained using equations (5) and (6) with modal reduction techniques,

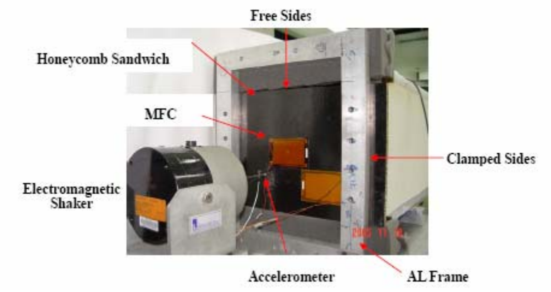
$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}(K^* - K_d P) \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \tag{7}$$

$$[y] = [I \quad 0]\begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} \tag{8}$$

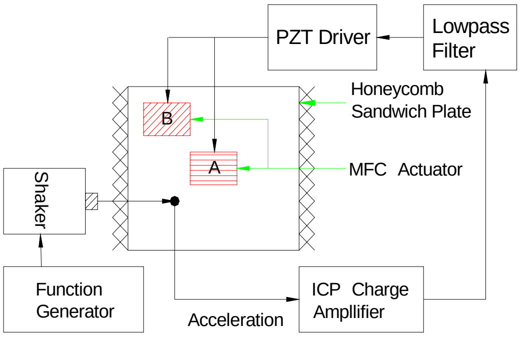
The suitable K_d values can be obtained by root-locus method.

4. ACTIVE CONTROL OF MFC/HONEYCOMB SANDWICH PLATE

In this section, the MFC (M2814P1，Smart Material Corp. Germany) actuators with velocity feedback control are utilized to suppress vibration and sound radiation of the honeycomb sandwich plate. The effective area of the MFC actuator is 28mm x 14mm and the thickness is 0.3 mm. Figures (8a) and (8b) show the picture of the experimental setup and the active control diagram, respectively. Figure (8b) shows two of the MFC bonded locations which is denoted as A and B. Locations A and B are carefully selected to target the first and second mode of flexural vibration of the honeycomb plate. It is worth mentioning that in order to investigate the directional actuating capability of MFC actuators, a MFC actuator with 45° oriented ply angle is bonded at location B. The electromagnetic shaker is used as a primary disturbance input. An accelerometer is used to measure the out-of-plane deflection at the node 34. The acceleration signal is integrated by using an integrator. The actuated voltage is provided by piezo driver (Trek 603C).



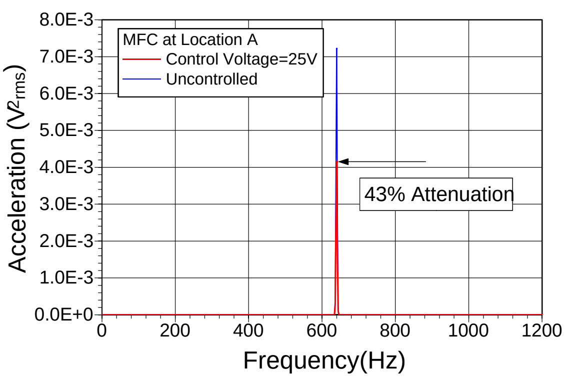
(a)



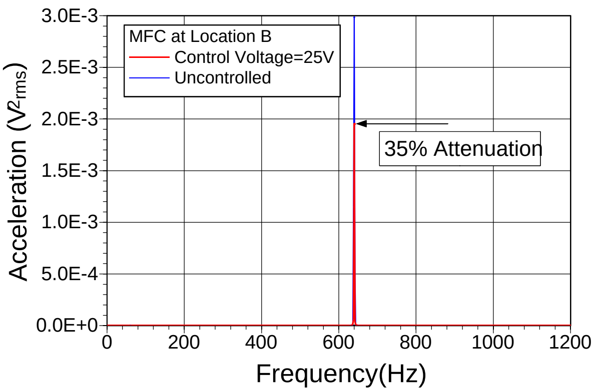
(b)

Figure (8) – (a) picture of experimental setup and (b) active control diagram.

Figures (9a, b) respectively show plots of the normalized experimental amplitudes of vibration of first mode for the MFC/honeycomb plate for the MFC actuations at location A and B. In Figure (9a), amplitude attenuation of 43% is obtained using the location A MFC treatment under control voltages of 25. In Figure (9b), amplitude attenuation of 35% is obtained using the location B MFC treatment for control voltages of 25V. Such attenuations are normalized with respect to the amplitude of vibration of the uncontrolled MFC/honeycomb plate.



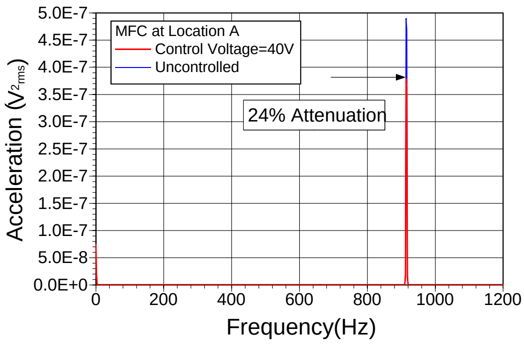
(a)



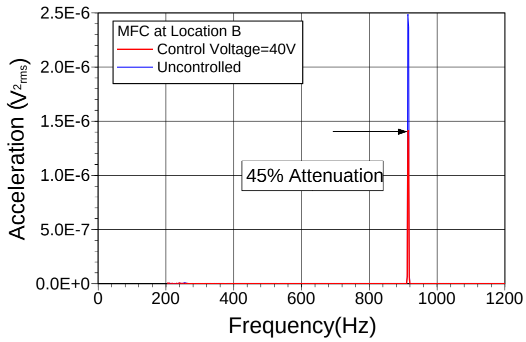
(b)

Figure (9) – experimental evaluation for velocity feedback control of first mode of vibration with actuating MFC actuator at (a) location A and (b) location B.

Figures (10a, b) respectively show plots of the normalized experimental amplitudes of vibration of the second mode for the MFC/honeycomb plate for the MFC actuations at location A and B. In Figure (10a), amplitude attenuation of 24% is obtained using the location A MFC treatment under control voltages of 40V. In Figure (10b), amplitude attenuation of 45% is obtained using the location B MFC treatment for control voltages of 40V.



(a)



(b)

Figure (10) – experimental evaluation for velocity feedback control of second mode of vibration with actuating MFC actuator at (a) location A and (b) location B.

It is evident that the activation of the MFC actuator at the location A has produced significant vibration attenuation in the first mode of vibration as compared to the attenuations developed by the MFC actuator at location B. Similarly, the activation of the MFC actuator at the location B has produced significant vibration attenuation in the second mode of vibration as compared to the attenuations developed by the MFC actuator at location A. The result leads support to the investigations of dynamic characteristics of the honeycomb plate in determining the bonded location for the MFC actuators in Section 2.

Figure (11) shows the location of microphone (ACO PS9200) in the vibroacoustic test setup. The microphone is located 10cm behind the center of honeycomb plate. This location is considered able to clearly measure the noise radiation produced by the first mode of vibration of honeycomb plate. In Figure (12), S.P.L. attenuation of 70% is obtained using the location A MFC treatment under control voltages of 25V. Figure (12) clearly demonstrates the effectiveness of using MFC to reduce the vibroacoustic radiation of the honeycomb sandwich plate.

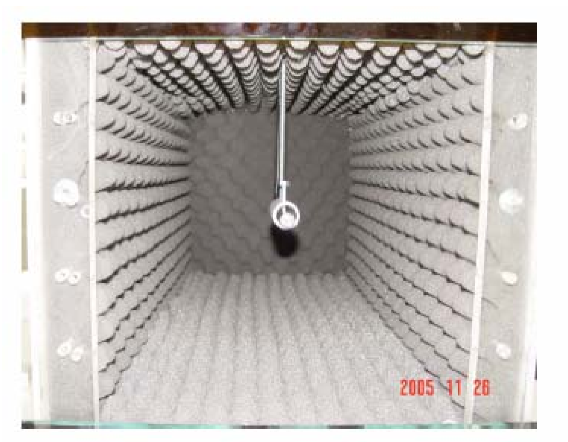


Figure (11) – vibroacoustic setup.

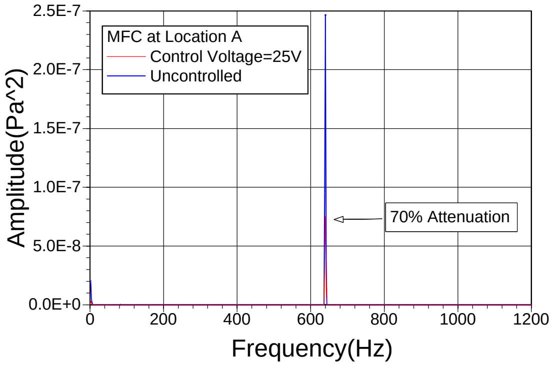


Figure (12) - vibroacoustic control of honeycomb sandwich plate

5. CONCLUSIONS

In this study, an ANSYS finite element of the honeycomb sandwich plate is developed and utilized to predict the natural frequencies and mode shapes of the honeycomb sandwich plate. This model provides a valuable tool to the understanding of the structural dynamic characteristics of the honeycomb sandwich plate. The accuracy of the developed finite element model has been validated experimentally. According to analytical and experimental results, it is suggested that the targeted control mode can be identified and the honeycomb sandwich plate can be simplified as a finite plate model with surface-bonded MFC actuators. The state-space model is used for the design of the velocity feedback control. The effectiveness of the MFC actuators in attenuating flexural vibration of the honeycomb sandwich plate has been clearly demonstrated experimentally. The results obtained indicate that the MFC/honeycomb sandwich plate produce significant attenuation of the structural vibration. The developed theoretical and experimental techniques provide an invaluable tool for the designing and predicting the MFC/structures performance which can in turn be used in many applications.

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