1. Introduction

Magnetoelectric (ME) composites require giant magnetostrictive and piezoelectric materials, with a strong coupling between them, and many applications of these composites such as magnetic field sensing devices, coil-less transformers and read/write devices are currently under investigation. Recently, energy harvesting devices can be used as the power source for structural health monitoring sensors, tire pressure monitoring sensors, medical implants and other wireless sensors. The devices of energy harvesting from ambient sources, such as mechanical loads, provide a promising alternative to battery-powered systems. Energy harvesting magnetostrictive/piezoelectric laminates are subjected to high mechanical loads, and these loads cause high response levels that increase the generated power but induce the delamination and reduce the lifetime of the laminates. In this work, we study the detection and response characteristics of clamped-free giant magnetostrictive/piezoelectric laminates under concentrated loading in a combined numerical and experimental approach.

2. Analysis

The basic equations for magnetostrictive and piezoelectric materials are outlined here. The equilibrium equations in the rectangular Cartesian coordinate system $O-x_1x_2x_3$ are given by

$$\sigma_{i,j} = 0$$

$$B_{i,j} = 0$$

$$D_{i,j} = 0$$

where $\sigma_{i,j}$ is the stress tensor, $B_{i,j}$ is the magnetic induction vector, $D_{i,j}$ is the electric displacement vector, a comma followed by an index denotes partial differentiation with respect to the space coordinate $x_i$, and the summation convention for repeated tensor indices is applied. The constitutive laws are given as follows:

$$\epsilon_{i,j} = s_{i,jkh}^{H} \sigma_{kh} + d_{i,jkh}^{H} E_{k}$$

$$B_{i} = d_{i,kh}^{H} \sigma_{kh} + \mu_{ik} H_{k}$$

for the giant magnetostrictive material, and

$$\epsilon_{i,j} = s_{i,jkh}^{E} \sigma_{kh} + d_{i,jkh}^{E} E_{k}$$

$$D_{i} = d_{i,kh}^{E} \sigma_{kh} + \varepsilon_{ik} H_{k}$$

for the piezoelectric material. Here, $\sigma_{i,j}$ is the strain tensor, $H_{i}$ is the magnetic field intensity vector, $E_{i}$ is the electric field intensity vector, $s_{i,jkh}^{H}, d_{i,jkh}^{H}, \mu_{ik}$ are the constant magnetic field elastic compliance, magnetoelectric constant and

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Fig. 1. Illustration of (a) two-layered and (b) three-layered magnetostrictive/piezoelectric laminate configurations.

The magnetic and electric field intensities are written as

$$H_{i} = \varphi_{i}$$

$$E_{i} = -\phi_{i}$$

where $\varphi$ and $\phi$ are the magnetic and electric potentials, respectively.

Two layered magnetostrictive/piezoelectric laminate is shown in figure 1(a), in which a magnetostrictive layer, Terfenol-D, of length $l_{m} = 15$ mm, width $w_{m} = 5$ mm and thickness $h_{m} = 1$ and $3$ mm is perfectly bonded on the upper surface of a piezoelectric layer, PZT, of length $l_{p} = 20$ mm, width $w_{p} = 5$ mm and thickness $h_{p} = 0.5$ mm. We will use subscripts $m$ and $p$ to refer to Terfenol-D and PZT layers, respectively. Dimensions $h_{m}(h_{p}), w_{m}(w_{p}), l_{m}(l_{p})$ are
measured along the \( x_1 = x, x_2 = y \) and \( x_3 = z \) axis, respectively. The origin of the coordinate system is located at the center of the bottom left side of upper Terfenol-D layer. The left end \( x = 0 \) is clamped and concentrated load \( P_0 \) is applied at \( x = y = 0, z = l_p \). Three layered laminate is also considered (see figure 1(b)). Easy axis of the magnetization of Terfenol-D layer is the \( z \)-direction, while the polarization of PZT layer in the \( x \)-direction.

As we know, a magnetic domain switching gives rise to the changes of the magnetoelastic constants, and the constants \( d_{35}, d_{51}, \) and \( d_{33} \) for Terfenol-D layer in the \( z \)-direction magnetic field are

\[
\begin{align*}
d_{35} &= d_{35}^m, \\
d_{51} &= d_{51}^m + m_{31} H_s, \\
d_{33} &= d_{33}^m + m_{33} H_s 
\end{align*}
\]

(11)

where \( d_{35}^m, d_{51}^m, d_{33}^m \) are the piezo-magnetic constants, and \( m_{31} \) and \( m_{33} \) are the second-order magnetoelastic constants. When the length of Terfenol-D is much longer than other two sizes (width and thickness) and a magnetic field is along the length direction (easy axis), the longitudinal (33) magnetostrictive deformation mode is dominant. So it is assumed that only the constant \( d_{33} \) varies with magnetic field, and the constant \( m_{33} \) equals to zero.

We performed finite element calculations to obtain the tip deflection, stress, induced voltage and induced magnetic field for the magnetostrictive/piezoelectric laminates under concentrated load \( P_0 \) at \( x = y = 0, z = l_p \). The average induced magnetic field in the \( z \)-direction at the side surface (at \( z = l_m \) plane) is calculated as

\[
B_{in} = \frac{1}{A} \int_A B_z(x, y, l_m) dA
\]

(12)

where the integration is over the surface area, \( A = w_m h_m \), of Terfenol-D layer. The basic equations for the magnetostrictive materials are mathematically equivalent to those for piezoelectric materials. So coupled-field solid elements in ANSYS were used in the analysis.

3. Experimental Procedure

Terfenol-D of \( l_m = 15 \text{ mm} \), \( w_m = 5 \text{ mm} \), \( h_m = 1 \text{ and } 3 \text{ mm} \) and PZT C-91 of \( l_p = 20 \text{ mm} \), \( w_p = 5 \text{ mm} \), \( h_p = 0.5 \text{ mm} \) were used to make giant magnetostrictive/piezoelectric laminates by epoxy bonding. The second-order magnetoelastic constants \( m_{33} \) of Terfenol-D layer with \( h_m = 1 \text{ and } 3 \text{ mm} \) of two-layered laminate are \( 5.0 \times 10^{-12} \) and \( 3.3 \times 10^{-12} \text{ m}^2/\text{A}^2 \), and the constants \( m_{33} \) of \( h_m = 1 \text{ and } 3 \text{ mm} \) of three-layered laminate are \( 5.2 \times 10^{-12} \) and \( 2.3 \times 10^{-12} \text{ m}^2/\text{A}^2 \), respectively.

Consider magnetostrictive/piezoelectric laminates under concentrated loading. Concentrated load \( P_0 \) was applied at \( x = y = 0, z = l_p \). First, the displacement for the two-layered and three-layered laminates under concentrated loading was measured with a laser displacement meter. Next, the induced voltage of these laminates was measured using an oscilloscope. The \( x = h_p \) plane was grounded. Then, the induced magnetic field over the total area on \( z = l_m \) plane of Terfenol-D layer was measured using a Tesla meter. The hall probe was touched on the edge of Terfenol-D layer, and this set-up allowed a precision of induced magnetic field measurement of \( \pm 0.01 \text{ mT} \).

4. Results and Discussion

Figure 2 shows the tip deflection \( w_{tip} \) versus applied concentrated load \( P_0 \) at \( x = h_p, y = 0, z = l_p \) for the two-layered laminates with \( h_m = 1 \) and 3 mm. The lines and plots denote the results of FEA and test. The experimental scatter is small, and the representative plots from the tests are shown. The tip deflection increases as the thickness of the Terfenol-D layer decreases. The FEA results are good agreement with experimental measurements. Figure 3 shows the induced voltage \( V_{in} \) versus applied concentrated load \( P_0 \) at \( x = 0 \) plane for the two-layered laminates with \( h_m = 1 \) and 3 mm, obtained from the FEA and test. As the concentrated load increases, the induced voltage increases. The comparison between the numerical predictions and the experimental results for the two-layered laminate with \( h_m = 3 \text{ mm} \) yields a good agreement. For the laminate with \( h_m = 1 \text{ mm} \), the trend is similar between the numerical predictions and the experimental results, though the experimental data are smaller than the predicted ones because of the voltage saturation under high mechanical loads.

![Fig. 2 Tip deflection versus concentrated load for two-layered magnetostrictive/piezoelectric laminates](image)

![Fig. 3 Induced voltage versus concentrated load for two-layered laminates](image)

References