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마그네토스트릭션 효과를 이용한 비접촉 모달 테스팅 기법

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Noncontact Modal Testing Method Using Magnetostriction Effects

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ABSTRACT

In this work, we propose to employ magnetostrictive sensors to develop a new non-contacting modal testing method. Specific applications are made in the modal testing of a beam in bending. The role of bias magnetic fields in measuring bending waves is addressed and an approximate analysis to explain the principle to measure bending signals is carried out. The measured modal data by the present method agree well with those by conventional methods using accelerometers.

1. INTRODUCTION

Modal testing is an important procedure for system identification. Conventional modal testing schemes employ accelerometers as sensors, but non-contacting measurements are often necessary. However, current laser-based techniques are not cost-effective though they can be applied to a wide class of experiments. As a new attempt to develop a cost-effective noncontact modal testing method, we propose to employ magnetostrictive sensors in order to measure signals without any contact. These sensors have recently been used to measure high-frequency wave signals, but no work has been reported in conjunction with modal testing.

Applications of magnetostrictive sensors (MsS's) in problems related to wave propagation are reported in a few papers[1-4], and typical frequencies considered in these works are over hundred ㎑. The use of these sensors in low-frequency modal testing applications (say, less than a few ㎑) requires special considerations.

In this paper, we develop a new MsS-based modal testing method for beams in bending. In particular, the significance of a bias magnetic field is addressed. An analysis and sets of experiments supporting the role of a bias

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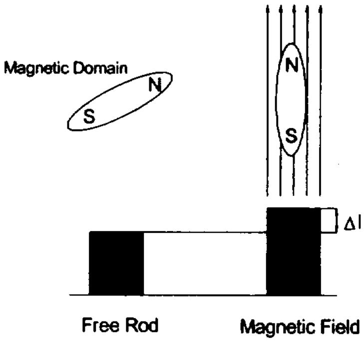

Fig. 1 Magnetostriction at the Crystalline Level

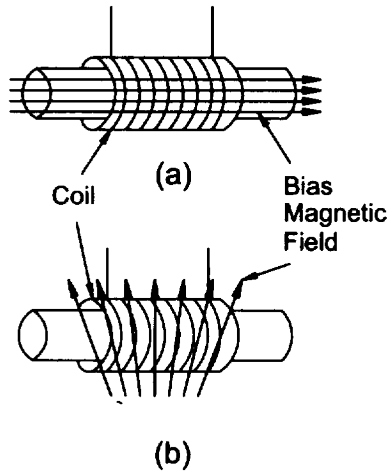

Fig. 2 Various bias magnetic fields used to measure (a) longitudinal and (b) flexural waves in a beam. (Coils surrounding beams are not in contact with beams.)

magnetic field are also presented. The modal data obtained by the present MsS-based modal testing method agree well with those by conventional methods using accelerometers.

2. THEORETICAL BACKGROUND

2.1 Magnetostriction

When a piece of some materials are placed in a time-varying magnetic field, its physical dimension varies accordingly. This effect is known as the Joule effect[2,3] and the opposite phenomenon is usually referred to as the Villari effect[2,3]. Magnetostriction effects refer to both of these phenomena. The Joule effect is the underlying principle for magnetostrictive actuators while the Villari effect for magnetostrictive sensors.

Typical magnetostrictive materials exhibiting magnetostrictive effects include ferromagnetic materials such as Fe, Ni and Co. Fig. 1 illustrates how the magnetostriction phenomena occur.

Various shapes of MsS's are possible but coil-type MsS's are commonly used to measure elastic waves in solid or hollow beams[3]. Especially in a circular beam, coil-type MsS's can be used to measure various elastic waves by changing bias magnetic fields.[1] A schematic diagram of several arrangements of coils and bias magnetic fields for acquiring various waves is shown in Fig. 2. Experimental studies[1,5] show that a coil in the absence of any bias magnetic field mainly detects longitudinal elastic waves. However, the bias field applied along an axis of a beam causes the coil to respond mostly to longitudinal waves, as illustrated in Fig. 2-(a). As indicated in Fig. 2-(b), a different flux density across the beam cross section makes it possible for flexural waves to be detected.

As illustrated in Fig. 2, only coils and some magnets generating bias fields are the essential elements of magnetostrictive sensors. As a result, the sensors are cost-effective and their installation is quite easy. This simplicity and cost-effectiveness motivates us to look for a MsS-based modal testing technique.

2.2 Mode Extraction

When a coil surrounds a beam made of a magnetostrictive material, the magnetic flux density B can be expressed as[6]

$$B = 4\pi\mu_r\lambda\frac{\partial u}{\partial x}, \tag{1}$$

where u is the axial displacement inside the beam. The reversible permeability and the magnetostrictive constant are denoted by μ_r and λ, respectively.

Using Eq. (1), the magnetic flux passing through a turn of the coil is

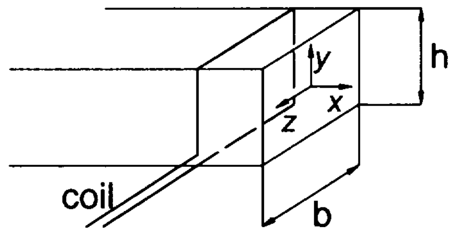

Fig. 3 The schematic diagram of a turn of a coil around a rectangular beam

$$\begin{aligned} d\phi &= BdA \\ &= 4\pi\mu_r\lambda\frac{\partial u}{\partial x}\,dA. \end{aligned} \tag{2}$$

In the presence of a bias magnetic field as shown in Fig. 2-(b), we propose to model $\mu_r\lambda$ as a function of the cross sectional coordinates y and z (see Fig. 3). If the bias magnetic field is constant along z axis, $\mu_r\lambda$ is a function of y only. Thus we approximate $\mu_r\lambda$ in a Taylor series as

$$\mu_r\lambda = c_0 + c_1 y + c_2 y^2 + \cdots. \tag{3}$$

Substituting Eq. (3) into (2) and integrating the resulting equation yields

$$\phi = \int_A (c_o + c_1 y + c_2 y^2 + \cdots)\frac{\partial u}{\partial x}\,dA. \tag{4}$$

In a beam theory, the displacement u can be approximated as[7]

$$u = u_0 - y\theta, \tag{5}$$

where u_0 and θ denote the average axial displacement across the beam section and the rotation of a beam normal. Substituting Eq. (5) into Eq. (4) and neglecting higher-order terms, one can find the following expression for the flux ϕ:

$$\phi = bhc_0 \frac{\partial u_0}{\partial x} - \frac{bh^3 c_1}{12} \frac{\partial \theta}{\partial x}. \tag{6}$$

Note that the given by result (6) is valid only when an applied bias field is configured as Fig. 2-(b); otherwise c_1 is assumed to be zero.

When a beam is so excited that flexural motions are dominant, the first term in Eq. (6) may be negligible in comparison with the second term. In this case, the output voltage generated in the coil by the change of the flux ϕ is written as

$$\begin{aligned} v_o &= -\partial\phi/\partial t \\ &\approx \frac{bh^3 c_1}{12} \frac{\partial^2 \theta}{\partial t \partial x}. \end{aligned} \tag{7}$$

Since the spatial derivative $\partial\theta/\partial x$ of the rotation θ is curvature x and $bh^3/12$ is the bending rigidity EI, the voltage v_o indeed measures the time-derivative of a bending moment M;

$$\begin{aligned} v_o &= c_1 \frac{\partial}{\partial t}(EIx) \\ &= c_1 \frac{\partial M}{\partial t}. \end{aligned} \tag{8}$$

In order to use the result obtain in Eq. (8), we consider the steady-state vibration response of the rotation degree $\theta(x, t)$

$$\begin{aligned} \theta(x, t) &= \Theta(x) e^{i\omega t} \\ &= \sum_{r=1}^{\infty} C_r(\omega) \Theta^{(r)} e^{i\omega t}. \end{aligned} \tag{9}$$

See Kim and Kang[7] for the explicit expressions of rotation mode shapes $\Theta^{(r)}$. Similarly, we can write the steady-state vibration response of the bending moment as

$$M(x, t) = \sum_{r=1}^{\infty} C_r(\omega) M^{(r)} e^{i\omega t}. \tag{10}$$

Following Reference (7), one can show that the frequency response of the MsS output is proportional to

$$\begin{aligned} a_{ij} &\equiv \frac{c_1 \frac{\partial M}{\partial t}(x_i, \omega)}{F_j} \\ &= c_1 \sum_{r=1}^{\infty} \frac{i\omega M^{(r)}(x_i) W^{(r)}(x_j)}{\Omega_r^2 - \omega^2}, \end{aligned} \tag{11}$$

where $W^{(r)}$ denotes the displacement mode shape. Symbols i and j in Eq. (11) denote the locations of measurement and excitation.

From equation (11), it is clear that one can determine bending moment mode shapes $M^{(r)}$ if

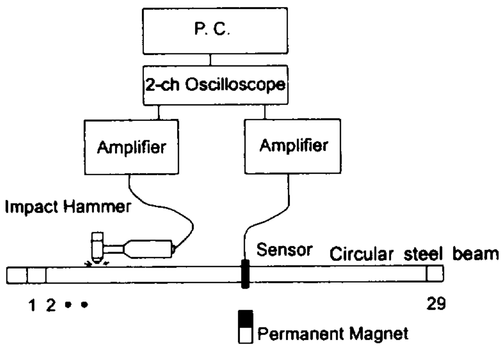

Fig. 4 The schematic diagram of the experimental arrangement. (beam diameter : 25 ㎜; length : 916 ㎜)

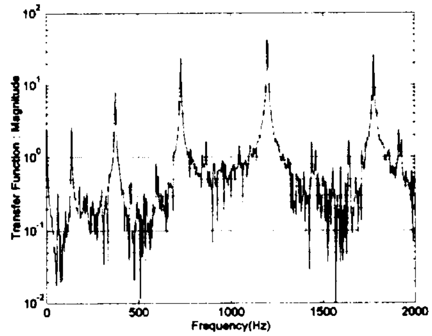

Fig. 5 Transfer function using the MsS sensor with the magnetization of the material.

the measurement locations vary for a fixed excitation location. On the other hand, measurements at varying excitation locations with a fixed measurement location should be made to determine the displacement mode shapes $W^{(r)}$.

3. VERIFICATION

3.1 Experimental Arrangement

Figure 4 shows a schematic diagram of the present experimental arrangement. To acquire a free-free boundary condition, both ends of the beam are suspended by elastic cords. A coil-type MsS has been manufactured in our laboratory for the present experiment. The length and inside diameter of the coil are 9 ㎜ and 33 ㎜, respectively. The coil has 150 turns made of 0.3 ㎜ wires. The magnetostrictive sensor is placed 412 ㎜ away from an end.

The bias magnet is placed at one side of the coil as in Fig. 2-(b). The distance from the sensor to the magnet was 100 ㎜ approximately.

3.2 Modal Testing Results

As an application of the present MsS-based modal testing method, the displacement mode shapes and the corresponding eigenfrequencies of the beam shown in Fig. 4 are obtained. For this experiment, the location of the magnetostrictive sensor is fixed while the beam is excited by an impact hammer at 29 locations marked in Fig. 4. Each excitation point is located 30.5 mm apart. To increase the S/N ratio, the signals measured at the sensor are averaged three times.

In the present application, two cases of experiments are conducted. Case 1 corresponds

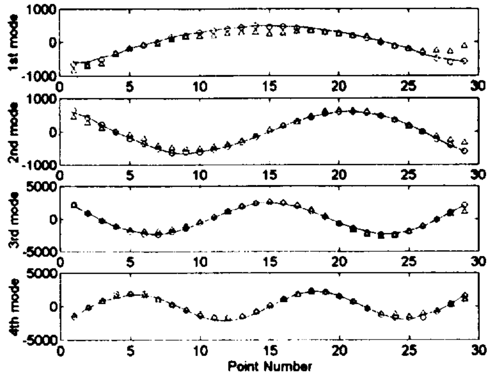

Fig. 6. Mode shapes of a free-free beam shown in Fig. 4. (Solid lines: by an accelerometer; Triangles: by MsS without any bias magnetic field; Circles: by MsS applied to a beam pre-magnetized)

to an experiment without using a bias magnetic field. In Case 2, a bias magnetic field is applied near the sensor during the whole experimental process. Since the bias magnet attracts the beam, the beam tends to bend slightly. To resolve this problem, the beam section covered by the sensor is magnetized, but the bias magnet is removed when measurements at the senor are made. For the verification of the present result, a conventional modal testing using an accelerometer was performed.

Table 1. Eigenfrequencies of the beam shown in Fig. 4 (unit: Hz, resolution: 1 Hz)

Mode number	1	2	3	4	5
Case 1 (MsS)	137	375	730	1199	1776
Accelerometer	137	375	730	1199	1776

Figure 5 shows a typical frequency response function $\alpha_{ij}(x_i, \omega)$ where the excitation is made at point 1. Figure 6 compares the displacement mode shapes obtained from Case 1 and Case 2, which are also compared against those by the conventional accelerometer-based modal testing method.

It is clear that the mode shapes obtained in Case 2 agree well with those by accelerometers. However, the results by Case 1 without using a bias magnetic field are not satisfactory; the use of bias magnetic fields are critical in measuring bending mode shapes. Table 1 compares the eigenfrequencies obtained from the present method (Case 2) and the conventional accelerometer-based method.

4. CONCLUSIONS

A new noncontact modal testing technique utilizing magnetostrictive sensors has been developed in this work. Magnetostrictive sensors had been mainly used to measure high-frequency elastic waves, but a successful application of the sensors for modal testing methods concerning a relatively low frequency range below 2 kHz is made here for the first time. The significance of a bias magnetic field is addressed and an approximate theory explaining the effects of the bias field on the type of measured signals is also presented. An interesting and useful application of this modal testing technique may be in the extraction of operating modal properties of hot engine manifolds.

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