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Active vibration control system of smart structures based on FOS and ER actuator

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Abstract. An active vibration control system based on fiber optic sensor (FOS) and electrorheological (ER) actuator is established in this paper. A new intensity modulated fiber optic vibration sensor is developed following the face coupling theory. The experimental results show that this new type of intensity modulated fiber optic vibration sensor has higher sensitivity in measuring the vibration frequency. At the same time, experimental investigations are focused on evaluating the dynamic response characteristics of a beam fabricated with ER fluid. It is noted that the most significant change in the material properties of ER fluid is the change of material stiffness and damping which varies with the electric field intensity imposed upon the ER fluid. Finally, the structural vibration of the smart composite beam based on ER fluid, fiber optic sensor and piezoelectric transducer has been monitored and controlled actively utilizing a fuzzy-logic algorithm.

1. Introduction

Smart structures have been designed inspired by living things, in particular their abilities to adapt their structure, morphology, shape and properties to the changing environment and aging process. Thus, smart structures have functions that allow them to change their shape, monitor their own health and in general display adaptive and kinetic features [1–4]. In other words, smart structures not only have traditional structural materials' functions, but also have actuating, sensing and control capabilities. Smart structures are hybrid composite material systems which are composed of three important parts: sensor, actuator and microprocessor. The sensor senses the variations of the circumstances; the microprocessor analyses these signals and then instructs the actuator to change the global mechanical characteristics of the structure. The fiber optic sensor, shape memory alloy, electrorheological fluid, magnetorheological fluid and piezoelectric materials are sensors and actuators used in smart structure systems [5].

Electrorheological (ER) fluids, first reported in the 1940s by Winslow, are suspensions of micro-fine particles in dielectric liquids [6]. ER fluids can be changed from liquid to gel-like solid within several milliseconds in the presence of strong imposed electric field. When the electric field is removed, the fluids revert to their original state. This unique property of controllable, fast, reversible gelation makes ER fluids very suitable for real-time active control of structural vibration. They are preferred actuator materials in smart materials and structure systems (SMSS) [7–12]. Active controllable devices featuring ER fluids such as the damper and isolators have been developed [13].

The fiber optic sensors (FOSs) provide several advantages over their electrical counterparts, namely high bandwidth, small size, low weight, corrosion resistance, geometrical flexibility and an inherent immunity to electromagnetic interference (EMI). FOSs can be embedded in composite materials in a non-obtrusive manner that does not degrade structural integrity. In general, the embedded fiber optic sensors can monitor the health of the structures in service condition. To fulfil such a purpose, a large number of fibre optic sensors have been developed for use in smart structures [2, 5].

Many researchers have studied active vibration control of structures using the ER fluids [7–12]. In this paper, a smart vibration control system including an internal sensor and ER fluid actuator has been developed. The traditional piezoelectric sensor and new fiber optic sensor (FOS) are used as sensors. A new type of intensity modulated fiber optic sensor based on the face coupling theory has been developed and embedded into a cantilevered beam featuring ER fluid. The vibration characteristics of such a specimen subjected to various electric field strengths are studied in detail. Finally, the active vibration control systems incorporating a fuzzy logic algorithm based on the FOS and ER actuator are established.

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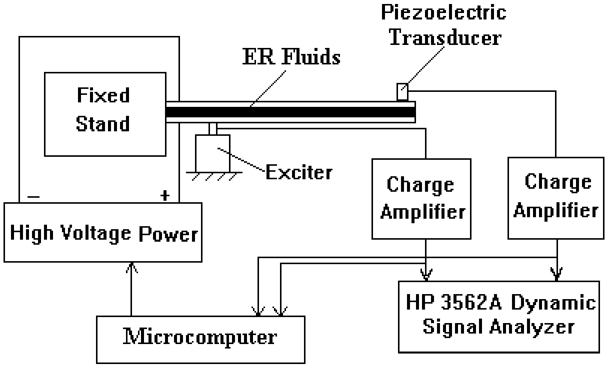

Figure 1. Test apparatus for smart composite beam containing ER fluids and piezoelectric transducer.

2. Experimental systems

2.1. Electrorheological (ER) fluids and the dynamic characteristics of smart structures

ER fluids are suspensions of porous particles in dielectric fluids, and they can be manufactured from a variety of fluid/solid mixtures. To obtain an ER fluid, it is important to choose the proper components. As the continuous phase of ER fluids, the fluids must have the following properties:

(a) high boiling point, low freezing point;
(b) low viscosity to keep the fluidity when solid particles are added;
(c) high dielectric constant to reduce the loss of power;
(d) density must match the density of the particles;
(e) perfect chemical stability, can not decompose under the operating conditions;
(f) non-toxic;
(g) high burning point;
(h) low price.

In the present paper, an ER fluid featuring silicone oil and phenol polymer is selected as the actuator. The dynamic characteristics of the beam specimen are tested using a piezoelectric transducer. The schematic diagram of the testing apparatus using a cantilever beam as the object is shown in figure 1. A vibration exciter is in contact at the beam's fixed end through a force transducer. An accelerometer is located at the free end of the beam. The collected vibration signals and input signals are sent to an HP 3562A dynamic signal analyser and used to obtain the frequency response. Sinusoidal scanning signals provided by the signal analyser are used in this experiment.

2.2. Novel fiber optic sensor (FOS)

Optical fiber sensors have a number of advantages with respect to conventional electronic sensor technology when applied to smart structures. Since the optical fibers are dielectric glass, conductive paths are eliminated, reducing hazards due to internal electrical discharges and lightning. Furthermore, there is good compatibility of the optical fiber with the composite matrix. Some of the issues to be addressed when designing fiber optic sensors used in smart structures are the parameters to be sensed such as vibration, strain, temperature and degree of cure. The fiber optic sensors (FOSs) are shown to be the preferred sensors in smart structures [1–5].

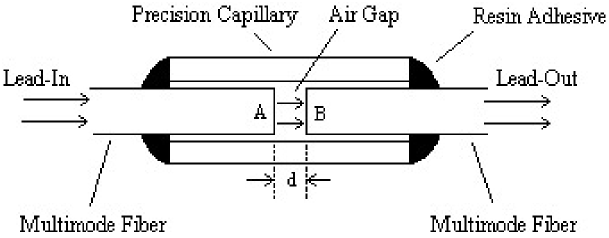

Figure 2. A schematic illustration of the intensity modulated optical fiber vibration sensor.

In this paper, a new light intensity modulated fiber optical sensor is developed following the face coupling theory. The advantages of this sensor are low cost and the ease of use. The construction of this sensor is similar to the extrinsic Fabry–Pérot interferometric (EFPI) sensor. The sensor is fabricated using conventional 50/125 μm multimode optical fiber and custom-drawn epoxy resin capillary tube. A suitable capillary tube for optical fiber is made first. Then the optical fiber is bonded to the ends of the capillary tube using the epoxy resin, forming an air gap cavity separating the cleaved ends of two multimode fibers. The schematic illustration of the intensity modulated optical fiber vibration sensor is shown in figure 2. Although the construction of this sensor is relatively simple, it is difficult to ensure a consistent gauge length. The fiber optic sensor is then embedded in a smart composite cantilevered beam.

If the beam with the embedded sensor is not deformed, the end-faces of the two multimode optical fibers are parallel and aligned. Once the beam is deformed due to an external force, the fiber end-face will tilt (i.e., the two fiber axes will not be parallel) and the fiber collecting the light presents a smaller cross-sectional target to the incident light elliptical core. The propagated light is thus modulated.

Embedding the fiber optic sensor in the smart composite beam (shown in figure 5), the following relation can be obtained [14]:

$$V = a(1 - KF) \tag{1}$$

$$K = \frac{d^2 L}{2\pi REI}. \tag{2}$$

Here, V is the output signal detected by the computer, a is related to input light intensity and detector sensitivity, F is the external force, d is the distance between face A and face B of the fiber, R is the radius of the optical fiber, L is the length of the cantilever beam, E is the elastic modulus of the beam and I is the moment of inertia of the beam. From equation (1), it is seen that the relationship between the output signal V collected by the sensor and external force F is linear. The static experimental results are shown in figure 3. The dynamic characteristics of this fiber optic sensor have been measured too. The frequency response comparative curves of the beam embedded optical fiber sensor with a piezoelectric sensor are shown in figure 4. It is seen that the novel intensity modulated optical fiber vibration sensor has comparable sensitivity to the traditional piezoelectric sensor for low frequency vibration.

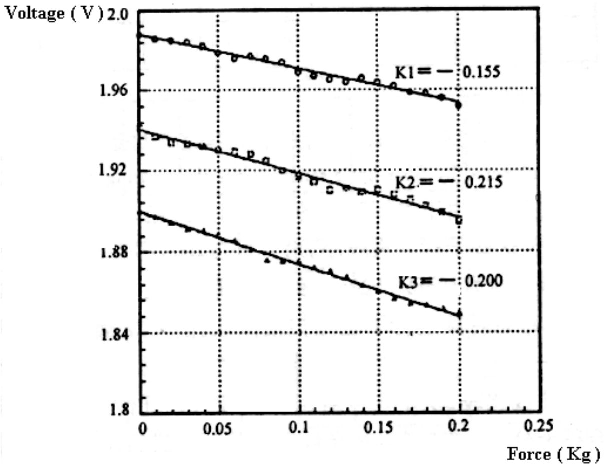

Figure 3. Static result of the beam embedded intensity modulated optical fiber vibration sensor.

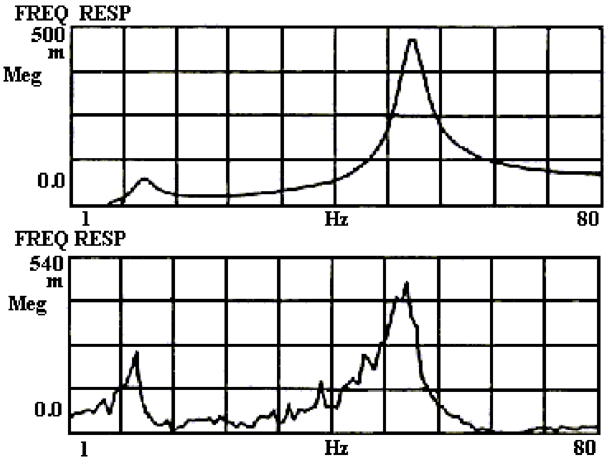

Figure 4. The frequency–response comparative curves of the beam embedded fiber optic sensor (below) with the piezoelectric sensor (above).

2.3. The fuzzy-logic vibration control of the smart structure using ER fluids, piezoelectric transducer and FOS

In the present experiment, the smart composite laminate beam is composed of two layers of structural material and one layer of ER fluid. The structural material used in the present beam is glass/epoxy composite with a very thin strip of copper as electrode on the inner face in contact with the ER fluid. To make the specimen, the fiber optic sensor (FOS) is first embedded in the structural material (glass/epoxy composites). Then the hollow beam made of the structural material embedded FOS must be filled with ER fluid, and sealed with silicone rubber. Terminals connected to a high voltage power are welded on each electrode face near the root section of the beam.

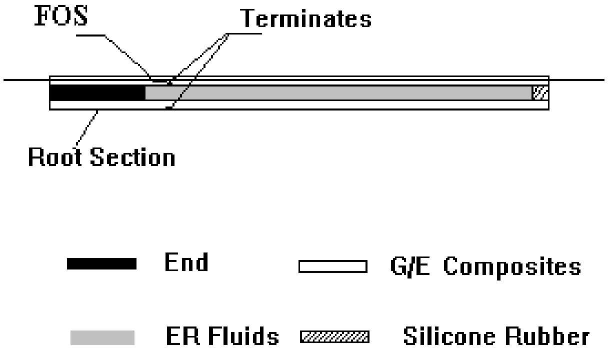

Figure 5. Structural diagram of the smart composite beam embedded fiber optic sensor (FOS) and ER fluids.

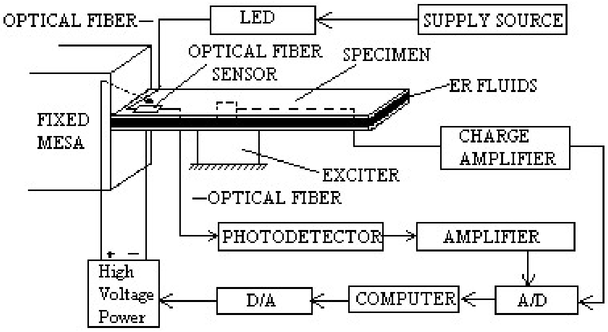

Figure 6. The experimental diagram of the active vibration control system of the smart composite beam embedded fiber optic sensor (FOS) and ER fluids.

The diagram of the experimental apparatus for active vibration control system based on the ER fluid and piezoelectric transducer is shown in figure 1. The traditional transducer can not be embedded within the smart composite structure. In addition, there is electromagnetic interference using the traditional transducer due to the high voltage applied on ER fluid. The structural diagram of the smart beam is shown in figure 5. So the experimental diagram of the active vibration control system of smart structure embedded ER fluid and FOS developed in this paper is shown in figure 6. The beam is supported at one end. A vibration exciter is contacted near the fixed end of the beam through a force transducer. An optical fiber vibration sensor is embedded at the fixed end of the beam as shown in figure 6. The collected vibration signals and input signals are sent to an HP 3562A dynamic signal analyser and used to obtain the frequency response. In addition, the signal is transferred to a computer through the A/D converter. The vibration natural frequencies of the smart composite beam embedded ER fluids and FOS can be calculated using FFT analysis in the computer. At the same time, the controlling signals (different electric field strengths) sent by the computer are transferred to high voltage power through the D/A converter. The appropriate electric field is supplied to the ER fluid according to the pre-programmed control algorithm in advance. Thus, vibration of the smart composite beam based on the ER fluid actuator and fiber optic sensor (FOS) can be actively controlled.

3. Results and discussions

Typical oscilloscope traces of free vibration of the beam are shown in figure 7. It shows the traces of a beam without electric field and with a 2.0 kV mm^{-1} electric field on ER fluid. It is seen that the beam's damping is increased with the electric field. The frequency–response

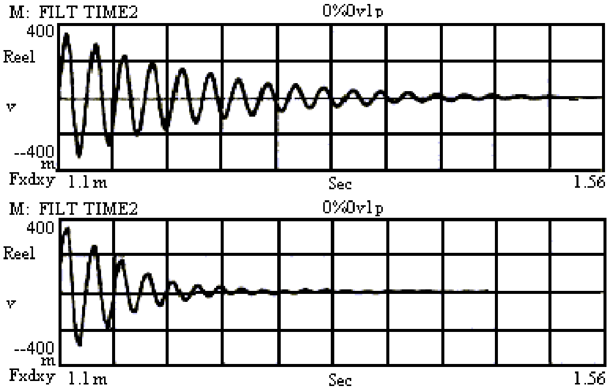

Figure 7. Oscilloscope traces of the smart composite beam featuring ER fluids: upper curve, without electric field; lower curve, 2 kV mm^{-1} electric field.

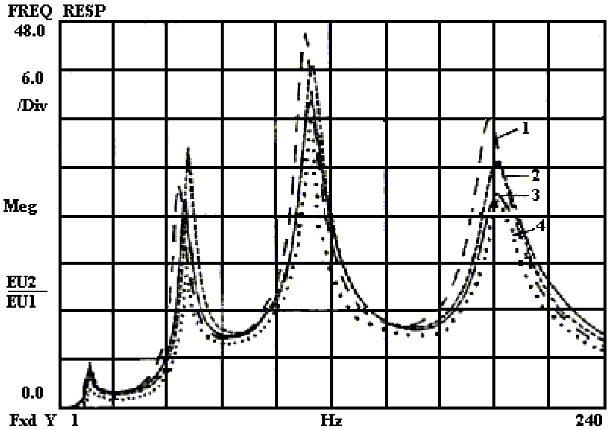

Figure 8. Frequency–response curve of smart composite beam based on the ER fluid and piezoelectric transducer. 1, 0 kV mm^{-1}; 2, 1 kV mm^{-1}; 3, 2 kV mm^{-1}; 4, desired curve.

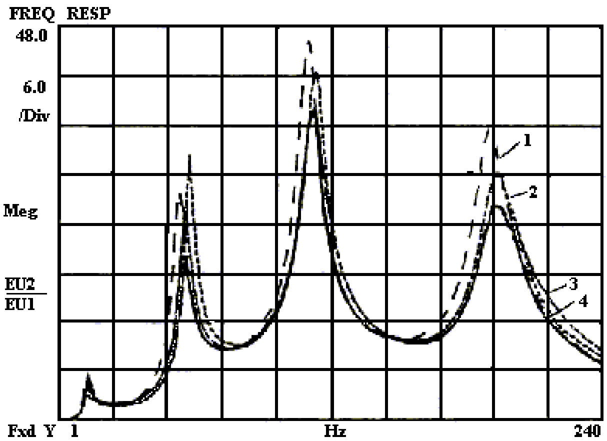

Figure 9. Active control curve of smart composite beam based on the piezoelectric transducer and ER fluids: 1, 0 kV mm^{-1}; 2, 1 kV mm^{-1}; 3, 2 kV mm^{-1}; 4, controlled curve (solid line).

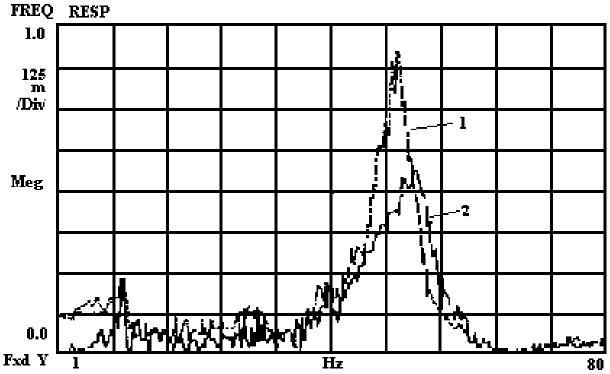

Figure 10. Frequency–response curve of smart composite beam embedded fiber optic sensor (FOS) and ER fluids: 1, 0 kV mm^{-1}; 2, 1 kV mm^{-1}.

curves measured using a piezoelectric transducer of the beam featuring ER fluid with various electric field strengths are shown in figure 8. In this experiment, the exciting signal is a sinusoidal scanning signal from 1 to 240 Hz. It is seen that the damping characteristic of the structure changes with changing electric fields [10]. The vibration amplitudes decrease with increasing electric field strength at the domains near the natural frequencies. The natural frequency is also increased with the increasing electric field strength. However, in the other range of vibration frequency the vibration amplitudes increase when an electric field is applied to the ER fluid. The desired controlled frequency response curve must be the frequency response curve with minimum vibration amplitude at different vibration frequency. To solve this problem, an active control algorithm based on fuzzy logic is proposed in this paper and used to actively control the vibration of the smart structure. This control rule can be expressed as:

$$\text{if } f_i < f < f_{i+1} \text{ then } E \text{ on (or } E \text{ off)} \tag{3}$$

where f is frequency; 'E on' (or 'E off') means an electric field would (or would not) be imposed on the ER fluid. The desired frequency–response curve with minimum vibration amplitude could be obtained by employing an electric field according to the frequencies indicated by the dotted line (curve 4) in figure 8. An active control rule for the beam with frequency response shown in figure 8 can be formulated as:

$$\begin{array}{ll}
\text{if } 1\ \text{Hz} < f < 56.87\ \text{Hz} & \text{then } E \text{ on } \left(1\ \text{kV mm}^{-1}\right) \\
\text{if } 56.87\ \text{Hz} < f < 81.06\ \text{Hz} & \text{then } E \text{ off} \\
\text{if } 81.06\ \text{Hz} < f < 113.63\ \text{Hz} & \text{then } E \text{ on} \left(2\ \text{kV mm}^{-1}\right) \\
\text{if } 113.63\ \text{Hz} < f < 151.57\ \text{Hz} & \text{then } E \text{ off} \\
\text{if } 151.57\ \text{Hz} < f < 202.66\ \text{Hz} & \text{then } E \text{ on } \left(2\ \text{kV mm}^{-1}\right) \\
\text{if } 202.66\ \text{Hz} < f < 240\ \text{Hz} & \text{then } E \text{ off.}
\end{array} \tag{4}$$

The experiment of active vibration control of a smart composite beam has been finished according to the above fuzzy-logic control rule. The results are shown in figure 9. The active controlled frequency–response curve of the smart composite beam is curve 4 presented in figure 9 (indicated by the solid line). From figure 9, it is seen that the active controlled frequency–response curve is along the desired frequency–response curve indicated by the dotted line in figure 8.

Similarly, the frequency–response curves of the smart composite beam embedded fiber optic sensor (FOS) and ER fluid with respect to different electric field strengths are shown in figure 10. The frequency response is detected by

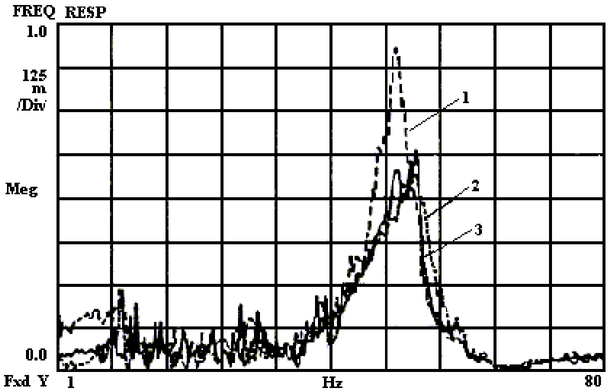

Figure 11. Active control curve of smart composite beam based on fiber optic sensor (FOS) and ER fluids: 1, 0 kV mm^{-1}; 2, 1 kV mm^{-1}; 3, controlled curve (solid line).

using the fiber optic vibration sensor. In this experiment, the exciting signal is sinusoidal, scanning from 1 to 80 Hz. From figure 10 it can be seen that the natural frequency increases under a 1 kV mm^{-1} electric field. The vibration amplitude decreases with increasing electric field intensity. The curves of the active controlled results are shown in figure 11. From here it can be found that the controlled frequency response curve is accurate along the desired minimum frequency response curve. Thus, the structural vibration of the smart structure based on the ER fluid, piezoelectric transducer and FOS can effectively control using the proposed control algorithm based on fuzzy logic.

4. Conclusions

From the above discussions, the following conclusions are obtained.

(1) Fiber optic sensor (FOS) is suitable for use in smart structures as an internal sensor. A new intensity modulated optical fiber vibration sensor based on the face coupling theory has been developed. It has sensitivity comparable to the traditional piezoelectric sensor at lower vibration frequencies. Also it is lower in cost.

(2) ER fluids can be used to change the structural damping characteristics effectively as an actuator due to their fast and strong reversible changes in rheological properties. So an ER fluid actuator can realize active on-line control for smart structures.

(3) A smart structure based on ER fluid, piezoelectric transducer and fiber optic sensor (FOS) has been developed. Also, the active vibration control of this smart structure has been accomplished using a fuzzy-logic control algorithm. The experimental results demonstrate that the structural vibration can be monitored and controlled more effectively using the smart structures based on the ER fluid, fiber optic sensor (FOS) and piezoelectric transducer.

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