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LETTERS TO THE EDITOR

ELECTRIC FIELD-DEPENDENT VIBRATION CHARACTERISTICS OF A PLATE FEATURING AN ELECTRORHEOLOGICAL FLUID

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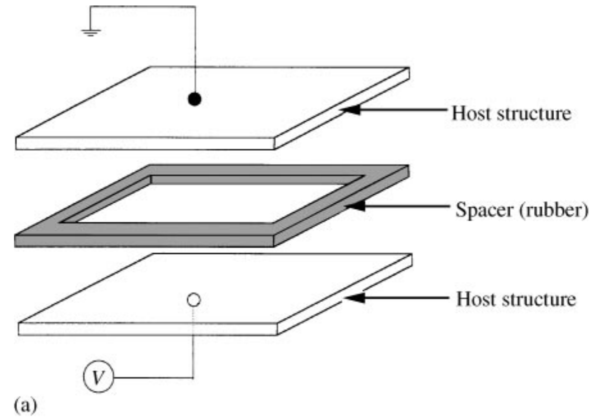
1. INTRODUCTION

Recently, smart structures with inherent adaptive capabilities to variable environments have made great progress as a new methodology for vibration control. Typically, incorporated with aluminium, steel, and composite materials, smart structures have exploited piezoelectric sensing and actuating technologies, shape memory alloy actuators, and electrorheological (ER) fluid actuators. It is well known that ER fluid itself exhibits dramatic and reversible phase change in the presence of electric fields. Embedded in voids of distributed parameter structures, ER fluid enables stiffness and damping properties of the structure, to be actively tuned by the intensity of the electric field applied to the ER fluid domain. Choi *et al.* [1] carried out experimental investigations on the field-dependent vibration characteristics of ER fluid-based cantilevered beams. The natural frequencies and loss factors are identified with respect to the intensity of the electric field. Choi *et al.* [2] experimentally implemented an active control scheme for an ER fluid-based beam via measured field-dependent transfer function between voltage input and changed damping and stiffness outputs. Gong and Lim [3] experimentally observed field-dependent vibration properties of a sandwiched beam clamped at both ends and fully or partially treated with an ER fluid layer. Yalcintas and Coulter [4] proposed an analytic model to predict field-dependent vibration characteristics of ER materials-based axially non-homogeneous beams. As evident from the aforementioned studies a lot of research has been carried out on ER fluid-based beams. However, research on the vibration characteristics of plates associated with ER fluids is considerably rare.

Consequently, the main objective of this work is to present experimentally obtained vibration characteristics of a two-dimensional plate filled with an ER fluid (we call it ER plate). A sandwich type of ER plate, in which chemical starch/silicon oil-based ER fluid is contained between two elastic face layers, is constructed. After establishing an experimental set-up, modal natural frequencies are investigated with respect to the intensity of the electric field. In addition, mode shapes of the ER plate are experimentally obtained in both absence and presence of the electric field.

2. EXPERIMENTAL APPARATUS

A schematic configuration of the proposed ER plate is shown in Figure 1. The plate consists of a rubber space, an ER fluid, and two elastic face layers of aluminium. The



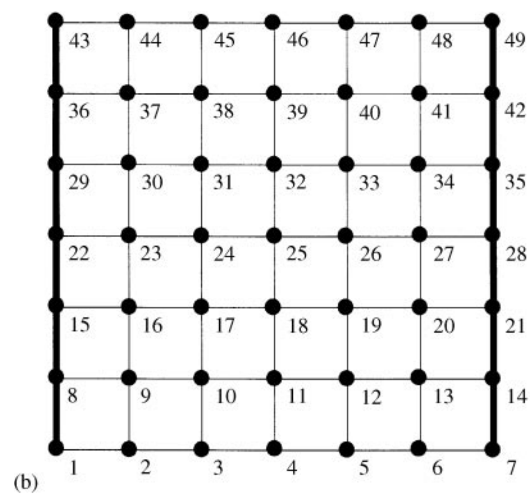
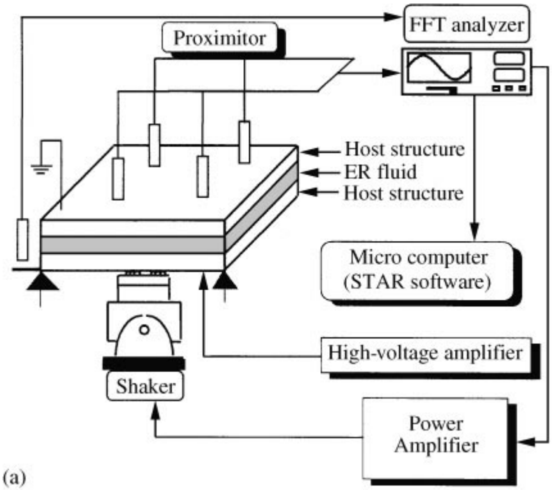


Figure 1. Schematic configuration of the proposed ER plate. (a) Configuration. (b) Measuring point.

aluminium layers (0·25 mm thickness) provide rigidity as a host structure, and also serve as electrodes, and the silicon rubber spacer acts as a seal to hold integrity of the structure, as well as an electrical insulator. The rubber spacer is perfectly bonded to the face layers with a silicon room-temperature vulcanite adhesive. The chemically treated starch particle/silicon oil-based ER fluid is inserted into the void between the two face layers. The particle concentration of the ER fluid is 55% by weight, and the volume fraction of the ER fluid to the total structure is 75%. It is noted that the composition of the ER fluid and the volume fraction are very important parameters in determining field-dependent vibration characteristics of the ER plate. The size of the plate is 400 mm $\times$ 400 mm with a total thickness of 4·35 mm, and 36 rectangular elements of a 6 $\times$ 6 array with 49 measuring points (refer to Figure 1(b)) are employed to obtain vibration characteristics such as mode shapes.

Figure 2 presents a schematic configuration and photograph of the experimental apparatus to investigate field-dependent vibration characteristics of the ER plate. The plate is mounted to a fixture on clamped–clamped boundary conditions along two opposite sides. The rigid fixture is bolted on the shaker, and both the fixture and the shaker are insulated from the applied electric field. A proximitor is located in the fixture to measure the input signal and another probe is set over the plate to pick up vibration responses. The shaker is excited with random signals from the dynamic signal analyzer (FFT analyzer) through the



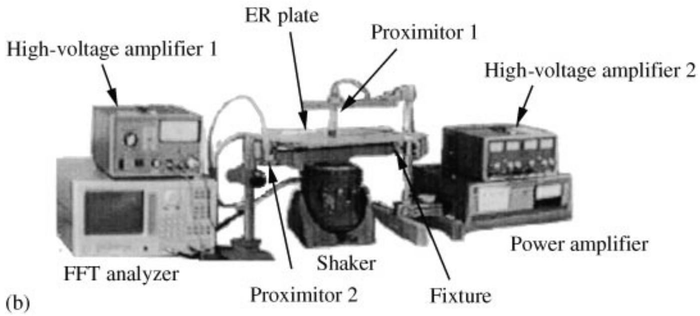


Figure 2. An experimental set-up. (a) Configuration. (b) Photograph.

power amplifier. Both the input and output signals form the two proximitors are used to obtain frequency responses (transfer functions) at an interested position over the focused frequency span of 0–100 Hz, which contains the first four modes of the ER plate. With the aid of commercially available system software called STAR installed on a microcomputer, the transfer functions measured at each measuring point are used to infer natural frequencies and mode shapes. High-voltage amplifiers independently furnish the ER plate with high electric fields in a continuous/discrete fashion. Considering both the effect of deflection suppressions and the measuring range of the proximitors, the random excitation magnitude is appropriately limited to a r.m.s. of 2·3 m/s^2. Furthermore, on the basis of the fact that the employed ER fluid easily changes into a solid phase at a low electric field because of the high particle concentration of 55%, the field of 1·0 kV/mm is chosen as a maximum electric field.

3. EXPERIMENTAL RESULTS

Table 1 presents predicted and measured modal frequencies of the proposed ER plate. The predicted one was obtained by incorporating field-dependent storage and shear modulus of the ER fluid with conventional sandwich plate theory [5]. As clearly presented, the agreement between the two results is fairly good at various electric fields. It is observed

Table 1

Field-dependent modal frequencies

Electric field (kV/mm)	Modal frequency (Hz)			
	(1, 1) mode	(1, 2) mode	(2, 1) mode	(2, 2) mode
Predicted				
0·0	11·00	14·01	37·99	49·00
0·6	11·21	17·28	41·87	56·20
0·8	11·68	18·42	43·02	58·24
1·0	11·75	19·66	44·93	60·45
Measured				
0·0	11·12	12·55	37·67	48·67
0·6	11·70	13·47	40·75	53·82
0·8	11·73	13·69	42·53	60·56
1·0	11·82	19·07	44·61	75·71

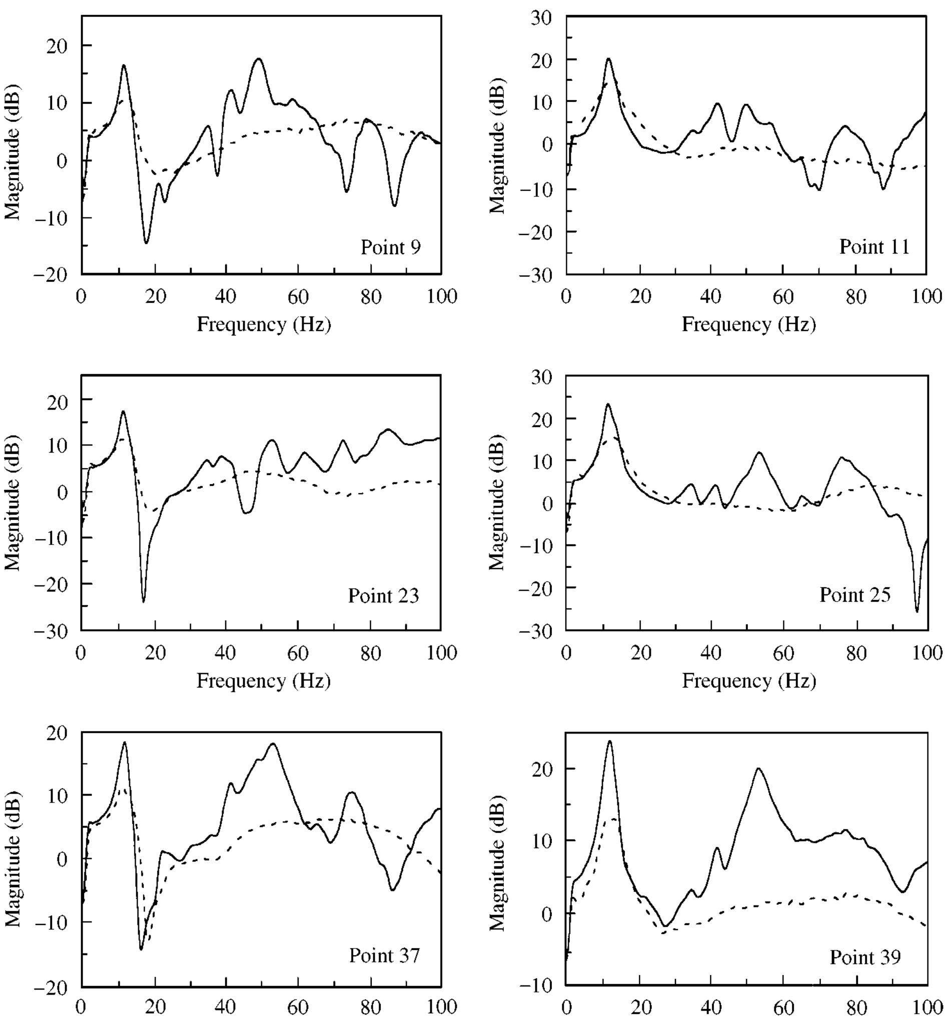


Figure 3. Frequency responses of the ER plate: — no voltage; - - - 1 kV/mm.

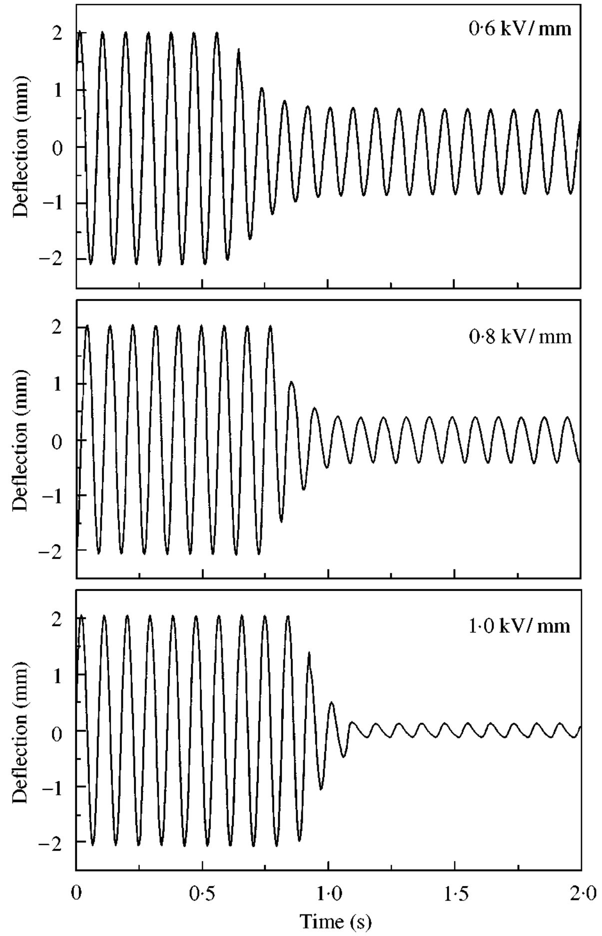


Figure 4. Time responses of the ER plate at the measuring point of 25.

from the measured one that the fourth mode (2, 2) natural frequency of 48·67 without electric field increases to 75·71 Hz by applying the electric field of 1·0 kV/mm. The tuning capability of the modal frequency of the ER plate can be exploited to control undesirable vibration by avoiding resonance phenomenon in an active manner [2].

Frequency responses of various measuring points are shown in Figure 3. As clearly observed, both the stiffness and damping characteristics of the ER plate are changed by applying the electric field, and the amount of change depends on the measuring point. Figure 4 presents the field-dependent capability of suppressing the forced vibration of the ER plate. The forced vibration is induced by exciting (1, 1) mode with the frequency of 11·12 Hz, and the responses are measured at the measuring point 25. We clearly see that the imposed vibration is quickly suppressed by applying the electric field. This is, of course, due to the tuning ability of stiffness and damping properties of the ER plate. The field-dependent mode shapes of the plate are also obtained from the measured frequency responses shown in Figure 3 using STAR modal software, and presented in Figures 5–7. We see that the amplitude of each mode shape is effectively suppressed by applying the electric field. It is noted that the amplitude of the mode shape is normalized with respect to the amplitude of mode (1, 1). Using the tuning capability of the mode shape of the ER plate, we

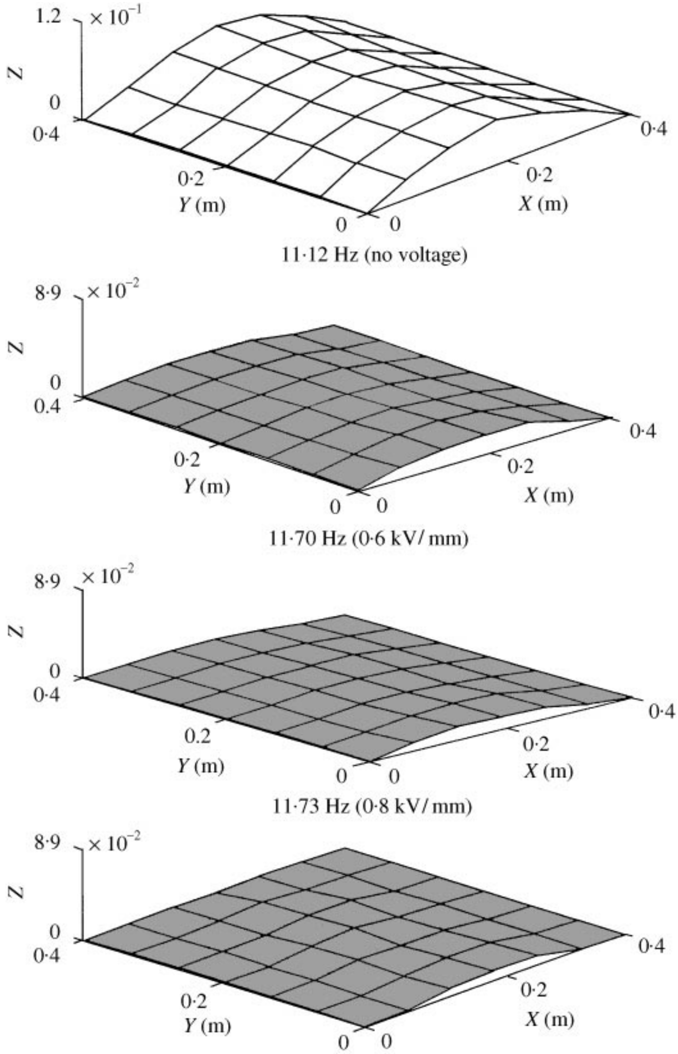


Figure 5. Mode shapes of the ER plate: Mode (1.1).

may devise various structure applications, such as aircraft wing, subjected to stringent environment conditions. This can be accomplished by achieving desired mode shape by actively controlling the intensity of the electric field in a real-time manner.

4. CONCLUSION

A plate filled with an electrorheological fluid was proposed and its vibration characteristics were experimentally evaluated with respect to the intensity of electric fields. It was observed that the natural frequencies are increased as the field intensity increases. It has been also demonstrated that the mode shapes of the plate can be tuned by the intensity of the electric field. The experimental results presented in this preliminary study indicate

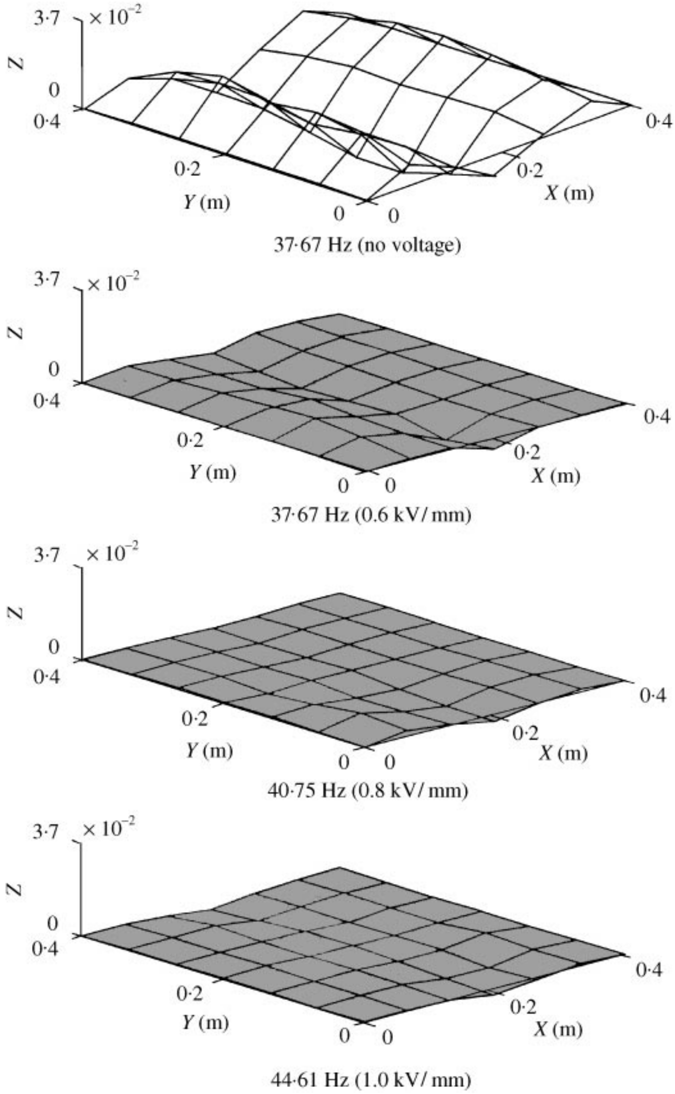


Figure 6. Mode shapes of the ER plate: Mode (2.1).

that desirable vibration characteristics of the ER plate can be achieved by controlling the intensity of the electric field. An active control algorithm to achieve desired (arbitrary) mode shape is being undertaken as the second phase of this study.

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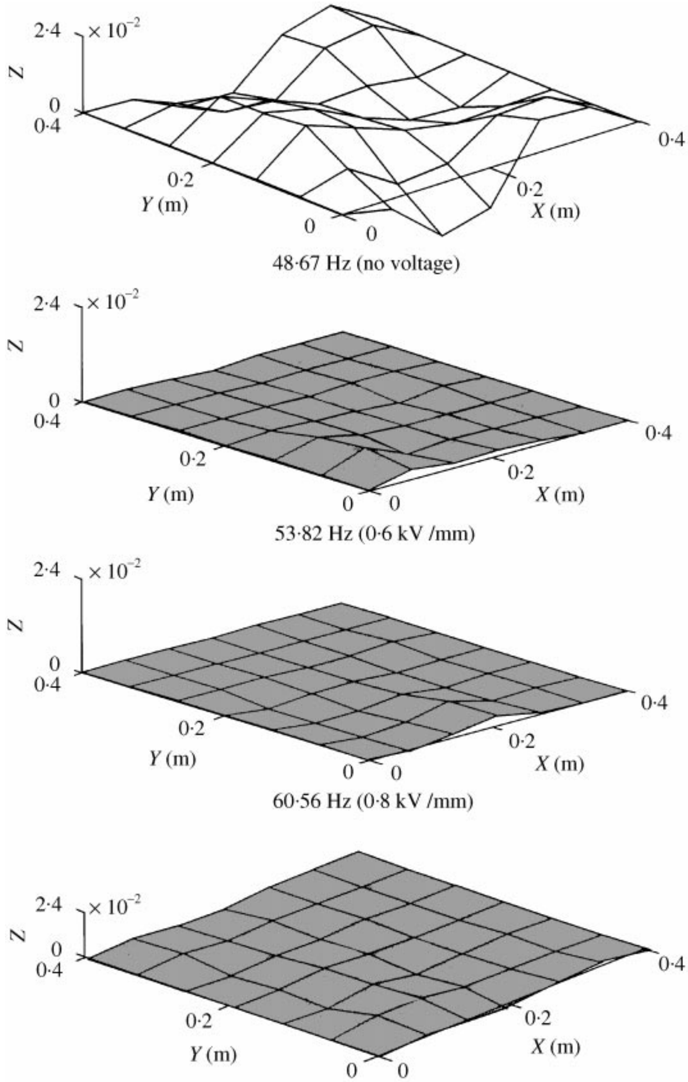

Figure 7. Mode shapes of the ER plate: Mode (2.2).

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