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Journal of Sound and Vibration 298 (2006) 1150–1158

JOURNAL OF SOUND AND VIBRATION

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Short Communication

Vibration control of variable speed/acceleration rotating beams using smart materials

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Received 9 June 2005; received in revised form 21 March 2006; accepted 29 May 2006
Available oline 28 July 2006

Abstract

The electrorheological (ER) sandwich structure is proposed for vibration control of the rotating flexible beams with variable speed/acceleration in this study. A sandwich beam specimen, which is treated with ER fluid sandwiched between two aluminum surface layers, is constructed. An experiment has been undertaken to investigate the vibration response performances of the rotating beam with respect to the intensity of the electric field, the rotating speed and acceleration. The experimental results demonstrate that the vibration of the beam caused by the rotating motion at different rotating speed and acceleration can be quickly suppressed by applying the electric field to the ER beam, and evaluate the feasibility of ER fluid in attenuating the vibration of rotating beams.

1. Introduction

Rotating beams are found in many practical engineering applications, such as robot arms, turbine blades, and aircraft rotary wings. Considerable interest has been directed towards the development of various control approaches to damp out the vibration of rotating beams. These techniques mainly fall into two categories: passive control and active control. In the former, constrained viscoelastic damping layers are usually used to attenuate the vibration of rotating beams [1,2]. This method is conventional and well developed. However, the passive approach suffers from the major drawback of being ineffective at low frequencies. In the active control systems, the piezoelectric composites are used extensively [3–6]. In the present study, a new approach, embedding electrorheological (ER) fluid into the sandwich structure, is considered to suppress the vibration of rotating beams.

ER fluid is a kind of smart material whose physical properties such as viscosity and shear modulus can undergo instantaneous and reversible changes when subjected to different electric field. These unusual properties enable ER fluid to be employed in numerous potential engineering applications, such as shock absorbers, clutch/brake systems, valves and intelligent structures. One of the most commonly researched of ER fluid structures is the ER fluid treated sandwich beam, in which the ER fluid completely fills the gap

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doi:10.1016/j.jsv.2006.05.033

between two containing surface layers [7]. These sandwich structures have adaptive control capabilities of varying the damping and stiffness of the beam by changing the intensity of the applied electric field. Since Gandhi et al. [8] first proposed the application of ER fluid to the adaptive structure, many achievements have been obtained in vibration control of beam [9,10] or plate structures [11].

However, research on the application of ER fluid to vibration control of rotating motion beams is considerably rare. In our previous work, the dynamic characteristics of the rotating sandwich beam filled with ER fluid were numerically analyzed [12]. The emphasis of this work is to experimentally present and discuss the feasibility of using ER fluid in controlling the vibration of rotating beams with variable speed/acceleration, especially the robot arm for IC packaging. In semiconductor and electronic components manufacturing, the robot arm operates at to-and-fro motion with a high velocity/acceleration and high accuracy. But the high velocity/acceleration motion will cause undesirable vibration at the arm tip, and decrease the positioning precision [13]. Suppressing the vibration of the arm tip in a very short time becomes more and more important in the field of semiconductor and electronic components manufacturing [14].

In this study, an ER sandwich beam specimen, in which an ER fluid layer is sandwiched between two aluminum surface layers, is constructed. An experiment setup is established to investigate the effect of the ER fluid on vibration suppression of the rotating beams. Vibration control responses subjected to different electric field intensity, rotating speed and acceleration are demonstrated and evaluated.

2. Theory and formulation

Although the theoretical derivation for the rotating sandwich beam with an ER fluid layer can be found in the previous work [12], a brief summary is described here for the completeness of this paper.

Fig. 1 shows the geometry of a rotating ER sandwich beam. The beam with a length L and width b is rotating in a horizontal plane at angular $\dot{\theta}$ about the axis of hub. According to Ref. [12], when there is no applied force, the finite element equation of a rotating ER sandwich beam is given by

$$\mathbf{M}\ddot{\mathbf{q}} + (\mathbf{K}_1 + \mathbf{K}_2 + \dot{\theta}^2\mathbf{K}_3)\mathbf{q} = 0 \tag{1}$$

with

$$\mathbf{M} = \sum_{i=1}^{n} \mathbf{B}_i^{\mathrm{T}} \int_0^{L_i} \sum_{k=1}^{3} [\rho_k A_k (\mathbf{N}_k^{\mathrm{T}}\mathbf{N}_k + \mathbf{N}_4^{\mathrm{T}}\mathbf{N}_4)]\,\mathrm{d}x\,\mathbf{B}_i,$$

$$\mathbf{K}_1 = \sum_{i=1}^{n} \mathbf{B}_i^{\mathrm{T}} \int_0^{L_i} \sum_{k=1}^{3} (E_k A_k \mathbf{N}_{k,x}^{\mathrm{T}}\mathbf{N}_{k,x} + E_k I_k \mathbf{N}_{4,xx}^{\mathrm{T}}\mathbf{N}_{4,xx})\,\mathrm{d}x\,\mathbf{B}_i,$$

$$\mathbf{K}_2 = \sum_{i=1}^{n} \mathbf{B}_i^{\mathrm{T}} \int_0^{L_i} \frac{G_2^* b}{h_2} \left[\mathbf{N}_1 - \mathbf{N}_3 + \frac{2h_2 + (h_1 + h_3)}{2}\mathbf{N}_{4,x}\right]^{\mathrm{T}} \left[\mathbf{N}_1 - \mathbf{N}_3 + \frac{2h_2 + (h_1 + h_3)}{2}\mathbf{N}_{4,x}\right] \mathrm{d}x\,\mathbf{B}_i,$$

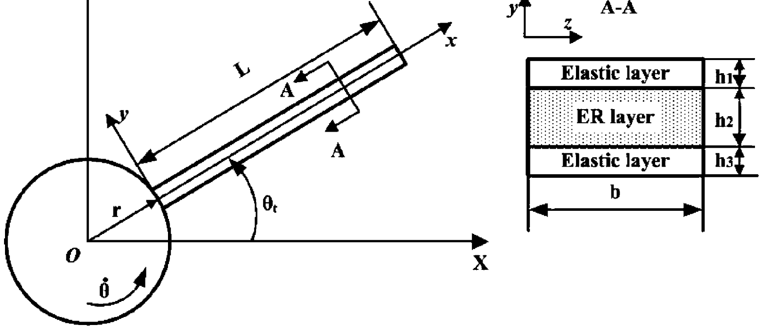

Fig. 1. The rotating sandwich beam embedded with ER fluid.

$$K_3 = \frac{1}{4}\sum_{i=1}^{n}\mathbf{B}_i^{\mathrm{T}}\int_0^{L_i}\sum_{k=1}^{3}\rho_k A_k\{[L^2-(x_i+x)^2]+2r[L-(x_i+x)]\}N_{4,x}^{\mathrm{T}}N_{4,x}\}\,\mathrm{d}x\mathbf{B}_i$$
$$-\sum_{i=1}^{n}\mathbf{B}_i^{\mathrm{T}}\int_0^{L_i}\sum_{k=1}^{3}[\rho_k A_k(N_k^{\mathrm{T}}N_k+N_4^{\mathrm{T}}N_4)]\,\mathrm{d}x\mathbf{B}_i \quad (2)$$

where $\mathbf{M}$ is the generalized mass matrices, $\mathbf{K}_1$ is the generalized stiffness matrices, while $\mathbf{K}_2$ and $\mathbf{K}_3$ are the matrix associated with the shear deformation of the ER fluid layer and centrifugal force by rotating, $\mathbf{B}_i$ ($i = 1\ldots n$) is the Boolean matrices; $\mathbf{N}_j$ ($j = 1,2,3,4$) and $\mathbf{q}$ are the finite element shape functions and the nodal deflection vector; E_k, I_k, ρ_k and A_k ($k = 1,2,3$) are the Young's modulus, moment of inertia, density and cross-section area of the kth layer, respectively; $G_2^* = G' + G''i$ is the complex shear modulus of ER fluid, while G' is the storage modulus and G'' is the loss modulus; and subscript (,x) denotes partial differentiation with respect to co-ordinate x.

The dynamic characteristics of the rotating beam can be got by the eigenvalue problem

$$\{[\mathbf{K}_1+\mathbf{K}_2+\dot{\theta}^2\mathbf{K}_3]-(\omega^*)^2\mathbf{M}\}\mathbf{\Phi}=0, \quad (3)$$

where ω^* is the complex radian frequency (rad/s) and $\{\Phi\}$ is the corresponding eigenvector. The complex eigenvalues $(\omega^*)^2$ can be expressed as

$$(\omega^*)^2=\omega^2(1+\mathrm{i}\eta), \quad (4)$$

where η is the modal system loss factor and ω is the nature frequency.

3. Experimental layout

The ER beam specimen, as shown in Fig. 2, is treated with an ER fluid layer which confined by a 2 mm rubber dam on the edges sandwiched between two aluminum face-plates. The aluminum face-plates also serve as the electrodes for the applied electric field. At one end of the beam, a glass/epoxy pad with a length 20 mm and width 35 mm is used as the mid-layer to provide the rigidity for the clamping force.

The ER fluid used in this study consists of corn starch suspensions in silicone oil. The carrier fluid has a viscosity of 50 cS, and the volume fraction of the suspension is 10%. The geometrical and material parameters of the ER sandwich beam specimen are listed in Table 1.

Fig. 3 presents a schematic configuration and photograph of the experimental setup to investigate vibration control response of the rotating ER beam at different electric strength and motion conditions. The test beam was clamped at a rotating platform driven by a variable speed/acceleration servomotor in a cantilevered configuration. Considering the ER beam was directly connected with a high-voltage power supply, a non-contact eddy current probe (model CWY-DO-20T08), which was also anchored on the rotating platform and can motion in company with the rotating beam, was used to measure the vibration displacement of the ER beam. In order to avoid the deflection displacement of the measuring point surpassing its measuring range, the eddy current probe was located at 17 mm far from the beam root. By the vibration theory, beam is a continuous system. Regardless of measuring point whether is located at the tip end of the beam, the deflection response curve should contain the vibration information of the beam, like mode, frequency and so on.

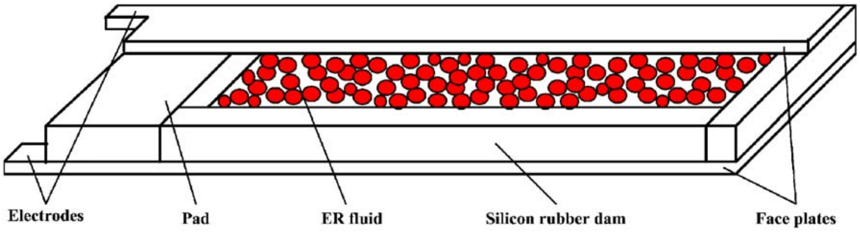

Fig. 2. Schematic diagram of the ER sandwich beam specimen.

Table 1
Main properties of the ER sandwich beam

Layer	Material	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)	Modulus (MPa)
Surface layer	Aluminum	320	35	0.4	2683.9	70
ER fluid layer	Corn starch/silicon oil	300	35	2	1338	

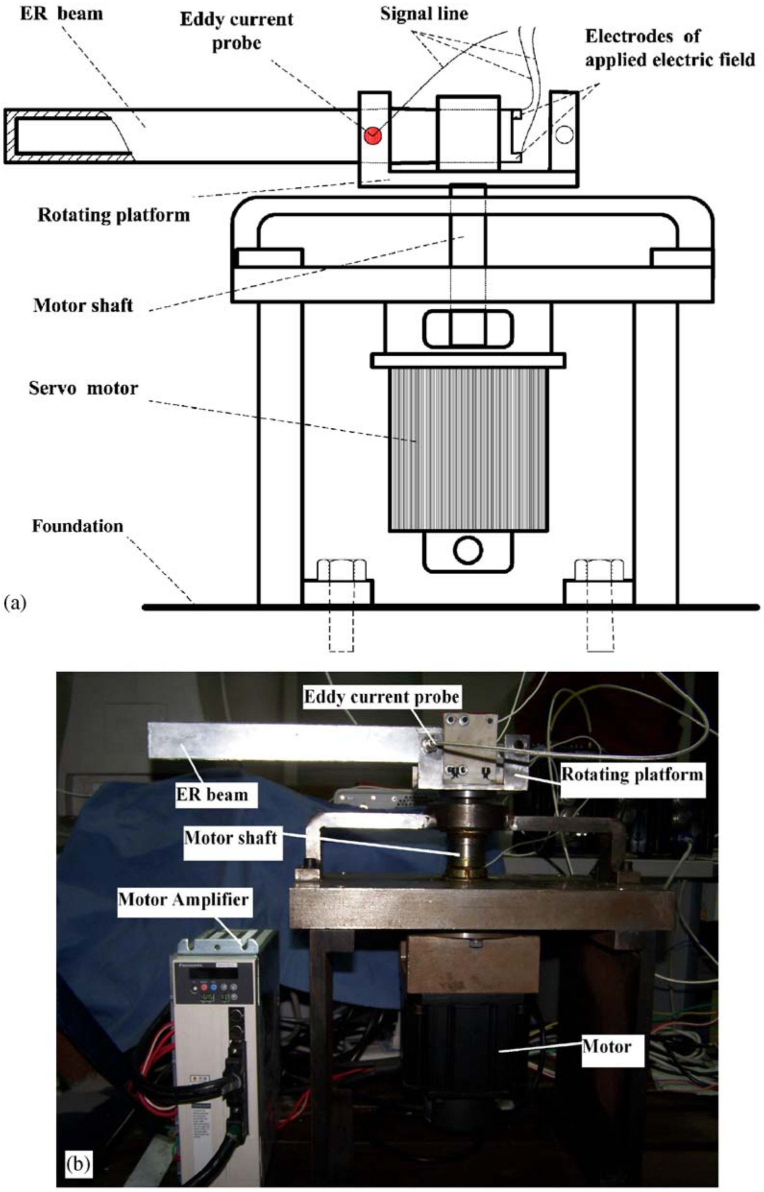

Fig. 3. Experimental setup for the rotating ER beam.

A dynamic signal analyzer, produced by Data Physics Corporation with model number SignalCalc430, is used to process the acquired analog signals from the eddy current probe. A high-voltage power supply connected with the aluminum face-plates provides the required electric field during the test.

4. Results and discussions

In this test, the rotating platform rotates from 0 to π, and then backtracks. The rotating angle acceleration is chosen as 20, 40, and 80 rad/s^2. Considering the specimen is sealed by silicon rubber, the rotating speed is limited to 120 rev/min (revolutions per minute). The motional track of the rotating platform is shown in Fig. 4. Four levels of electric field strength (0 , 0.5, 1, and 1.5 kV/mm) are applied to the rotating ER beam.

The vibration control responses of the rotating ER beam at different electric field strength, rotating speed and acceleration are shown in Figs. 5–8, respectively. Fig. 5 presents the response curves at different intensity of applied electric field when maximal rotating speed $\dot{\theta} = 30$ rev/min and angle acceleration $\ddot{\theta} = 20$ and $\ddot{\theta} = 40$ rad/s^2. It is shown that the vibration response characteristic of the beam is almost not affected by the

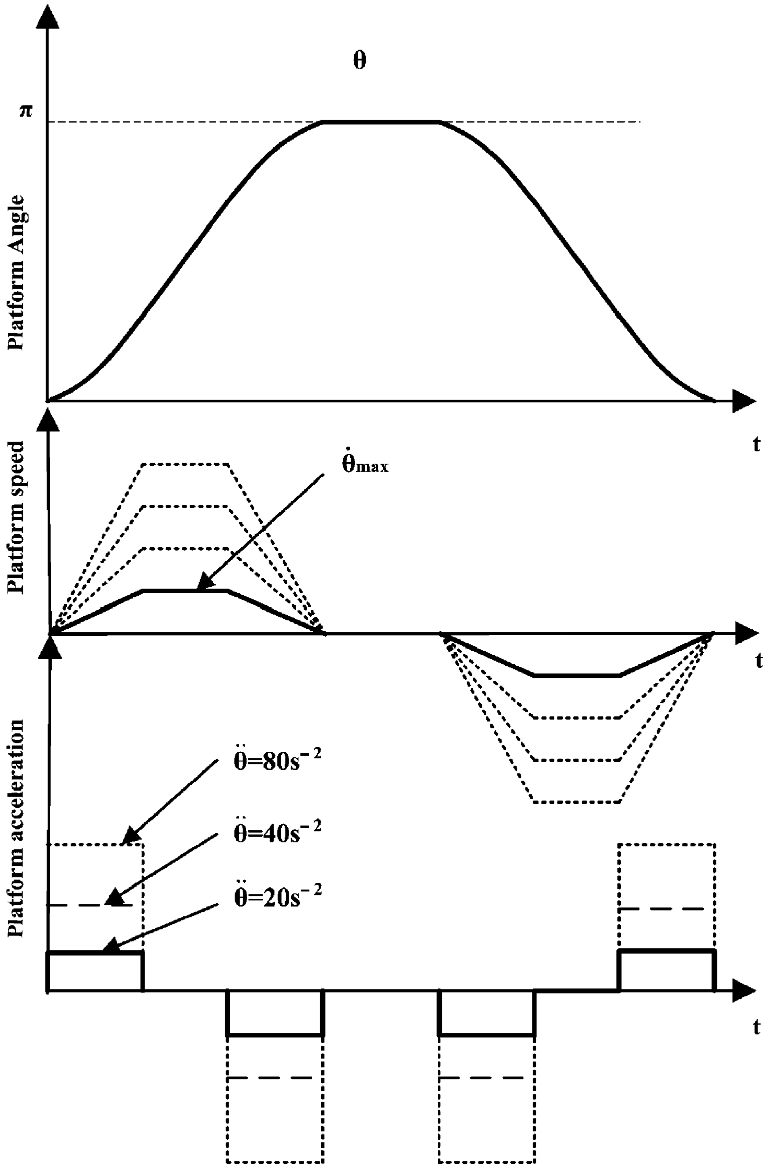

Fig. 4. Motion track of the rotating platform.

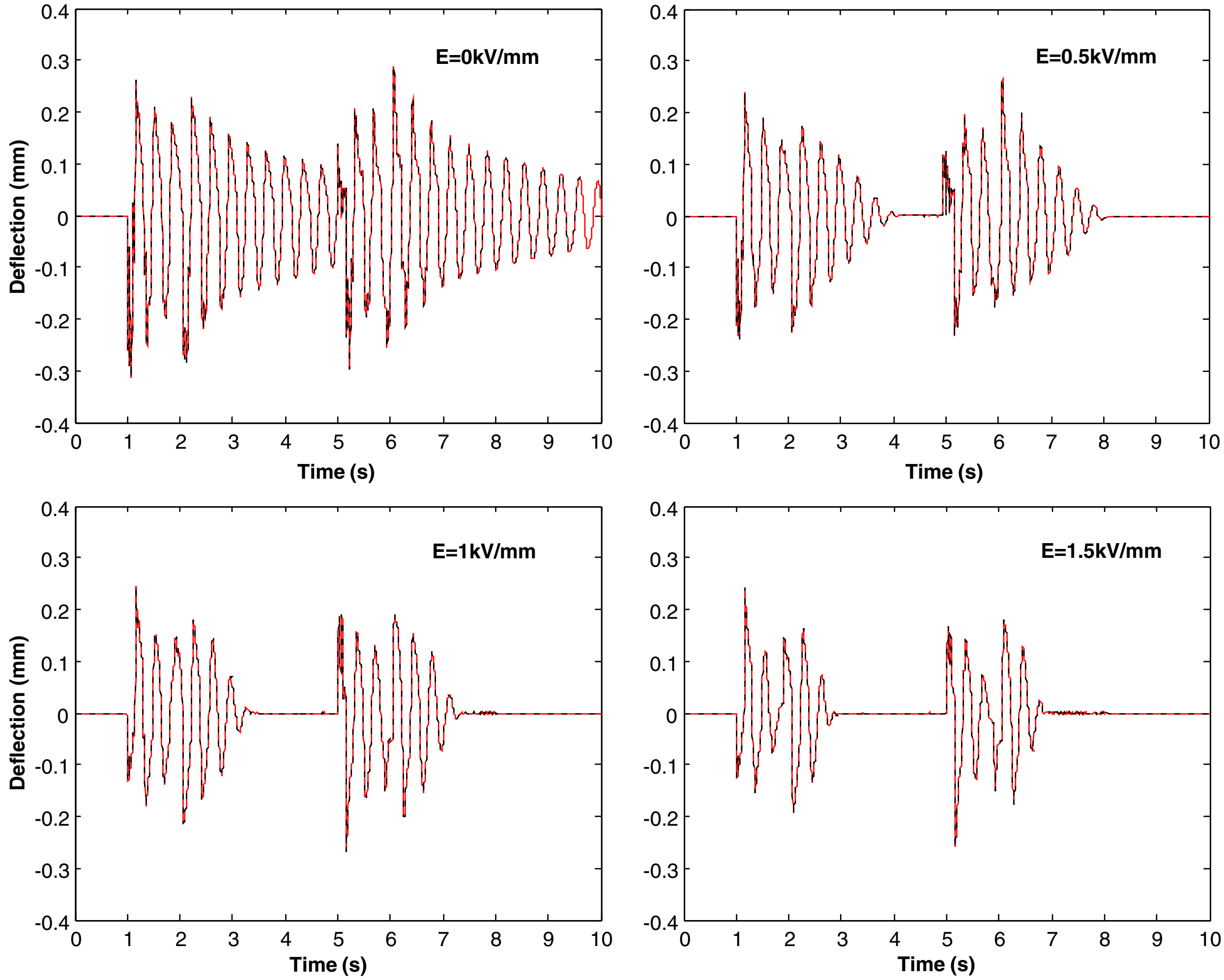

Fig. 5. Vibration responses at maximal rotating speed $\dot{\theta} = 30$ rpm: —— 20 rad/s^2; - - - - - 40 rad/s^2.

angle acceleration. In both state, the vibration decay time is nearly same, and only the vibration amplitude is a little change. But the effect of electric field strength on the decay time is all very obvious for different angle accelerations. The beam vibrations are all eliminated in less than 3 s with applied electric field intensity $E = 0.5$ kV/mm, while the vibrations last for more than 5 s without applied electric field. By increasing the intensity of electric field, the decay times are further shortened. For example, when the electric field strength is increased from 0.5 to 1.5 kV/mm, the vibration decay times are shortened about 1 s. From Fig. 5, we also can see that the vibration frequencies are not varied with the electric field strength. The number of vibration cycle is three in each second at different intensity of electric field. This demonstrates that the ER fluid mainly tunes the damping of system to suppress the vibration of the beam by applying an electric field.

Fig. 6 is the vibration response of the rotating beam under maximal rotating speed $\dot{\theta} = 60$ rev/min and angle acceleration $\ddot{\theta} = 40$ and $\ddot{\theta} = 80$ rad/s^2. It can be seen that the vibration suppression capability of the rotating ER beam under applied electric field is similar to that when maximal rotating speed $\dot{\theta} = 30$ rev/min. Only the maximal vibration amplitude is increased. This is due to increasing rotating speed/acceleration will cause a larger centrifugal force applied on the beam, and intensify the vibration of the beam. At same time, we can see that the angle acceleration also hardly affects the vibration response of the beam from this figure. So we only discuss the variety of rotating speed in the following part.

Fig. 7 illustrates the measurement under maximal rotating speed $\dot{\theta} = 90$ rev/min and angle acceleration $\ddot{\theta} = 80$ rad/s^2 at different electric field strength. In this case, the effectiveness of vibration control of the

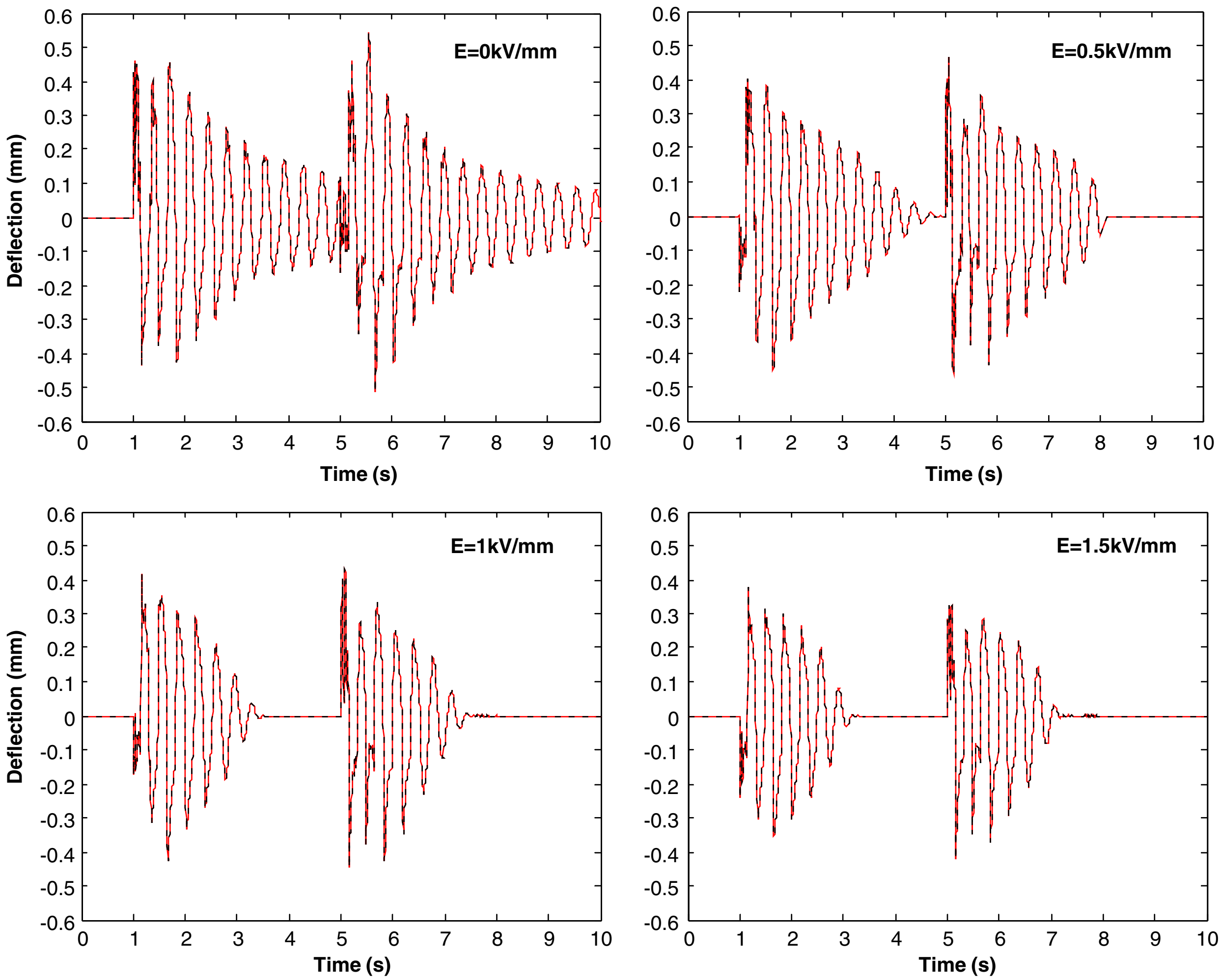

Fig. 6. Vibration responses at maximal rotating speed $\dot{\theta} = 60$ rpm: —— 40 rad/s^2; - - - - - 80 rad/s^2.

ER fluid is most obvious. The decay time of the beam vibration is less than 1.5 s under applied electric field strength $E = 1.5$ kV/mm, while the decay time is about 2 s in Figs. 5 and 6, respectively.

In order to only investigating the effect of the rotating speed on vibration responses, we fixed the angle acceleration $\ddot{\theta} = 80\,\mathrm{rad/s^2}$ and changed the rotating speed from 60 to 120 rev/min. The response characteristics with or without applied electric field are shown in Fig. 8. From this figure, we can see that the vibration response characteristic is not varied at different rotating speed when electric field strength $E = 0$ kV/mm. But when applied an electric field, the decay time is different although the vibration control effect is very obvious at different speed. The decay time is shortest at angle speed $\dot{\theta} = 90$ rev/min. This means that the rotating beam filled with ER fluid might have an optimum vibration control effect for one rotating speed by applying electric field. In the next study, this needs to be further investigated.

5. Conclusion

The vibration of a rotating beam with variable speed/acceleration has been controlled by using the sandwich beam filled with ER fluid. The vibration response performance of the rotating ER beam was experimentally evaluated with respect to the intensity of the electric field, the rotating speed and acceleration. The results obtained have indicated that the residual vibration of the rotating beam caused by the base motion at different

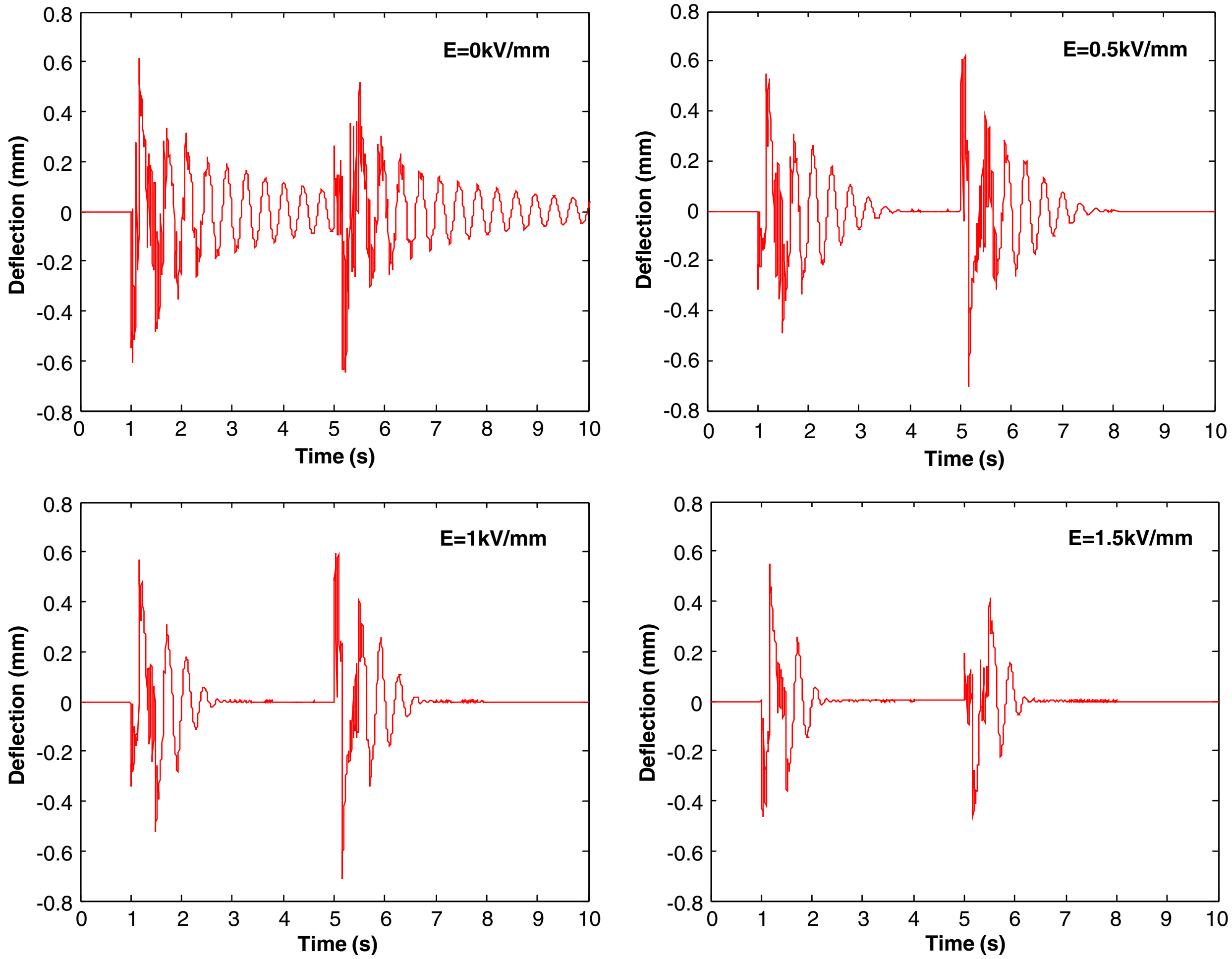

Fig. 7. Vibration responses at maximal rotating speed $\dot{\theta} = 90\,\text{rpm}$.

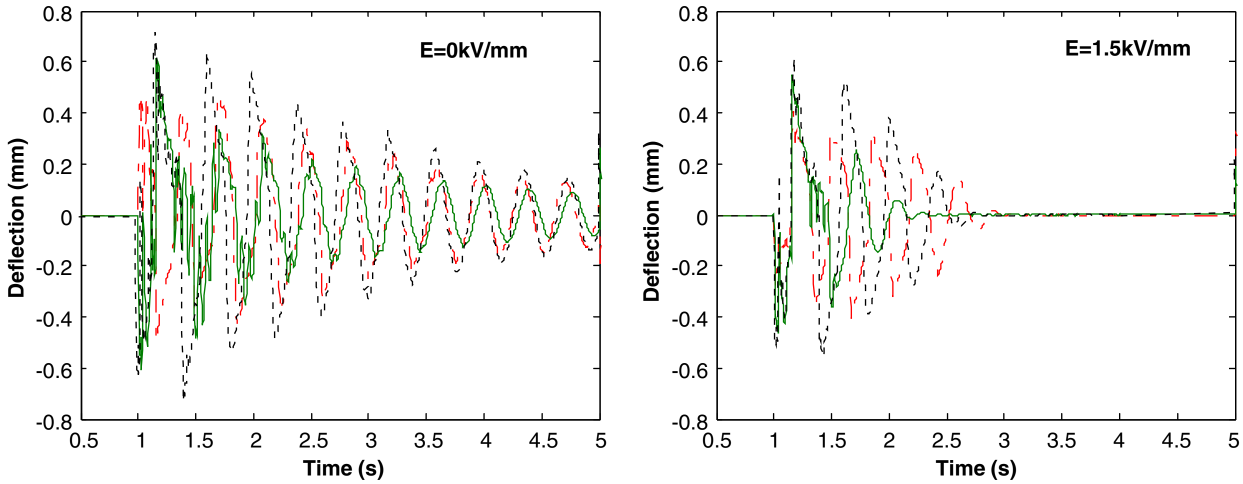

Fig. 8. The effect of rotating speed on vibration responses at angle acceleration $\ddot{\theta} = 80\,\text{rad/s}^2$: —·— 60 rpm; —— 90 rpm; - - - - - 120 rpm.

rotating speed and acceleration can be quickly suppressed by controlling the intensity of the electric field applied on the ER beam. These demonstrate the feasibility of the ER fluid in attenuating the vibration of rotating beams. An optimum control algorithm to achieve desired control effect will be undertaken in the next study.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSFC) under the Grant No. 50390063, and the Foundation of National Key Lab. of Defense Technology under the Grant No. 51463040403JW0301.

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