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LETTERS TO THE EDITOR

INVESTIGATION OF SEMI-ACTIVE FLUTTER CONTROL OF AN AIRCRAFT CONTROL SURFACE USING ER FLUID

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1. INTRODUCTION

Electro–rheological fluid is known as one of the high functional fluids whose apparent viscosity can be changed by an externally applied electric field. It is generally classified into two groups: colloidal suspension and homogeneous liquid. ER fluid has two attractive characteristics: controllability of its apparent viscosity and quick response to applied electric field. Thus it is suitable for mechanical components such as brakes, clutches, valves and controllable dampers.

Researchers on the performance of ER fluid dampers as well as its applications to structural vibration controls have conducted much work [1–3]. The most promising application of ER fluid is in semi-active damper systems, or active damping control systems. Many types of ERF dampers exist, such as shock absorbers, engine mounts, squeeze film and dynamic dampers [4, 5].

To be used as a controllable damping medium in a controllable damper or a similar mechanical device, ER fluid should have very low viscosity at zero electric field and a high viscosity gradient at an increasing electric field. With this type of ER fluid, a dynamic damper or pivot can serve as a controllable energy-consuming device for strucural stability control problems. This paper describes the performance of a controllable ERF damping pivot and its application to flutter control.

For a control surface of an aircraft wing, when operating normally, frequently demands a small amount of damping to provide a manipulative sensitivity, but near its flutter boundary or in a gust, desires a much higher level of damping to absorb the energy and hence alleviate flutter or oscillation tendency. The control surface is a small lifting surface, which rotates about a pivot. Obviously it is difficult to use an active control mechanism to control this tendency, but an ERF pivot is suitable for use as an active controllable damper. In the present study, the pivot was designed as a multi-ply rotating plate electrode damper, and the equivalent viscous damping of ERF pivot was measured and estimated. Furthermore, a prototype control surface with this type of pivot was constructed to demonstrate the feasibility of semi-active flutter control of wing control

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surface. Wind tunnel tests show that by using ERF pivot and bang–bang control law, the critical flutter speed can be increased by 36%.

2. ELECTRO–RHEOLOGICAL FLUID

2.1. *ER effect*

In the colloidal suspension type ER fluid, fine semi-conductive particles are dispersed in dielectric liquid, some with specific additives. As a colloidal suspension, ER fluid has little difference compared with ordinary colloidal suspensions. The main feature of ER fluid lies in its performance at an electric field. Generally, ER fluid consists of polarizable particles and insulating oil, and its rheological properties mainly depend on its ingredients, but particles are the most important. Typically, they are required to have strong polarity and different dielectric constants.

When an external electric field is not applied, fine particles suspend uniformly in the disperse liquid for the densities of semi-conductive particles and disperse liquid are nearly the same. When an electric field is applied, polarized charges appear on the surface of the dielectric particles, forming electric dipoles. The dipoles interact with each other by electrostatic forces and then the suspended particles form chain-like clusters along the electric field direction. The attraction of adjacent dipoles is the main reason for increasing viscosity and yield stress; the stronger the electric field, the stronger the attracting force between dipoles, and hence the bigger the yield stress.

2.2. *ER fluid*

This study considers the requirement of a controllable damping medium. It is found that starch dispersed in silicon oil with certain additives results in a type of ER fluid which has fairly good ER effect and low viscosity at zero electric field. For this type of ER fluid, various mass ratios (particle/oil) are selected and

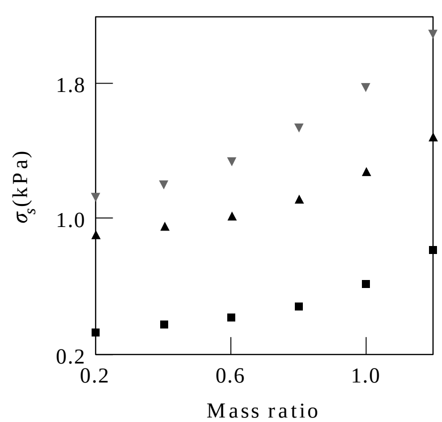

Figure 1. Shear strength for different mass ratios. Key for elecric field strengths (kV/mm): ■, 1·0; ▲, 2·0; ▼, 3·0.

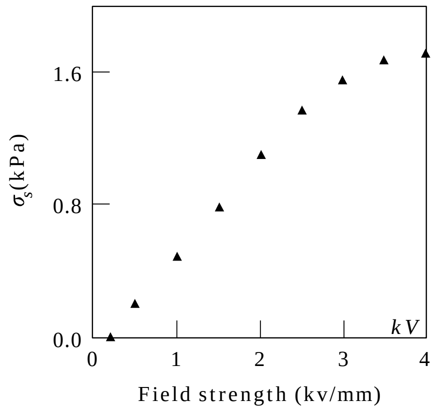

Figure 2. Shear strength at different electric fields.

their static yield stress was measured using an ERF static yield stress meter (see Figures 1 and 2).

Also, its yield stress increases with mass ratio and there is a critical mass ratio (about 0·8). When the critical mass ratio is exceeded, the yield stress increases rapidly and this critical value has little relation with the electric field. Note that the mass ratio should be limited because the viscosity should be low at zero electric field. As a result of trade off, a mass ratio of 0·8 is adopted in this work and its static yield stress is 0·3 kPa at zero electric field and 1·6 kPa with the 3 kV/mm electric field. The measured current passing through the two electrodes is about 3–4 μA at 3 kV/mm, so the energy consumption is a few milliwatts.

3. ERF DAMPING PIVOT

3.1. *Pivot design*

The pivot is essentially a multiply plate electrodes damper, as shown in Figure 3. The cylinder and covers form a sealed capsule. Two sets of plates act as positive and negative electrodes respectively. The subassembly of 1–2–7 and 3–6

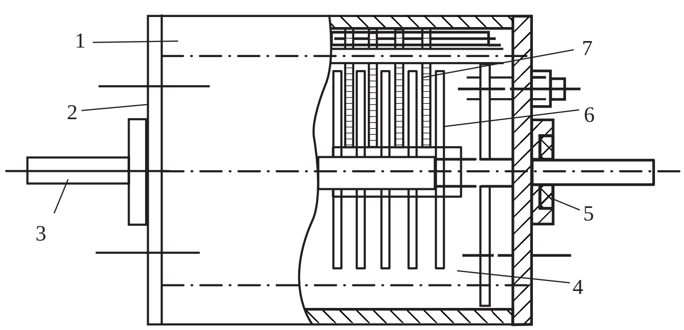

Figure 3. Diagram of ERF damping pivot: 1, cylinder; 2, cover; 3, axle; 4, ERF; 5, bearing; 6, positive electrode; 7, negative electrode.

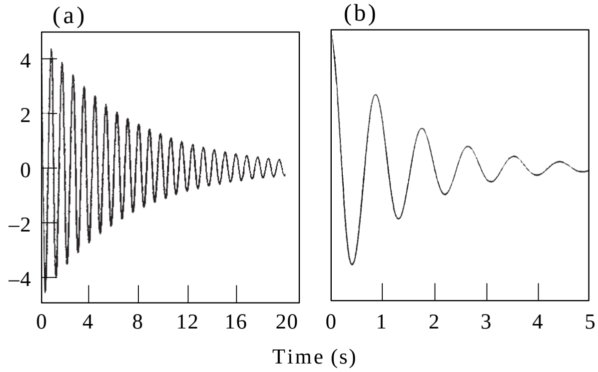

Figure 4. Free decay responses at (a) zero and (b) 1·0 kV/mm electric field.

can rotate relatively. By adjusting the applied electric field, the viscosity of the ERF is changed and hence controllable damping is obtained.

3.2. *Damping properties*

The damping property of the ERF pivot was experimentally studied. A physical pendulum swinging about this pivot was designed and built. The pivot was filled with the home made ER fluid. The fluid between the electrodes was electrically stressed by the electric field applied to the pivot using a high voltage power supply. The responses were measured by an accelerometer attached on the pendulum. Signals were amplified and fed into a SA390 Analyzer.

The logarithmic decrement method was employed to obtain the damping coefficient of the damping pivot at zero and at lower electric fields (see Figure 4), while curve fitting was used at higher electric fields because critical and supercritical damping were achieved (see Figure 5). For example, in Figure 4 the damping coefficient can be expressed by

$$c = 2I\ln[(x_1/x_2)/(t_2 - t_1)], \tag{1}$$

where I is the rotating inertia of the pendulum, and t_1, t_2 are the times at which the consecutive amplitudes occur.

The response of Figure 5a may be treated as critical damping, so $\zeta = 1$ and $c = 2I\omega_n$. The response in Figure 5b should be treated as supercritical damping.

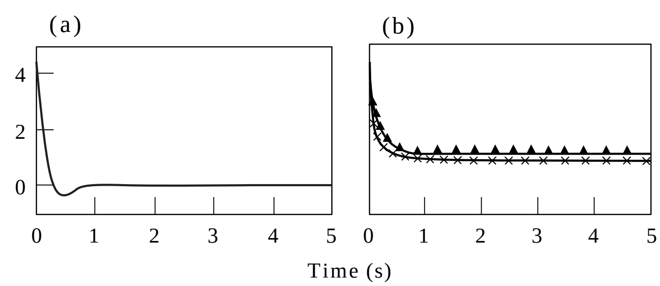

Figure 5. Free decay response at (a) 2·0 kV/mm and (b) —×—, 3·0 kV/mm; —▲—, ζ = 5·0.

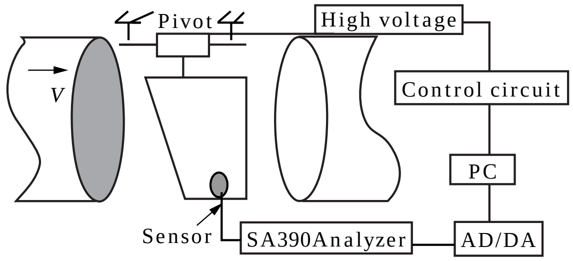

Figure 6. Setup of wind tunnel tests.

The damping coefficient can be fitted from

$$\theta = a_1 e^{(-\zeta+\sqrt{\zeta^2-1})\omega_n t} + a_2 e^{(-\zeta-\sqrt{\zeta^2-1})\omega_n t} \tag{2}$$

and

$$c = 2I\omega_n\zeta \tag{3}$$

Note that in Figure 5b, the upper curve is the measured response not decaying to zero because the ERF damper not only has viscous damping effects but also frictional damping effects, which are notable in a high electric field. The lower curve was calculated with the fitted value of ζ.

4. FLUTTER SUPPRESSION OF A CONTROL SURFACE

4.1. *Model design*

The control surface model has a trapezoidal layout; it is made of wood and can be considered as rigid compared with its support flexibility. As shown in Figure 6, the model has two degrees of freedom; θ, rotating about the pivot axis (X-axis) and ϕ, pitching about the Y-axis. The elastic recovery moments are supplied by two sets of leaf springs.

4.2. *Theoretical calculation*

The motion equation of the flutter system is

$$[\mathbf{M}]\begin{Bmatrix}\ddot{\theta}\\ \ddot{\phi}\end{Bmatrix} + [\mathbf{C}]\begin{Bmatrix}\dot{\theta}\\ \dot{\phi}\end{Bmatrix} + [\mathbf{K}]\begin{Bmatrix}\theta\\ \phi\end{Bmatrix} = \{\mathbf{Q}\} \tag{4}$$

where $[\mathbf{K}]$, $[\mathbf{M}]$, $[\mathbf{C}]$ are the stiffness, mass and damping matrices respectively, $\{\mathbf{Q}\}$ is the aerodynamic force. Using the V-g method, equation (4) can be solved to obtain the critical flutter speed at different electric fields, or damping levels. As the damping matrix is involved in the equation, the conventional V-g method does not work directly, so a modified V-g method, which involves an iterative procedure, was introduced. For this model, the critical flutter speed is 11·6 m/s at zero electric field and 16·8 m/s at 3 kV/mm electric field; the latter is increased by 45·1% compared with the former. It is evident that increasing the damping of the ERF pivot the flutter speed can be increased and therefore the flutter can be suppressed.

4.3. *Wind tunnel tests*

Wind tunnel tests were performed in a closed circuit low speed wind tunnel with an open test section of 1 m diameter, the maximum air speed attainable being 60 m/s. The installation of the model in the wind tunnel is shown in Figure 6.

Two control procedures were incorporated in the tests. The first procedure requires applying an electric field of 3·0 kV/mm to the damper when flutter occurs. After the flutter is suppressed, the electric field is set to zero and when the flutter occurs again, the electric field is re-applied. This control law was used to show the flutter suppression ability of the ERF damper and to test the response speed of the damper. The second law requires applying an electric field of 3·0 kv/mm to the damper when flutter occurs and after the flutter is suppressed, holding the voltage constant and increasing wind speed until flutter occurs at another higher speed. Figures 7a and 7b show the results of wind tunnel tests under the above control procedures respectively.

Shown in Figure 7a is the response time history under the first control procedure where the flutter speed is 12·4 m/s. It can be seen that when flutter occurs and the electric field is exerted, the system damping increases considerably, the critical flutter speed of the system increases and flutter is suppressed. When the electric field is removed and the damping level is decreased, flutter occurs again. This process was repeated several times to check the reaction speed of the ERF damping pivot. Figure 7b shows the response time history with the second control scheme. When flutter occurs (V_F = 12·4 m/s), an electric field of 3·0 kV/mm was applied to the pivot, so increasing damping and suppressing flutter at this speed, and the response decays rapidly. When the electrical field is held constant and the wind speed is increased to V_F = 16·8 m/s, flutter occurs again. The flutter speed is increased by 35·5% compared with that at zero electric field, and the results coincide with those predicted by theoretical calculation. It can been seen that though the response time of ERF is in the

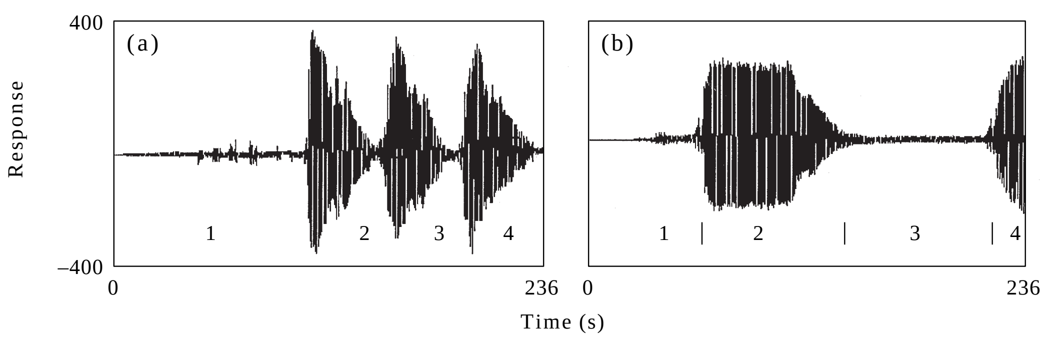

Figure 7. Flutter control using (a) first control procedure and (b) second control procedure.

order of milliseconds, the flutter control process takes a few seconds for the time delay of the control switch of the high voltage power supply.

5. CONCLUSIONS

1. For the purpose of developing a controllable ERF damping pivot, various types of ER fluids were tested and one type was developed, whose shear strength is 0·3 kPa at zero electric field and 1·6 kPa at 3·0 kV/mm electric field.

2. A multiply sliding plate damping pivot was designed and manufactured. Damping property testing indicates that at different electric fields, its damping level can be adjusted within a wide range.

3. An aircraft control surface flutter model with an ERF damping pivot was designed and flutter control wind tunnel tests were conducted. The results show that using an ERF damping pivot as a controllable damper, the flutter tendency of this control surface can be suppressed successfully.

ACKNOWLEDGMENTS

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