Parametric design of an electrorheological shock absorber with the mixed-mode

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Abstract: A mathematical model based on an electrorheological (ER) shock absorber with the mixed-mode is presented. Its application to the parametric design of an electrorheological fluid shock absorber with the simulation calculation performed by program MATLAB demonstrates that the model can predict the behavior of ER shock absorbers satisfactorily, shorten the design period of an electrorheological shock absorber, and reduce the cost in the prototype manufacturing. The strength analysis based on a three-dimensional finite element model for the electrorheological shock absorber confirm that the structure design of the ER shock absorber is reasonable, and the stress distribution is uniform.

Keywords: semi-active suspension; ER shock absorber; design

1. Introduction

As is known, the function of a suspension system is to support an entire vehicle at axles so as to improve ride comfort by vibration absorption. It also provides handling stability in steering and acceleration as well as braking. However, the solution of the design contradiction between ride comfort and handling stability can’t be achieved by passive suspension system elements. Some active suspension systems have been developed in order to handle the compromise, but they require high cost and power, large package size and poor operating economy. So D.C. Karnopp suggested a novel semi-active suspension system combining the advantages of both passive and active suspension systems. A variable shock absorber employed in the semi-active suspension is a central element that changes damping force continuously within a response time of several milliseconds via a feedback control scheme. But it is impossible for conventional shock absorbers filled with oil to change damping force continuously due to complicated mechanical elements and slow respond time. Since Winslow [1] reported on the ER fluid, many researchers have been actively studying the mechanism and application of ER fluids. Various engineering applications such as shock absorbers [2-5], engine mounts [6], squeeze film dampers [7], clutches and brakes [8] are developed. Especially, because electrorheological fluid (ER) or magnetorheological (MR) shock absorbers have demonstrated their superiority over a conventional shock absorber by that the damping force of the ER shock absorber can be increased effectively with the applied electric field, they provide a good alternative of variable shock absorbers employed in a semi-active suspension system. Lou et al.[4] classified the types of ER shock absorbers into three modes: flow mode, shear mode and mixed mode. Right now, most of design and research about ER shock absorbers is concentrated on ER shock absorbers with flow mode, but the design and research about ER shock absorbers with mixed mode is relatively rare.

The purposes of this work are to systematically analyze the damping force of an ER shock absorber with mixed mode, and present its mathematical model to predict its performance, with simulating calculation implemented by a program of MATLAB.

2. Characteristics of ER fluid

The rheological properties of ER fluids changes reversibly depending upon the electric field imposed on it. ER fluids are changed from Newtonian flow in which particles move freely to Bingham behavior in which particles are aligned in a chain by the electric field applied to the fluid domain. Under the electric potential, a constitutive equation for the ER fluid is a form of Bingham plastic behavior expressed as:
\[ \tau = \eta \dot{\gamma} + \tau_y(E) \]  
where \( \tau \) is the shear stress, \( \dot{\gamma} \) is the shear rate, \( \eta \) is the viscosity in zero-field, and \( \tau_y(E) \) is the yield shear stress of the ER fluid. \( \tau_y(E) \) here is a function of the electric field \( E \) and exponentially increases with respect to the electric field, which is presented by

\[ \tau_y(E) = \alpha E^\beta \]  
where the proportional coefficient \( \alpha \) and the exponent \( \beta \) are the intrinsic values of the ER fluid, which are functions of the applied electric field, particle size, particle shape and concentration, carrier liquid, water content, temperature and polarization factors such as particle conductivity.

The intrinsic values \( \alpha \) and \( \beta \) of the ER fluid adopted in this study were obtained by experiments, and turned out to be \( \alpha = 81.5 \), \( \beta = 1.8 \). A rotational shear-mode type electro-rheometer was employed to obtain the Bingham property of the ER fluid. Silicate and plant oil were chosen as particles and liquid, respectively, and the mass ratio of the particles to the ER fluid is 29%.

Fig.1 presents the Bingham properties of the ER fluid at 25 °C, which shows that the yield shear stress is increased exponentially with respect to the electric field.

![Fig.1. Bingham properties of the ER fluid: (a) shear stress; and (b) yield stress](image)

### 3. Mathematical model

The schematic diagram of an ER shock absorber with mixed mode is shown in Fig. 2. The motion of the piston pushes the ER fluid through the annular duct via the opening at either end of the duct. The piston is composed of a part of the annular duct moves at a velocity \( \nu \). When a voltage is applied to the piston and the cylinder is connected to the ground, an electric field is created perpendicular to the fluid flow. The ER fluid is assumed to instantly change from Newtonian to Bingham-plastic, so exhibit a yield stress that increases the resistance of flow through the duct. This may cause an increase in pressure drop across the piston and a shear force in the moving piston surface, which increases the resistance to piston move. In order to simplify the analysis of the ER shock absorber, it is assumed that the ER fluid is incompressible and the pressure in one chamber is uniformly distributed, at the same time, \( E \) is constant in the duct.

![Fig.2. Schematic diagram of the ER shock absorber](image)

If the piston displacement \( X \) is defined by

\[ X = X_{\text{max}} \sin \omega t \]  
where \( X_{\text{max}} \) is the maximum displacement, \( \omega \) is the angular frequency, the piston velocity \( \nu \) can be presented by

\[ \nu = \dot{X} = \omega X_{\text{max}} \cos \omega t = \nu_{\text{max}} \cos \omega t \]  
and the flow rate \( Q \) by

\[ Q = \frac{\pi (d_i + h)^3}{12\eta} \Delta p \frac{h}{L} \]  
where \( \Delta p \) is the pressure drop across the duct; \( L \) is the height of the piston; \( h \) is the distance between the inner wall of the cylinder and the surface of the piston; \( d_i \) is diameter of the piston; and \( \eta \) is the appearance viscosity.

From Eq.(5), \( \Delta p \) is
\[ \Delta p = \frac{12\eta L}{\pi(d + h)h} Q + \frac{\pi(d + h)}{2} \varepsilon h L \]  
(6)

where \( C_{y_{\text{min}}} \) is the minimum damping coefficient in the compression stroke, \( C_{s_{\text{min}}} \) is that in the extension stroke.

The above equations, the dimensions of an ER shock absorber can be determined.

4. Simulation and calculation

The above mathematical model was applied to the parametric design of an ER shock absorber, and acquired the relationship of the simulated damping force with the velocity and displacement of the piston, as is shown in Figs. 3 and 4. Simulation results show that the performance of the ER shock absorber in agreement with the requirements of semi-active system for a small-sized passenger car can be achieved. The application of this method to determining the parameters of an ER shock absorber in the design process shortens the design period of products, and decreases the cost in prototype manufacturing. In addition, a control algorithm can be developed based on the above model.
and that in extension stroke as shown in Figs. 5 and 6, respectively. Fig. 7 shows the elements of the cylinder with a total element number of 1937, a total node number of 1948 and the element type of shell 63. The above results demonstrate that the structure design of the ER shock absorber is reasonable, and the stress distribution is uniform.

5. Conclusions

The mathematical model elaborated can not only predict the behavior of ER shock absorber with mixed mode but also develop the control algorithms for semi-active suspension systems. The method can obviously shorten the design period of a new product and reduce the cost in prototype manufacturing. In addition, the static strength analysis testifies that the stress distribution and structural design of the ER shock absorber are reasonable.

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