Modeling Damping Force for a Translational Damper Based on Shear-Thinning Giant Electrorheological Fluid

Liufeng Chu*, Yi Yang* and Yi Sunb

School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China

*Corresponding author e-mail: zhiweinideng@shu.edu.cn, ^yiyang@shu.edu.cn,
byisun@shu.edu.cn

Abstract. The mathematical model of electrorheological fluid damper which is based on the flow mode has been proposed in many articles. In this paper, a new optimization model of the giant electrorheological fluid damper, which is based on the shear thinning mathematical model, is proposed and simulated numerically with Matlab. The mathematical model of giant electrorheological fluid damper without considering the shear thinning model is also simulated numerically in this paper. The data of the damping force-excitation displacement of the damper are tested by the 810 Material Test System. By comparing the simulated data with the experimental data, it can be seen that the model considering the shear thinning mode can predict the damping force that the damper can produce.

1. Introduction
Electrorheological (ER) fluid is a composite fluid which is composed of high dielectric constant particles having a particle size ranging from nanometers to micrometers and a kind of insulating fluid. ER fluid have a property which is called electrorheological effect. The electrorheological effect means that the rheological property and viscosity of the fluid can vary with the externally applied electric field [1]. When the applied electric field strength is greater than a certain value, the ER fluid will become a nearly solid substance. The transition of the fluid and solid state of ER damper is reversible and its transition time is typically on the order of milliseconds [2, 3]. When the electric field strength applied on the ER damper reaches the extreme value (5kV/mm), the maximum shear strength is about several thousand Pa, which limits the application of electrorheological fluid. Wen et al. [4] proposed a novel electrorheological (ER) fluid which is consisted of [Ba-TiO(C2O4)2] nanoparticles and silicone oil. With the applied electric field, the shear strength of this ER fluid far exceeds the upper limit predicted by the general theory, reaching more than 130 kPa.

Previous studies have developed cylindrical ER fluid-flow dampers and the mathematical model has been proposed to predict the damping force characteristics of the damper. Due to the limitation of the rheological properties of the ER fluid under applied electric field strength, the ER fluid damper entered a period of stagnation. However, the shear strength of the GER fluid is nearly an order of magnitude greater than the shear strength of the ER fluid when the electric field is equal. Therefore, it is necessary to study GER damper and optimize damping force model of the damper.
2. Material properties of GER fluid

2.1. Composition of GER fluid
In order to verify the effectiveness of the proposed optimized model considering the phenomenon of shear thinning, a piston type ER fluid damper is designed and manufactured in this paper. The GER fluid used in this paper is a composite fluid which is composed of [Ba-TiO(C2O4)2] nanoparticles coated with a thin layer of urea and silicone oil. The silicone oil type is No. 10 silicone oil with a particle concentration of 46.2%.

2.2. The field-independent properties test of GER fluid
In this paper, the Hakee Mars III advanced rotational rheometer manufactured by Hakee, Germany, was used to test the viscosity and shear strength of GER fluids as a function of external electric field. Fig. 1 shows the variation of the field-independent viscosity with the average shear rate of the measuring plate.

![Figure 1. The field-independent viscosity-average velocity curve.](image)

The field-independent viscosity-average velocity curve (shown in Fig. 1) is curve fitted by using the MATLAB tool and the fit formula can be described as

\[ \eta = a_1 V^{b_1} + c_1 \]  

(1)

Where \( V \) is the average velocity of the measuring plate and \( \eta \) is the viscosity independent of electric field strength of the GER fluid. The units of \( V \) and \( \eta \) are m/s and Pa·s. The coefficients \( a_1 \), \( b_1 \) and \( c_1 \) are determined to be 9.634E-4, -1.254 and 0.2533, respectively. The shear average speed of the measuring plate can be calculated by the formula \( V = 0.5r \), where \( V \) is the shear average speed of the measuring plate, \( r \) is the radius of the measuring plate and \( n \) is the test frequency.

Fig. 2 shows the relationship between the field-dependent shear strength of the GER fluid and the external electric field strength. The relationship between the field-dependent yield strength of the GER fluid and the external electric field strength (shown in Fig. 2) is curve fitted by using the MATLAB tool and the fit formula can be described as

\[ \tau = a_2 E^3 + b_2 E^2 + c_2 E + d_2 \]  

Where \( \tau \) is the field-dependent yield strength of GER fluid and the value is the average of the experimental yield strength under different field strengths. E is the electric field strength applied to the
GER fluid. The units of $\tau$ and $E$ are kPa and kV/mm. The coefficients $a_2$, $b_2$, $c_2$ and $d_2$ are determined to be -0.2124, 1.674, 0.6262 and -0.1241, respectively.

Figure 2. The shear strength of GER fluid varies with external electric field.

3. Schematic diagram and modeling of GER damper
The Schematic diagram of GER damper is shown in Fig. 3(a). The GER damper is tested on the 810 Material Test System and the test device diagram can be shown in Fig. 3(b).

![Figure 3](image-url)

Figure 3. Prototype of the GER damper. (a) Schematic diagram. (b)Schematic diagram of experimental setup.

The mode of operation of the GER fluid in the damper is flow. The principal structural sizes of the GER damper are shown in Table 1.

| Parameter | Value |
|-----------|-------|
| $t$       | 1.5 mm|
| $r$       | 6 mm  |
| $R$       | 25 mm |
| $L$       | 50 mm |
| $L_a$     | 36 mm |
By ignoring the compressibility of the GER fluid and the quasi-static nature of the hypothetical damper (balanced state in every state) and considering the frictional force and the minor loss pressure drop, the damping force of the GER damper is expressed as follows [5]:

\[
F = P_1 A_s + F_f + F_{\eta \text{f}} + F_{\text{sign}(V_p)}
\]

\[
= P_1 A_s + c_{\text{vis}} V_p + c_{\text{loss}} V_p^2 + F_{\text{sign}(V_p)}
\]

Where

\[
c_{\text{vis}} = \frac{6 \eta L (A_p - A_s)}{\pi t_{\text{i}} (t_{\text{i}} + t/2)^2} A_p;
\]

\[
c_{\text{loss}} = \frac{\rho (A_p - A_s)^2 \rho}{2 A_s^2} (K_{\text{EN}} + K_{\text{EX}});
\]

\[
F_{\eta} = \frac{c(a 2E^3 + b 2E^2 + c 2E + d 2) L_s}{t} A_p + F_f;
\]

\[
c = 2.07 + \frac{12Q \eta}{12Q(aV^n + c) + 0.8\pi (t_{\text{i}} + t/2)^3 (a 2E^3 + b 2E^2 + c 2E + d 2)}.
\]

Among them, \(P_1\) is the atmospheric pressure, \(A_s\) is the cross-sectional area of the piston shaft, \(A_p\) is the cross-sectional area of the piston, \(r_1\) is the radius of the inner electrode ring, \(F_f\) is the frictional force, \(\rho\) is the density of GER fluid, \(Q\) represents the volumetric flow rate of the GER fluid flowing through the flow channel and \(Q = (A_p - A_s)V_p\). \(K_{\text{EN}}\) represents the entry coefficient and \(K_{\text{EX}}\) indicates the exit coefficients [6,7]. The data used in the formula are shown in Table 2.

### Table 2. The data used in the formula.

| Parameter | Value           | \(r_1\)  | \(F_f\) | \(K_{\text{EN}}\) | \(K_{\text{EX}}\) | \(P_1\) |
|-----------|-----------------|---------|---------|-----------------|-----------------|--------|
| \(\rho\)  | 1333 kg/m³      | 17 mm   | 10 N    | 0.5             | 1               | 101.325 kPa |

4. Comparison of simulation and experimental data

4.1. Simulation of the model without considering shear thinning

For a mathematical model without considering the phenomenon of shear thinning, the viscosity of the fluid is a fixed value. Therefore, the viscosity value in equation (3) is a fixed value. It can be seen from Fig. 1 that the viscosity of the GER fluid is 0.255 Pa \(\cdot\) s. The excitation displacement and frequency during simulation are 3 mm and 2 Hz, respectively.

The simulation curve of the damping force model without considering the phenomenon of shear thinning can be seen from Fig. 4. At different external electric field, the value of the damping force of the damper is different. And the value of the damping force increases as the applied electric field strength increases. However, when the displacement of the piston is large, the shear rate is small, the model can not accurately predict the trend of damping force.

4.2. Simulation of the model without considering shear thinning

Regardless of the mathematical model of shear thinning, the model becomes a bit distorted when the shear rate is small. Therefore, this paper considers the phenomenon of shear thinning. It is considered that the value of the liquid viscosity is not a fixed value. For the shear thinning model, the fitting formula is equation (2). The excitation displacement and frequency during simulation are 3 mm and 2 Hz, respectively.

The simulation curve of the damping force model considering the phenomenon of shear thinning can be seen from Fig. 5. At different external electric field, the value of the damping force of the...
The value of the damping force increases as the applied electric field strength increases. Compared with the model without considering the shear thinning phenomenon, the optimized model can predict the general trend of the damping force even when the shear rate is low.

**Figure 4.** The simulated damping force characteristic of the model without considering the phenomenon of shear thinning under different applied electric field strengths.

**Figure 5.** The simulated damping force characteristic of the model considering the phenomenon of shear thinning under different applied electric field strengths.

### 4.3. Damping force-displacement experimental data

Fig. 6 illustrates the experimental force-displacement curve characteristics of the prototype GER damper (as shown in Fig. 3b) with sinusoidal excitation condition. The excitation displacement and frequency during the experimental test are 3 mm and 2 Hz, respectively. It can be seen from Fig. 5 and Fig. 6 that although the model without optimization can predict the damping force of the damper, the model after optimization can predict the variation trend of the damping force at low shear rate.

### 5. Conclusion

In this paper, a new optimization model of the giant electrorheological fluid damper, which is based on the shear thinning mathematical model, is proposed. In order to verify the effectiveness of the proposed shear thinning model, a damper based on GER fluid flow-mode is designed and manufactured. In this paper, the material properties of the GER fluid and the shear strength
characteristics with applied field strength are tested. MATLAB is used to simulate the proposed optimization model and the unoptimized model. After testing the damping force-displacement of the damper, it can be seen that the optimized model can better predict the damping force characteristics of the GER damper. This proves the validity of the model after optimization.

![Damping Force vs Displacement](image)

**Figure 6.** The experimental force-displacement curve characteristics of the GER damper under different applied electric field strengths.

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