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The Effect of Excitation Current on Shear Stress of Magnetorheological Fluid

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Abstract

Rheometer Anton Paar Physica MCR 301 was applied to do the experimental study on the responses of shear stress under a step and a linear excitation current. The results indicate that shear stress of magnetorheological fluid shows a step change under an applied step external excitation current. When the strength of the excitation current is small, the dependence of shear stress on excitation current is exponential function whose index value is 1.25. When the excitation current is big, their relationship would change into a quadratic polynomial function. The magnitudes of the shear stress under two kinds of excitation current are linked to the shear rate.

Keywords - *Magnetorheological fluid, Shear stress, Step excitation current, Linear excitation current, Response*

I. INTRODUCTION

Magnetorheological fluid (MRF) is a kind of new intelligent material with a millisecond response rate [1], which is normally composed of ferromagnetic particles, suspensions and a little additive. When exposed to an external magnetic field, the apparent viscosity of MRF increased instantly and its shear stress will add several orders of magnitude. With the increase of shear stress, the free flowing MRF change into solid rapidly. The magneto rheological effect of MRF is reversible and controllable [2].

Shear stress is one of the important properties of MRF [3]. Therefore, the study on the influencing factors and variation law of its shear stress can widen its application range and make it better applied to the mechanical braking and shock absorption. The shear stress of the MRF conforms to the classical Bigham model as shown in equation (1):

$$\tau = \tau_0(H)\,\mathrm{sgn}(\dot{\gamma}) + \mu\dot{\gamma} \qquad (1)$$

Where τ denotes the shear stress, τ_0 is magnetic shear stress which is depends on the magnetic field intensity H, μ means the apparent viscosity, $\dot{\gamma}$ is the shear rate. Ginder[4] et al. analyzed the shear stress under external magnetic field by finite element method, the analysis result shows that when magnetic field is weak, the relationship between shear stress τ and magnetic strength H is $\tau \propto H^2$, when magnetic field is strong, their relationship becomes $\tau \propto H^{1.5}$. Through experimental method research, Felt[5] et al. finds out that the relationship between shear stress and magnetic field strength is $\tau \propto H^2$. Daniela[6] et al. fitted the experimental data and according to the fitting results, they reached the conclusion that the relationship between shear stress and excitation current is $\tau \propto I^{2.1}$. Miao[7] et al. came to a conclusion that magnetic field strength is the main influence factor of the mechanical properties of MRF. Yi[8] et al made a comparison among the Dipole Theory, Simplified Dipole Theory and Maxwell Stress Tensor, he found that Simplified Dipole Theory is more practical. The above studies have indicated that the shear stress of MRF changes with the magnetic field strength.

II. EXPERMENTS

A. Particle Chains Observation

With a good magnetorheological effect, ferromagnetic particles in MRF can be assembled into chains quickly. The Fig.1 that taken by 3D high speed microscope system is magnified 1000 times, it shows the microstructure of the particle chain. When exposed to an external magnetic field, interaction between particles will cause the particles to align along the direction of the magnetic field forming a series of structured chains. When loading a force that normal to the chain, it will be pulled off and generate the shear stress.

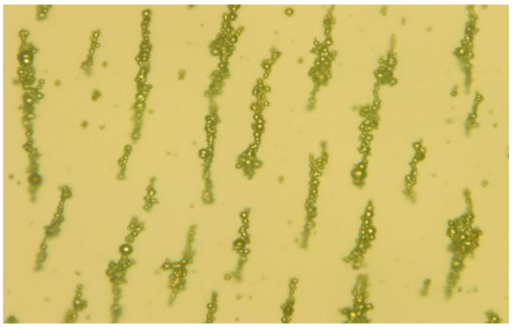


Figure 1 The micro structure of the particle chain.

B. Samples Preparation

MRF can be manufactured using a mechanical mixture method. Owing to its high saturation magnetization and appropriate particle size, carbonyl iron powder was selected to be the ferromagnetic particles. As to the suspensions, silicone oil is used in the preparation process. Calculate and weight out the carbonyl iron powder and silicon oil that needed based on the volume ratio of MRF. Grinding them with high speed ball mill for 1h and then bottling the prepared mixture [9].

C. Shear Stress Test

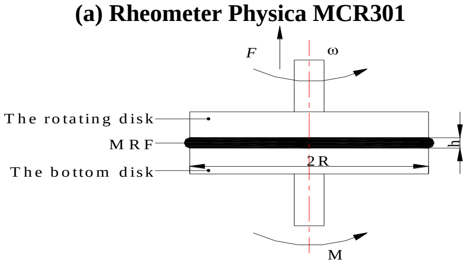
Rheometer Physica MCR301 is used to test the prepared MRF. Apply step and linear excitation currents on MRF and record the data of its shear stress to analyze the response of shear stress on different excitation currents. As shown in Fig.2, MCR301 is composed of two coaxial equal radius disks, the bottom one is fixed and the rotating one is coupled to the rotor through a shaft. Between the two mentioned disks, there is a gap that filled with MRF. The values of stress and strain can be acquired by testing the torque and angular velocity of the rotor. Theoretical consideration of the magnetic field leads to the following equation (2) and (3) [10]:

$$B = 7.539 \times 10^{-4} K \frac{I}{0.0035 d \left(\frac{\mu_r - 1}{\mu_r}\right)} \qquad (2)$$

$$H = \frac{B}{\mu_0 \mu_r} \qquad (3)$$

Where B is the Magnetic Flux Density in [T], The Calibration Factor K is an adjustment parameter dependent on the geometry. Here, this parameter equals one for the measuring system being used (20 mm diameter parallel-plate and 1 mm gap), I denotes the current in [A], μ_r is the permeability of the sample which is not a constant but depends on the magnetic field strength, μ_0 is permeability of vacuum whose value is 1.256×10^{-6} [11]. It can be seen from the above formula that the magnetic field intensity is proportional to the excitation current. Therefore, the dependence of shear stress on excitation current can reflect the relationship between shear stress and magnetic field strength [12].

(a) Rheometer Physica MCR301



(b) Working principle diagram

Figure 2 The structure of Rheometer Anton Paar Physica MCR 301

Preparing sample A of MRF according to the mechanical mixture method that mentioned above. The volume ratio of the sample A is 40% and its kinematic viscosity is 10cst. In order to study the response of shear stress on step excitation current, pour a proper amount of sample A into Rheometer Anton Paar Physica MCR 301 to do the experimental test. The shear rate is set to 1000 s^{-1}. The excitation current is increased every 10s with a step type, but not all the value of steps are the same. In 0s-60s, each step value is 0.1A, in 61s-90s, each step value became 0.2A, in 91s-160s, each step value turned into 0.4A. Record the values of shear stress and excitation current every 0.1s and draw Table 1 and Fig.3 according to the recorded data.

Pour another set of sample A into Rheometer Anton Paar Physica MCR 301 to study the response of shear stress on linear excitation current by the same method. The linear excitation current whose function is $I(t) = 0.3t - 0.03$ is increased from 0A to 3A. The shear rate is set to 1000 s^{-1}. Record the value of shear stress and excitation current every 0.1s. Draw Fig.4 based on the recorded data.

In order to make a comparative study on the magnitude of shear stress between step and linear excitation current, do some tests on sample A that divided into 5 groups by Rheometer Anton Paar Physica MCR 301. The shear rate that applied on the 5 groups are set to 100s^{-1},300s^{-1},500s^{-1},700s^{-1} and 1000s^{-1}. Each group of MRF was applied step and linear excitation current. The step excitation current increased from 0A to 3A. It changes every 10s and each step value is 0.1A. Record the value of shear stress and excitation current every 0.1s and calculate the average of the 100 sets of data that recorded in each step. The function of the linear excitation current is $I(t) = 0.3t - 0.03$. It increased from 0A to 3A too. Record the value of shear stress and excitation current every 0.1s. With the excitation current I as X-axis, shear stress τ as Y-axis, the response of shear stress under two kinds of excitation current is plotted in Fig.5.

III. RESULTS AND DISSCUSSION

Fig. 3 shows the resulting shear stress curves for the tested MRF with an applied step external excitation current. A noticeable increase in the shear stress with increasing excitation current is observed. The results indicate that when apply a step excitation current, the shear stress of MRF also changes with a step type. When the excitation current is constant, shear stress of MRF will remain the same. Table 1 is a step numerical table of shear stress at different step value of excitation current in the experiment. According to the data in Table 1, it can be seen that when step values of current are the same, the step values of shear stress will remain equal. The step value of shear stress is not increased linearly when doubling the step current value. With the increase of the excitation current, MRF tends to be magnetized to saturation which can cause the step value of shear stress reduced gradually.

Table 1 Step numerical table of shear stress under different step value of excitation current

Time *T*/s	The step value of the excitation current *I*/A	The step value of the shear stress τ /kPa
1-10	0.1	1.52
11-20	0.1	1.474
21-30	0.1	1.55
31-40	0.1	1.436
41-50	0.1	1.453
51-60	0.1	1.411
61-70	0.2	4.802
71-80	0.2	4.89
81-90	0.2	4.68
91-100	0.4	9.535
101-110	0.4	7.85
111-120	0.4	5.41
121-130	0.4	3.52

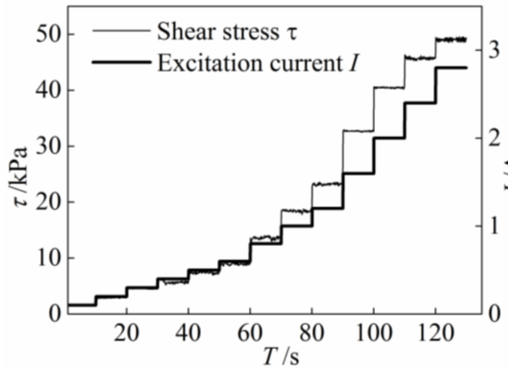


Figure 3 Response curve of shear stress under step excitation current

Fig 4 shows a fitting curve of shear stress under applied linear excitation current. The fit result of the curve is a piecewise function that shown in the following equation:

$$\begin{cases} y = 3.59t^{1.28} & 0 \le t < 6.5 \\ y = 12.45t - 0.58t^{2} - 18.09 & 6.5 \le t \le 10 \end{cases} \quad (4)$$

The fitting values of goodness of the piecewise function are 0.9988, 0.9987. It can be seen from the fitting results that when the shear rate is $1000s^{-1}$, shear stress of MRF increases with the enlarged linear excitation current. Under a low excitation current, the dependence of shear stress on shear rate is exponential. As shown in the above formula, the index value of the exponential function is 1.25. When the excitation current is raised to 2.5A, as can be obviously seen from the figure 3, the shear stress curve becomes smooth which means MRF begins to be magnetized to saturation. The relationship between shear stress and shear rate is changed from exponential to quadratic polynomial. It can be concluded from the mathematical derivation of the quadratic polynomial that when increase the excitation current to 3A, MRF with 40% by volume is completely magnetized to saturation which means its shear stress is no longer increased with the excitation current.

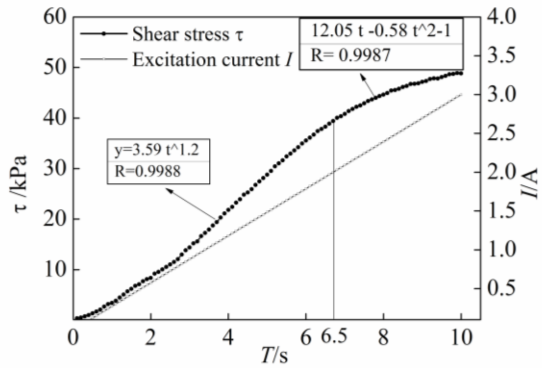
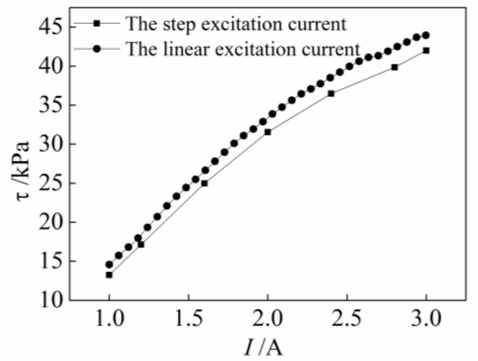
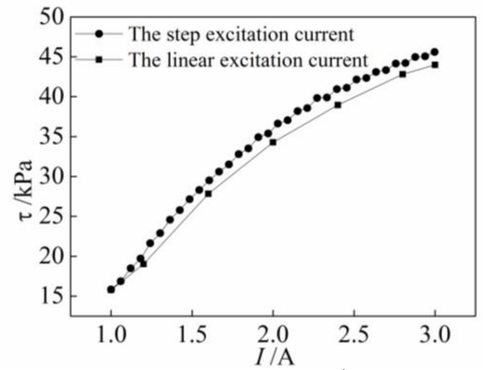


Figure 4 Fitting curve of shear stress under linear exciting current

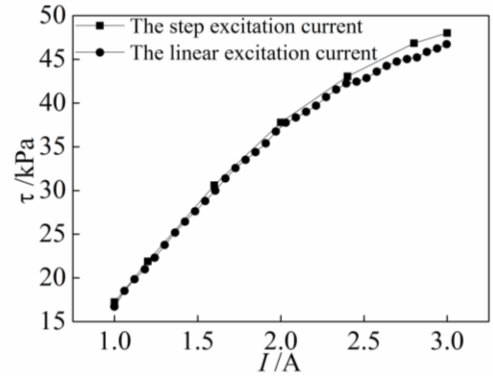
As it can be seen from the curves shown in Figure 5, response curves of shear stress under two kinds of excitation currents are not coincidence. It indicates that the mode of the excitation currents have an impact on the shear stress of MRF. When the excitation currents of MRF are increased to the same value but in different ways, the shear stresses are not equal. The magnitudes of the shear stress under linear and step excitation current are related to the shear rate. When the shear rate is low like $100s^{-1}$, $300s^{-1}$, as shown in Fig5 (a) and Fig (b), shear stress under linear excitation current is significantly higher than that under the step excitation current. By contrast, when the shear rate is higher like $500s^{-1}$,$700s^{-1}$,$1000s^{-1}$ that shown in Fig5 (c), Fig (d) and Fig (e), shear stress under step excitation current is higher than that under the linear excitation current.



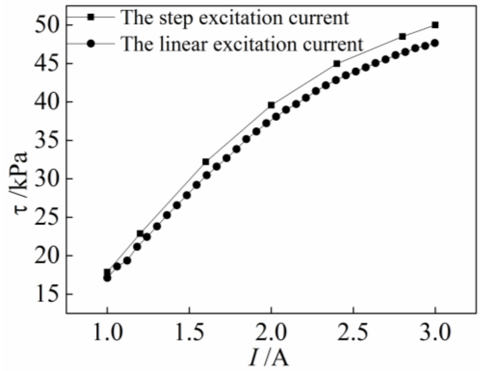
(a) Shear rate 100s-1



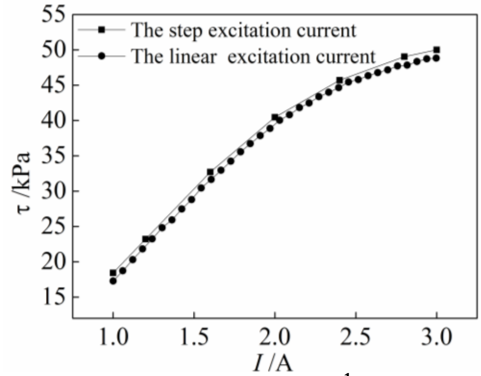
(b) Shear rate 300s-1



(c) Shear rate 500s-1



(d) Shear rate 700s-1



(e) Shear rate 1000s-1

Figure 5 response curves of shear stress under two kinds of excitation currents with different shear rate

IV. CONCLUSIONS

(1) Shear stress of MRF changes with a step type under an applied step external excitation current. When the step value of the current is the same, the step values of shear stress will remain equal. But the step value of shear stress is not increased linearly when doubling the step current value.

(2) With a low linear excitation current, the dependence of shear stress on shear rate is exponential function whose index value is 1.25. When the excitation current is raised to 2.5A, the relationship between shear stress and shear rate is changed from exponential to quadratic polynomial. When MRF is completely magnetized to saturation, its shear stress would no longer increase with the excitation current.

(3) The magnitude of the shear stress under linear and step excitation currents is related to the shear rate. When the shear rate is low, shear stress under linear excitation current is significantly higher than that under the step excitation current. By contrast, when the shear rate is higher, shear stress under step excitation current is higher than that under the linear excitation current.

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