Study on Mechanical Model of the Magneto Rheological Fluid

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Keywords: magneto rheological fluid, mechanical model, parameters identification.

Abstract. In order to effectively apply the magneto rheological technology into the cutting chatter suppression, the reasonable mechanical model which could properly describe the mechanical behavior of magneto rheological fluid (MRF) is very important. According to principle of rheology, the mechanical performance test of MRF is conducted under different exciting currents, and the nonlinear mechanical model of MRF is established on the basis of the experimental data of shear stress versus shear strain rate, the dynamical parameters which respectively represent the viscosity, elasticity and plasticity of MRF are identified. The mechanical model agrees well with the experiment result.

Introduction

The cutting chatter of machine tool is one of the important factors which restrict manufacturing industry in the direction of high speed cutting, high efficiency and high precision. In recent years, a new intelligent material - magneto rheological fluid (MRF) has grown up rapidly, and it is widely used in the field of vehicle suspension, building vibration, etc [1-3]. As a result, the magneto rheological device used for cutting is being developed step by step. MRF is a no colloidal suspension liquid, the magnetic particles of micron sizes disperse in carrier fluid, and the rheological characteristic changes with the applied magnetic field [4], thus this feature can be used to control the cutting chatter actively in real time.

The domestic and foreign scholars made a lot of researches on the mechanical model of MRF. Spencer [5] proposed a damper model based on Bouc-Wen, the model expressed with differential equation containing the 14 parameters, which can accurately reflect the force-displacement relations and energy dissipation of magneto rheological damper at low speeds. Based on the phenomenon of Spencer model, Ali Fellah Jahromi [6] put forward the frequency dependent model, the model was the function of frequency and the model parameters were identified by the integrated use of genetic algorithm and successive quadratic programming method. Bouc-Wen model can accurately reflect the nonlinear performance of magneto rheological damper at low speeds, but the force-displacement curve of damping force changes with the excitation frequency, which differs from the actual performance—the force-displacement curve of magneto rheological damper does not change with frequency, and it diverges easily in the process of parameter determination, so it is not suitable for engineering application.

In domestic magneto rheological modeling research, Zhang Lijie [7] made impact test with the long stroke magneto rheological damper, using the nonlinear least squares fitting method, the hyperbolic tangent function was adopted to establish the dynamic model of the damper, and the correctness of the model was verified by simulation. Sun Qing [8] designed a kind of double pole flow model of magneto rheological damper. According to the damping characteristics experiment, the nonlinear model was established, and the influence of the exciting current and vibration frequency on nonlinear model parameters was analyzed, the results showed that double viscous nonlinear hysteretic model could better reflect the nonlinear mechanical properties of magneto rheological damper.

The above models are based on the performance test of magneto rheological device, which has

low universality and applicability, the model will vary with the different damper and the model concept of the engineering physics is not clear. In order to increase the versatility of MRF, the best mechanical model of material can be set up through the mechanical performance test of material rather than rely on the performance test of vibration damping device under different conditions. According to the above ideas and rheological theory, the paper puts forward a mechanical modeling method which is based on the rheological property test of material. The MRF mechanical model with a clear physical meaning is established on the basis of the MRF rheological test data, then the characters of the MRF are analyzed by the parameter identification results. Finally the changing rules between currents and MRF properties such as viscosity, elasticity, plasticity are obtained so as to enrich the modeling method of the MRF mechanical property.

Mechanical Modeling Based on the Steady-State Flow Test

Test Materials and Methods. Rheological measurement types can be generally divided into steady-state measurement, transient measurement and dynamic measurement. In the steady-state measurement, the velocity of measuring head of rheometer does not change with time, this method is generally used to study the constitutive equation of the material whose shear rate field, pressure field and temperature field are constant. During the transient measurement, the excitation occurs in the stress or strain rate of the fluid, this method is usually applied to measure a variety of mechanical properties. In the dynamic measurement, the material is affected by the alternating stress or strain, and the strain usually changes with the sine law [9].

The MCR300 rheometer and the special MRF test components are used to test the shear stress-shear strain flow curves of MRF under different exciting currents. The magneto rheological fluid selected for the study is MRF-132DG made by Lord Corporation. The testing device is shown in Figure 1.Before the test, set the test method for steady-state flow test, the mode of shear strain rate is changed for linear mode, and the variation range is 0-1000 1/s, the environment temperature is set to room temperature 20℃, the currents ranges from 0A to 5A with an interval 1A. The test results describing the relation of shear strain rate (1/s) versus shear stress (Pa) are obtained.

Fig.1 testing device

Mechanical Model of the MR Fluid. In the field of materials science and rheology, Hooke, Newton and Saint Venant body are regarded as the ideal elastomer, viscous and plastic body respectively, the mechanical properties of various materials or objects can be described through the different combination of these three basic elements.

Under different magnetic field, the magneto rheological fluid exhibits the features of liquid and solid-like state, respectively. According to the principles of rheology, the changing rules of stress and strain rate are used to establish the mechanical model which represents the constitutive relation of material, the model can be described by the series and parallel combination of elastic, viscous and plastic components. The mechanical model and the curves of stress-strain rate are analyzed and the results illustrate the three aspects: Firstly, curves of the mechanical model built by a single element can not fit well with the test curve. Secondly, the test curve is similar to the curve of power

function, it can be simulated by mechanical model with parallel combination of elastic component and viscous component, subsequently series connecting with elastic component or viscous component. Thirdly, the plastic component f is a constant term in the function expression, which does not determine the curve trend. According to the three laws mentioned above, a model is established to describe the visco-plastic property of MRF under various magnetic field, as shown in Figure 2. The shear elastic modulus of the springs K_1 and K_2 are G_1 and G_2 respectively. The viscosity coefficient of dashpot c is η, f denotes the ultimate shear stress of plastic components, τ denotes the shear stress.
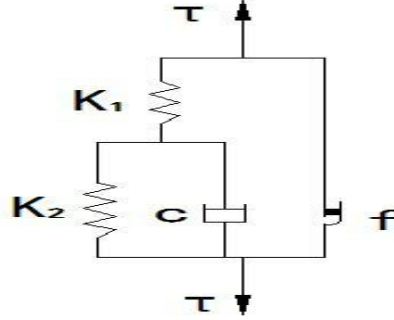

Fig.2 Mechanical model of MRF

From the Fig. 2, it is displayed that when the shear stress is lower than the limiting shear stress f of the plastic components, the plastic components can't deform, so the other components in parallel will keep the original length. When τ is more than f, the force $(\tau - f)$ will make the other components produce strain. The shear stress applied on the spring K_1 is $(\tau - f)$, supposing its shear strain is γ_1. The spring K_2 is in parallel with the dashpot c, so their shear stresses are equal, supposing the shear strain is γ_2, the sum of shear stress applied on them should be equal to $(\tau - f)$, and the total strain of the system is the sum of γ_1 and γ_2. As analyzed above, we can get the following equations:

$$\tau\text{-f}=G_1\gamma_1 \tag{1}$$

$$\tau\text{-f} = G_2\gamma_2 +\eta\dot{\gamma}_2 \tag{2}$$

$$\gamma = \gamma_1+\gamma_2 \tag{3}$$

By substituting the differentiation of equation (3) into (1), equation (4) can be obtained:

$$\dot{\gamma}_2 = \dot{\gamma} - \frac{\dot{\tau}}{G_1} \tag{4}$$

By substituting the equation (4) into (2), equation (5) can be obtained:

$$\tau + \frac{\eta}{G_1+G_2}\dot{\tau} = \frac{G_1G_2}{G_1+G_2}\gamma + \frac{\eta G_1}{G_1+G_2}\dot{\gamma} + f \tag{5}$$

According to the steady-state flow test, suppose $\dot{\gamma} = \lambda t$, after integrating it, $\gamma = \lambda t^2/2 + c$ can be obtained, where c is an integral constant and it is assumed to be zero for simplification. Thus, equation (5) can be rewritten as

$$\tau + \frac{\eta}{G_1+G_2}\dot{\tau} = \frac{\lambda G_1G_2}{2(G_1+G_2)}t^2 + \frac{\eta G_1\lambda}{G_1+G_2}t + f \tag{6}$$

By substituting $\dot{\gamma} = \lambda t$ into the solution of equation (6), the expression of shear stress τ versus

shear strain rate $\dot{\gamma}$ can be obtained as

$$\tau = a_1\dot{\gamma}^2 + a_2\dot{\gamma} + a_3 + a_5 e^{-a_4\dot{\gamma}} \tag{7}$$

Where $a_1 = \frac{G_1 G_2}{2\lambda(G_1+G_2)}$, $a_2 = \frac{\lambda G_1^2}{(G_1+G_2)^2}$, $a_3 = f - \frac{\lambda\eta^2 G_1^2}{(G_1+G_2)^3}$, $a_4 = \frac{G_1+G_2}{\eta\lambda}$

And a_5 is an integral constant.

Parameter Identification of the Mechanical Model

According to the steady flow experiment of shear stress and shear strain rate, the nonlinear least square method is used to fit data in this paper. The steady-state flow test results are described as dotted lines and the fitting results are described as the solid lines, as shown in figure 3.

Based on the fitting results, the coefficient values of mechanical model can be obtained under different conditions. Figure 3 shows that curves are well fitted by using the presented model.
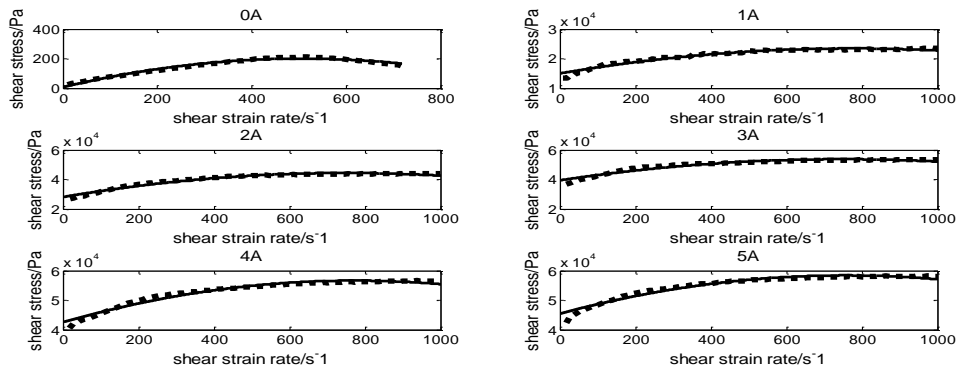

Fig.3 Fitting results at 0A-5A currents

According to the expression of a_1, a_2, a_3, a_4, the model parameters can be figured out,

$$\eta = \frac{a_2^2 a_4^2 + 4a_1 a_2 a_4 + 4a_1^2}{a_2 a_4^2} \ , \ f = \frac{a_2}{a_4} + a_3$$

$$G_1 = (a_2 a_4 + 2a_1)\lambda \ , \ G_2 = \left(2a_1 + \frac{4a_1^2}{a_2 a_4}\right)$$

Based on the experiment, $\lambda = 10$, combining with the coefficient values obtained from the fitting results, thus the dynamic parameters (f, G_1, G_2, η) of MRF at different currents are listed in table 1.

Tab.1 Model parameters

	f(Pa)	G_1(Pa)	G_2(Pa)	η(Pa s)
0A	7.67	400.60	0.015	0.762
1A	15043.39	12090.56	0.281	21.80
2A	28147.63	29882.56	0.579	43.49
3A	39483.52	28117.82	0.508	38.12
4A	42553.51	25974.41	0.471	36.47
5A	45465.52	22691.30	0.452	34.24

According to the results in the table 1, when the current is zero, the plastic force f of the MRF is small and presents weak plastic performance. On the energized state, the plastic force caused by magneto rheological effect has a linear increase, and its value is far outweigh the viscoelastic parameters of the MRF. When the current is 2A, the value of G_1 is the maximum, then it decreases with the increasing current.

Viscous property of magneto rheological effect becomes the lowest when there is no current, at the current of 1A-5A it increases slowly. When the current is 2A, it achieves the maximum value, then decreases with increasing electric current.

The trend of the dynamic parameters shows that the rheological effect becomes the largest at the current of 2A and then due to magnetic saturation effect, the viscoelasticity is weaken and the plastic character continues strengthening.

Conclusion

The mechanical model is established under different magnetic flux density based on the steady-state flow test, and the dynamic parameters of the model are identified in the paper. All in all, the following conclusions can be naturally obtained:

To begin with, the stress-strain rate simulation curves of the model are depicted and the fitting curves fit well with the experimental data, the error evaluation parameters are close to 1. Therefore, it shows that the model which can effectively reflect the mechanical property of MRF has stronger applicability in engineering.

Through the calculation, parameters of viscosity, elasticity and plasticity are obtained. The comparison among the parameters indicates that the viscous and elastic parameters are maximum at the current of 2A, the plastic property of MRF monotonically increases with the currents.

The results of the parameter identification show that the limiting stress of the MRF increases with the current in the plastic yielding phase. Therefore, at the same exciting force, the material under high field strength is easier to stay in the preyield phase, elastic and viscous force will play the main role in the damping effect.

Acknowledgements

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