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Novel magneto-rheological fluid damper for passive force/torque feedback

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Abstract: The damper is capable of providing a continuously variable dampering force/torque in response to a magnetic field. It consists of an upside cap and an underside cap with a rotor located between them, the magneto-rheological (MR) fluid is filled into the gaps between the rotor and the caps. When the viscosity of the MR fluid increases under the influence of the magnetic field, the movement of the rotor will be resisted. The output torque is made up of the torque caused by the magnetic field, the torque caused by the plastic viscosity of the MR fluid, and the torque caused by the coulomb friction. The viscous torque can be calculated by a simple method and the frictional torque can be obtained by experiments. The torque dependent on the magnetic field is obtained by electromagnetic finite element analysis. Experiments are done on the damper prototype and the validity of the design is verified.

Key words: force/torque feedback; magneto-rheological fluid; damper; electromagnetic finite element analysis

Force/torque feedback is very important when robots need to interact with an unknown environment. This is especially true for robotics systems such as assembly manipulators, haptic devices, and so on[1]. Many types of force/torque systems are now available, but most of them are active systems using servomotors or other actuators. While these active systems can provide operators with a variety of force senses, they inherently involve a potential hazard in that they can uncontrollably move and hurt operators if something really goes wrong[2]. Because of their high structural stiffness, they are not suitable for biomimetic haptic devices, which require both compliant and precise force control. Furthermore, active systems are often unstable[3].

On the other hand, passive systems using dampers to present resistance to operator force or movement are quite safe[4]. Using magneto-rheological (MR) fluid as a functional material, the authors have developed a novel damper that is capable of providing a continuously variable dampering force/torque in response to a magnetic field. The force/torque display system made of the damper can simulate compliant organ tissue. In this paper, the design of the damper based on MR fluids is presented, the basic experiments on it are performed and the results are discussed.

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1 MR Fluid Damper

MR fluids are smart materials that can respond to an applied magnetic field with a drastic change in rheological behavior. The fluid changes state from liquid to semi-solid in about 6 ms, just as quickly as it returns to liquid state by removal of the field. Typically, this change is manifested by the development of a yield stress that monotonically increases with the applied field[5]. MR fluids are increasingly being considered in a variety of devices such as shock absorbers, vibration insulators, brakes or clutches[6–7].

The behavior of controllable fluids is often represented as a Bingham plastic with variable yield strengths. In the absence of an applied field, MR fluids exhibit Newtonian-like behavior. In this model, the flow is governed by the Bingham's equation[8]. When τ is larger than the field dependent yield stress τ_y, it can be expressed as

$$\tau = \tau_y(B) + \eta\dot{\gamma} \qquad \tau \geqslant \tau_y \tag{1}$$

where η is the plastic viscosity, and $\dot{\gamma}$ is the shear strain rate. When this is not the case, the material behaves viscoelastically:

$$\tau = G\gamma \qquad \tau < \tau_y \tag{2}$$

where G is the complex material modulus that is also field dependent.

The main goal of this study is to design, develop and understand the performance of a novel MR fluid damper for passive force/torque feedback. By varying the input current to the damper, one can achieve a variable torque. Other factors such as geometric constraints and magnetic properties of materials play major roles in the performance of the MR fluid damper.

Fig. 1 shows the sectional view of the MR fluid damper. The MR fluid is located in the gaps formed by the rotor and the upside and underside caps, and the rotor is connected to the shaft by a key. The shaft is supported by two ball bearings. The electromagnet circuit of this damper consists of an electromagnetic coil, which is wound around an antimagnetic ring, a magnetic core around the coil. The magnetic core, the upside cap and the underside cap which act as the return path for the magnetic field are made of a kind of high magnetic permeability material. The O-ring located between the shaft and the upside cap is to prevent the leakage of the MR fluid. The MR fluid damper is activated by a power supply connected to the end of the electromagnetic coil. The MR fluid will be filled into the gaps through the ventilative holes in the underside cap.

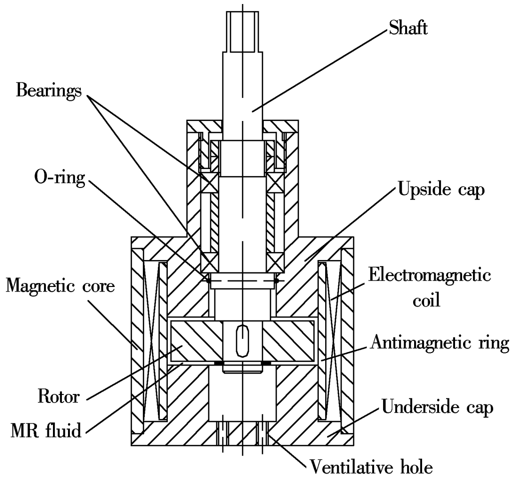

Fig. 1 Sectional view of the MR fluid damper

Fig. 2 shows a conceptual sketch of a single degree freedom hybrid active/passive force feedback system. The active force acting on the handle is produced by the elastic element actuated by the motor, and the passive force to resist the movement of the handle is produced by the MR fluid damper. A large range of force can be simulated by this system.

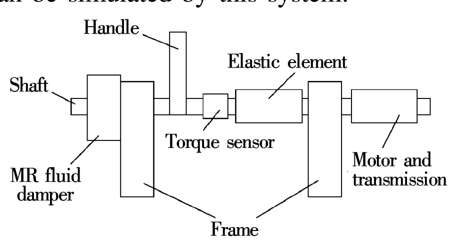

Fig. 2 Hybrid active/passive force feedback system

2 Model of MR Fluid Damper

2.1 Mathematical model

In order to derive the output force/torque equation for this damper, the Bingham model expressed in Eq. (1) is used as the constitutive equation for the behavior of the MR fluid. The first term of the right hand side of Eq. (1) produces a torque which is dependent on the magnetic field, and the second term generates a viscous torque. Therefore, the total output torque can be expressed as

$$T_{out} = T_{MR} + T_{vis} + T_f \tag{3}$$

Derivation of the MR torque T_{MR} requires the relationship between the MR fluid shear yield stress τ_y and the applied magnetic flux density B. The relationship can be obtained by experiments. T_f is the torque caused by the Coulomb friction.

Since T_f depends on the machining and assembly tolerances of the MR fluid damper, it is hard to estimate. After the MR fluid damper is fabricated and the MR fluid is selected, however, the variation of T_f is negligible. Here, it is treated as a system dependent constant that can be obtained by experiments. Therefore, the key issue in the model is to calculate T_{MR} and T_{vis}.

Assuming that the fluid is incompressible, the flow between the rotor and the upside and underside caps is laminar as shown in Fig. 3.

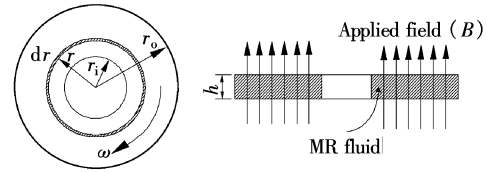

Fig. 3 Operational mode of the MR fluid damper

The output torque caused by the MR fluid can be expressed as

$$T = T_{MR} + T_{vis} = 2\int_{r_i}^{r_o} [\tau_y(B) + \eta\dot{\gamma}](2\pi r^2)\,\mathrm{d}r \tag{4}$$

where r_i and r_o are the inner and the outer radii of the MR fluid section in the gaps, respectively. For small thickness of the MR fluid section, one can derive the tangential fluid velocity by assuming no slip condition and linear velocity distribution as follows:

$$u(r, y) = \frac{r\omega}{h} y \tag{5}$$

where ω is the angular velocity of the rotor, h is the depth of the gap between the rotor and the upside and underside caps, and y is the coordinate axis normal to rotor surfaces. Differentiation of Eq. (5) with respect to y gives the shear rate:

$$\dot{\gamma} = \frac{\partial u}{\partial y} = \frac{r\omega}{h} \tag{6}$$

Integrating Eq. (4), the output torque of the MR fluid damper can be obtained.

$$T = \frac{4}{3}\pi(r_o^3 - r_i^3)\int_{r_i}^{r_o}\tau_y(B)\,dr + \frac{\pi\eta\omega}{h}(r_o^4 - r_i^4) \quad (7)$$

2.2 Electromagnetic finite element analysis

As mentioned in section 1, the MR fluid damper is actuated by a current supply. The relationship between the current I and the magnetic flux density B can be obtained by solving the Maxwell's equations[9] as

$$\oint \boldsymbol{H}\cdot d\boldsymbol{L} = I + \int_S \frac{\partial \boldsymbol{D}}{\partial t}\cdot d\boldsymbol{S}$$

$$\oint \boldsymbol{E}\cdot d\boldsymbol{L} = -\int_S \frac{\partial \boldsymbol{B}}{\partial t}\cdot d\boldsymbol{S}$$

$$\oint_S \boldsymbol{D}\cdot d\boldsymbol{S} = \int_{vol}\rho dv$$

$$\oint_S \boldsymbol{B}\cdot d\boldsymbol{S} = \boldsymbol{0}$$

But due to the high nonlinearity, the solution of the equations can hardly be calculated. Furthermore, the error is too great to tolerate for the leakage of the magnetic flux and for other reasons.

Electromagnetic finite element analysis can precisely obtain the relationships among the parameters in the electromagnetic field, such as the relationship between the current and the magnetic flux density[10]. Fig. 4 shows the contour plot of the flux line density of the designed MR fluid damper for an input current of $NI = 1\ 500$ A, where N is the turns of the coil, and I is the current supplied to the coil. For this case, magnetic flux density as a function of the radius of the rotor in the MR fluid section can be seen in Fig. 5. As described in section 2.1, the result shown in Fig. 5 can be used in theoretical torque output calculations for a given input current by Eq. (7).

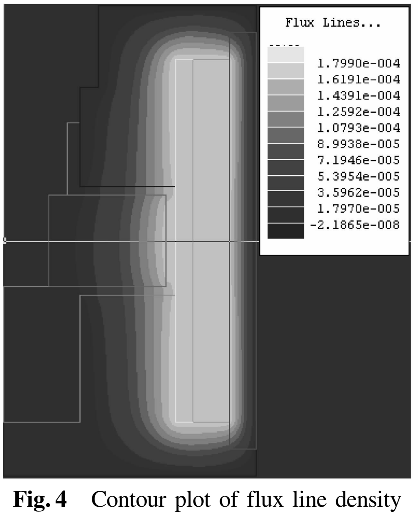

Fig. 4 Contour plot of flux line density

With variations in the input current, the magnetic flux density in the MR fluid section will change as a function of the current. The relationship between the current and the magnetic flux density obtained by electromagnetic finite element analysis is shown in Fig. 6.

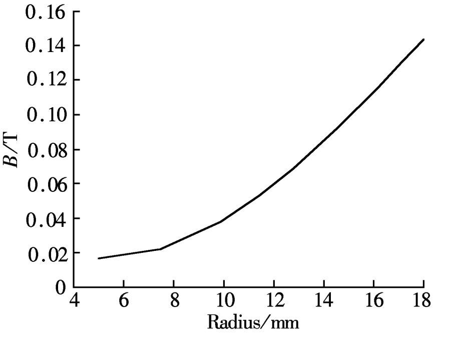

Fig. 5 Relationship between the radius and the magnetic flux density in the MR fluid section

Given that relationship, the output torque of the damper can be calculated directly by the current supplied from Eq. (7) as follows:

$$T = C_1 I^{C_2} + C_3\omega \quad (8)$$

where C_1 and C_2 are the constants obtained numerically using electromagnetic finite element analysis; C_3 is the constant dependent on the dimensions of the damper.

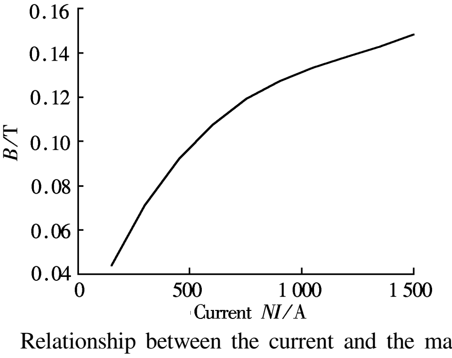

Fig. 6 Relationship between the current and the magnetic flux density

Electromagnetic finite element analysis can also be used to optimize the design of the MR fluid damper. This is done to determine the material and the dimensions of each individual element of the damper. One of the design goals is to increase the magnetic field of the MR fluid as much as possible.

2.3 Performance analysis

In Eq. (3) T_{MR} is the controllable part of the output torque of the damper. Only when T_{MR} is sufficiently large can the MR fluid damper be useful. To evaluate the effect of T_{MR}, we compare the output torque of the MR fluid damper with and without an applied magnetic field. The relative controllable range of the output damping torque of the MR fluid damper is

$$K = \frac{T_{MR} + T_{vis} + T_f}{T_{vis} + T_f} = 1 + \frac{T_{MR}}{T_{vis} + T_f} \quad (9)$$

Ignoring the effect of Coulomb frictional torque T_f, Eq. (9) can be expressed as

$$K = 1 + \frac{T_{MR}}{T_{vis}} \quad (10)$$

From Eqs. (10), (8) and (7), we obtain

$$K = 1 + \frac{4h(r_o^3 - r_i^3)}{3\eta\omega(r_o^4 - r_i^4)}\int_{r_i}^{r_o}\tau_y(B)\,\mathrm{d}r = 1 + \frac{C_1 I^{C_2}}{C_3\omega} \quad (11)$$

Eq. (11) implies that an increase in the yield stress of the MR fluid is the key factor in improving the performance of the damper. A decrease in the plastic viscosity η is an effective method to increase the relative controllable range of the damper[11].

3 Experimental Study

To verify the mathematical model of the MR fluid damper, a prototype whose dimensions are shown in Tab. 1 is set up and its performance was tested. The MR fluid was bought from the Chongqing Instrument Material Research Institute, China. The density of this fluid is 2.65 g/cm^2. The plastic viscosity is less than 1 Pa·s. The yield stress is more than 50 kPa. The operation temperature is 25 to 35 ℃. During the test, a current from 0 to 2 A was applied to the magnetic coil to activate the damper.

Tab. 1 Dimension of the MR fluid damper

r_o/mm	r_i/mm	N/turns	h/mm
18	8.5	500	1

According to the theory of the MR fluid, the yield stress is the function of the magnetic flux density,

$$\tau_y = \alpha B^n \quad (12)$$

where the parameters α and n are obtained through experiments by the manufacturer, the value of n is between 1 and 2. Submitting Eq. (12) and the numerical parameters to Eq. (7), the results are calculated and the theoretical torque varying with current is given by the solid line in Fig. 7. The curve of the experimental results and its fitting are shown in Fig. 7. The experimental results confirm the theoretical analysis.

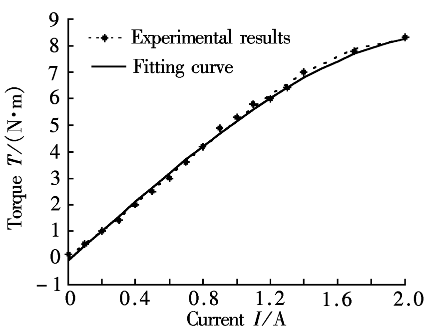

Fig. 7 Theoretical torque as a function of current

4 Conclusion

In this paper, a novel MR fluid damper for passive force/torque feedback is presented. The MR fluids, called smart fluid materials, are the key elements to developing the novel damper. The structure of the damper is introduced. The kinetics model is set up and the output force/torque is derived from the model. Finally an experiment is done on the damper, and the results confirm the validation of the design approach.

References

[1] Chew Chee-Meng, Hong Geok-Soon, Zhou Wei. Series damper actuator: a novel force/torque control actuator [C]//*Proc of IEEE/RAS International Conference on Humanoid Robots*. Los Angeles, CA, USA, 2004: 533 − 546.

[2] Sakaguchi M, Furusho J, Takesue N. Passive force display using ER brakes and its control experiments[C]//*Proc of IEEE Conference on Virtual Reality*. Yokohama, 2001: 7 − 12.

[3] Pratt Gill A, Williamson Matthew M. Series elastic actuators [C]//*Proc of IEEE/RSJ International Conference on Intelligent Robots and Systems*. Pittsburgh, PA, 1995: 399 − 406.

[4] An Jinung, Kwon Dong-soo. Haptic experimentation on a hybrid active/passive force feedback device[C]//*Proc of IEEE Conference on Robotics and Automation*. Washington, DC, USA, 2002: 4217 − 4222.

[5] Jolly Mark R, Bender Jonathan W, Carlson J David. Properties and applications of commercial magnetorheological fluids[J]. *Journal of Intelligent Material Systems and Structures*, 2000, **10**(1): 5 − 13.

[6] Kelso Shawn, Denoyer Keith, Blankinship Ross, et al. Experimental validation of a novel stictionless magnetorheological fluid isolator[C]//*Proc of SPIE Conference on Smart Structures and Materials*. San Diego, CA, 2003: 186 − 197.

[7] Ouellette Jennifer. Smart fluids move into the marketplace [J]. *Industrial Physicist*, 2003, **9**(6): 14 − 17.

[8] Liao Changrong, Yu Miao, Chen Weimin. Study on design theory for magnetorheological fluid damper using eyring constitutive relationship and experimental test[J]. *Chinese Journal of Mechanical Engineering*, 2005, **41**(10): 132 − 136. (in Chinese)

[9] Hayt William H, Jr Buck John A. *Engineering electromagnetics*[M]. Beijing: China Machine Press, 2002: 322 − 338.

[10] Kavlicoglu B, Gordaninejad F, Evrensel C A, et al. A high-torque magneto-rheological fluid clutch[C]//*Proc of SPIE Conference on Smart Materials and Structures*. San Diego, CA, 2002: 1 − 8.

[11] Li Jianjun, Gruver William A. An electrorheological fluid damper for vibration control[C]//*Proc of IEEE International Conference on Robotics & Automation*. Leuven, Belgium, 1998: 2476 − 2481.

用于被动力/力矩再现的新型磁流变液阻尼器

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摘要:研制了一种用于被动力/力矩再现的新型磁流变液阻尼器,该阻尼器能够在磁场的作用下产生连续变化的阻尼力/力矩. 阻尼器的结构包括一个上盖和一个下盖,一个转子设置于上盖和下盖之间,转子与上下盖之间的间隙充满磁流变液,在磁场作用下其粘度变大时,转子相对于壳体将受阻尼力作用. 阻尼力矩的模型主要由以下几部分组成:一是由磁场作用于磁流变液产生的力矩,二是由磁流变液的动力粘度产生的力矩,最后是由装置的摩擦产生的力矩. 由动力粘度产生的力矩可以通过简单的方法进行计算,由摩擦产生的力矩可以通过实验测得,而由磁场产生的力矩则要通过电磁场的有限元分析得到. 最后,对研制的阻尼器原型进行了性能实验,检验了设计方法的有效性.

关键词:力/力矩再现;磁流变液;阻尼器;电磁场有限元分析

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