17th International Conference
ENGINEERING MECHANICS 2011
Svratka, Czech Republic, 9 – 12 May 2011

CHANGING THE BEHAVIOR OF MR FLUIDS DURING LONG TERM OPERATION

J. Roupec*, I. Mazůrek*, Z. Strecker*

Abstract: *The article describes results of durability test of a magnetorheological fluid (MRF) which was carried out in a custom design rheometer. The rheometer design allows measurement of the rheological properties of MR fluid and its exposure to a long-term loading simultaneously, without any manipulation of the measured sample. Owing to this, changes of the two most important parameters describing the behavior of MR fluids - dynamic viscosity and yield stress - could be followed during the durability test. The dependence of yield stress and dynamic viscosity on temperature and magnetization current was evaluated. The results show a significant change of the yield strength (500%) during the durability test. Independence of the yield stress on the temperature was conclusively proven. The viscosity decreased by 35% from its initial value after dissipation of 9000kJ out of total 119000kJ and then remained the same until the end of the durability test. Viscosity dependence on temperature was evaluated.*

Keywords: ***Magnetorheological fluid, MRF, durability test, yield stress, dynamic viscosity, shear rate.***

1. Introduction

Current magnetorheological (MR) fluids are suspensions formed by a carrying fluid and ferromagnetic particles, most commonly powdered iron. Upon the application of an external magnetic field (Fig.1) the MR fluids can change their state from fluid to a semi-solid or plastic state, and back, in several milliseconds.

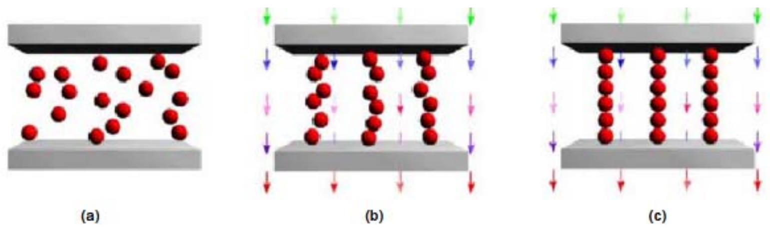

Fig. 1: MR fluid behavior (a) without application of a magnetic field; (b) with application of a magnetic field; (c) with full activation of a magnetic field (Lord Corporation, 2008).

These properties can be appropriately utilized for regulation of linear and rotary motion. The widest commercial application of these fluids is in mechatronic damping elements – MR dampers. MR dampers are frequently used in car suspension systems, suspension of driver seats in goods vehicles, vibration damping during seismic activity or damping of cable bridge vibrations caused by wind and rain. For rotary or linear MR devices the resultant effects of the magnetic field can be described simply by the Bingham model which is represented by the following equation:

$$\tau = \tau_y(H) + \eta \cdot \dot{\gamma}\,, \qquad (1)$$

where τ_y is a yield stress component which depends on the intensity of the magnetic field and acts in the direction of fluid flow, η is the dynamic viscosity of MR fluid in off-state and $\dot{\gamma}$ is the shear rate. Most of the research teams concerned with production of MR fluids and their testing use commercial rheometers to measure rheological properties (yield stress, dynamic viscosity, storage modulus G', loss modulus G", etc.). The measuring ranges of such devices are up to the shear rates of about 10^3 s^{-1} (the

* Ing. Jakub Roupec, assoc. prof. Ing. Ivan Mazůrek, CSc. and Ing. Zbyněk Strecker: Institute of machine and industrial design, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, e-mails: jroupec@hotmail.com, mazurek@fme.vutbr.cz, streckerz@gmail.com

most commonly used one is Anton Paar Physica MCR). For linear MR devices the maximal shear rate typically ranges from 10^4 to 10^5 s^{-1} which is far beyond the measuring range of commercial rheometers. Most of the new MR fluid samples have never been subjected to durability tests (Cheng, 2008; Fang et al., 2009; Bombard et al., 2009; etc.) because the commercial rheometers do not allow sufficient mechanical loading. In addition, the long-term operation could destroy this expensive equipment. The knowledge of MR fluids behavior in real life devices and of the fluid lifetime represents one of the basic parameters considered by designers when designing a machine set. The research team around Carlson and Ahmadian developed their own design of a piston slit rheometer which can measure the shear rates up to 10^5 s^{-1} (Goncalves, 2005). However, it is unsuitable for the long-term loading required for durability tests of MR fluids. For these reasons, our research team designed and constructed such a slit-flow rheometer (Fig. 2) which can measure yield stress and dynamic viscosity dependence on accurately measured temperature in the active zone of MR valve during durability test. Furthermore, it is possible to ensure stable thermal conditions due to the regulated water cooling.

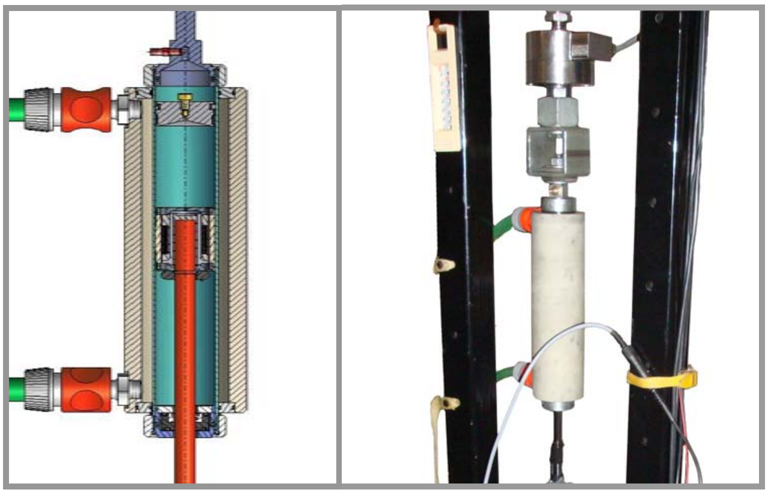

Fig. 2: The new design of slit-flow rheometer.

2. Methods

2.1. Operating parameters of the rheometer

Rheometric unit is designed to be mounted in a mechanical, hydraulic or pneumatic pulsator. The maximum piston speed of 7.8 $m.s^{-1}$ corresponds to the maximum shear rate of $8.7.10^5$ s^{-1} inside the throttle slit. Maximum operating magnetizing current is 2 A. This current flowing through the coil creates the magnetic field of 160mT in the air gap of the rheometer throttle slit. The exact description of the magnetic and hydraulic conditions can be found in (Mazůrek et al., 2009).

2.2. Properties of tested MR fluid

Properties of the tested MR fluid are given in Tab. 1. It is the liquid with the highest ratio of Fe particles to the carrier fluid from the range offered by LORD Corp. company.

Tab. 1: Properties of the MR fluid used.

fluid type	*140-CG*
density	*3.69 kg/dm^3*
mass percentage of Fe particles	*86.4%*
volume percentage of Fe particles	*40.5%*
mean size of Fe particles	*1.89 μm*
viscosity at 20°C and $\dot{\gamma}$= 800 s^{-1}	*0.880 Pa.s*
indicated Lifetime Dissipated Energy (LDE)	*10^7 $J.cm^{-3}$*

2.3. Experiment progress

Rheometer was filled with 100 ml of the MR fluid. Before the start of the durability test current and temperature characteristics were measured for temperatures between 20 and 80 °C and for currents 0 A, 0.5 A, 1 A, 1.5 A and 2 A. The temperature inside the throttle slit was obtained from the temperature dependence on the magnetization coil winding resistance. Thus, at least a minimum current had to pass through the circuit in order for the temperature to be measurable. In fact, the measurement for 0 A was carried out with the actual current of 50 mA. In order to increase the mechanical load during the loading cycle the magnetizing current was set to the maximum operating level of 2 A and the maximum operating speed of the mechanical pulsator in which the rheometric units was installed was set to the constant level of 126 rpm. This rate of rotation corresponds to the maximum piston velocity of 0.33 m/s which results in the shear rate of $3.7.10^4$ s^{-1} for given hydraulic conditions of the MR valve active zone. During the durability test the temperature was maintained within the range of 45-56°C by water cooling. After each load cycle the mechanical pulsator was stopped and the operating parameters (system pressure, lubrication of pulsator, flow rate of cooling, fixture of rheometer, etc.) were checked. Series of measurements of rheological properties of the MR fluid was then carried out followed immediately by the next loading cycle. Changes of properties of the MR fluid during the long-term operation were evaluated in inactivated state, thus with the current of 0 A. The dynamic viscosity and yield stress of the MR fluid were determined from the flow curves using the methodology described in (Mazůrek et al., 2009). Dissipated energy of the rheometric unit was described by a parameter named *Lifetime dissipated energy* (LDE) (Carlson, 2003), which can be defined as:

$$LDE = \frac{1}{V} \cdot \int_0^{life} P \cdot dt \qquad (2)$$

where V is a working volume of MR fluid and P is a dissipated performance of MR device.

3. Conclusions

Fig. 3 shows the values of dynamic viscosity measured during the durability test. Pink points indicate the visco-temperature characteristics of MR fluid at the beginning of the durability test. Between 1500 and 9000 kJ of dissipated energy, the dynamic viscosity decreased on average by 36% (yellow points). The dynamic viscosity and yield strength were not measured in a wider temperature range after further load cycles but the measured viscosity was compared with the viscosity curve of new MR fluids and the curve after the first loading cycle. As Fig. 3 shows, the values of dynamic viscosity in consequent load cycles (green, red, blue and black points) lie very close to the viscosity curve after the first loading cycle. Equation coefficients from the exponential regression curves of the new MR fluid and fluid after the first loading cycle are almost identical (Fig. 3). This means that the percentage change of the dynamic viscosity in the given range of the temperatures is the same for both curves. Therefore, it was possible to convert the measured values of dynamic viscosity from the entire durability test into one reference temperature. The temperature of 45 °C which lies at the center of the measured interval was selected as the reference temperature (Tab. 2). The results show that after the first load cycle the dynamic viscosity did not change significantly.

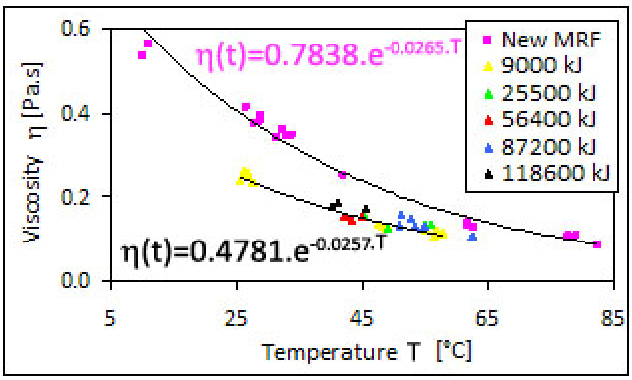

Fig. 3: Viscosity measurements during the durability test.

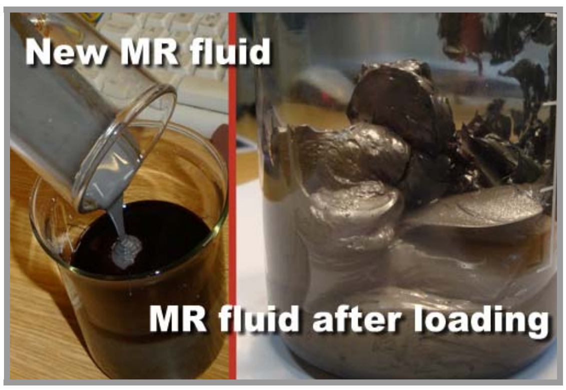

Fig. 4: New MR fluid and after loading.

Tab. 2: Dynamic viscosity during the durability test at the reference temperature.

	new MRF (regression)	***9.000 kJ (regression)***	***25.500 kJ***	***56.400 kJ***	***87.200 kJ***	***118.600 kJ***
η(45°C) Pa.s	*0.238*	*0.150*	*0.164*	*0.146*	*0.167*	*0.169*

Yield stress was another monitored parameter describing the behavior of the MR fluid. First, the hypothesis that the yield strength is independent of the temperature (Fig. 5a) was confirmed and then evolution of the yield stress during the durability test was analyzed. It was found that the yield stress increased up to five times with respect to the original value (Fig. 5b). The yield stress is the parameter which, similarly to the consistency of the MR fluid, changed significantly during the loading (Fig. 4). Therefore, it can be concluded that the increase in yield strength has a direct influence on the consistency of the fluid but not on its dynamic viscosity which is in contrast to what has been presented in many publications to date.

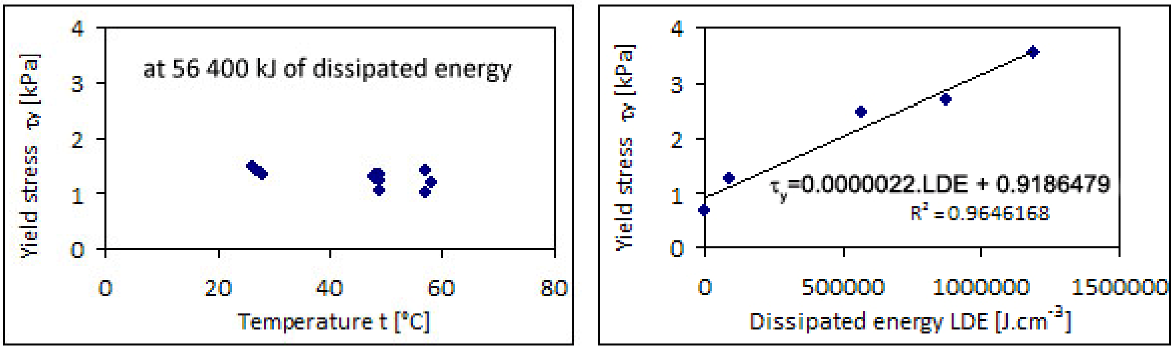

Fig. 5: a) Yield stress dependence on temperature; b) yield stress during the durability test.

These findings have serious consequences in particular for control in the off-state and for lifetime considerations in an MR node design. It is important to note that a fivefold increase in yield stress leads to a fivefold increase in force (torque) required for initial motion of MR device. For an MR damper this means that up to a certain force it will not absorb and, from the mechatronic point of view, it will behave rather like a spring. This implies, e.g. for MR clutch, an increase in torque in the switched-off mode. The LORD Company declares the MR fluid LDE of up to 10^7 $J.cm^{-3}$. However, at $1.2.10^6$ $J.cm^{-3}$ already the MR fluid is not a liquid anymore.

Acknowledgement

This work was developed with the support of the research plan MSM 0021 630 518, and grant BD 130 02003.

References

Specialty Adhesives & Coatings - Environmentally Friendly Adhesives, Water Based, Aqueous Rubber [online]. c2008 [cit. 2010-05-10]. URL: <http://www.lord.com>.

Cheng, H.B. (2008) Stability and anti-oxidization of aqueous MR fluids improved by modifying iron particle surface with organic molecule. Acta Physico-Chimica Sinica, 24, 10, pp.1869-1874.

Fang, F.F., Byung, I.Ch. & Choi, H.J. (2009) Magnetorheological characteristics of carbon nanotube wrapped carbonyl iron particles. Journal of Physics: Conference series, 149, 1.

Bombard, A.J.F., Antunes, L.S., Balestrassi, P.P. & Anderson, A.P. (2009) Magneto-rheological fluids redispersibility - a factorial design study of phosphate shell on carbonyl iron powder with dispersing additives. Journal of Physics: Conference series, 149, 1.

Goncalves, F.D. (2005) Characterizing the behavior of magnetorheological fluids at high velocities and high shear rates. Dissertation on Faculty of the Virginia Polytechnic Inst. Dissertation advisor Mehdi Ahamadian.

Mazůrek, I., Roupec, J. & Klapka, M. (2009) Identification of MR Fluids properties in Mechatronic Damping Elements, in: Recent Advances in Mechatronics 2008 – 2009, Berlin, pp.115-120.

Carlson, J.D. (2003) Critical factors for MR fluids in vehicle systems. International Journal of Vehicle Design. 33, 1-3, pp.207-217.