The behavior of the MR fluid during durability test

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Abstract. The article describes results of durability test of a magnetorheological fluid (MRF), which was carried out in rheometer of own design. The rheometer design enables to measure the rheological properties of MR fluid and to expose it to a long-term loading simultaneously, without any manipulation of the measured sample. During the durability test a change of the two most important parameters of Bingham model describing the behavior of MR fluids can be followed – dynamic viscosity and yield stress. In this paper the yield stress and viscosity were evaluated depending on temperature in OFF-state. The results show a significant change of yield strength during durability test depending on temperature of loading. Dependence of yield stress on temperature was proved. The viscosity decreased by 36% from its initial value after the dissipation of 9÷20kJcm⁻³ from total 1.2 MJcm⁻³ and then has remained the same until the end of durability test. Viscosity was evaluated depending on temperature.

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 the MR fluids can change their state from fluid to a semi-solid or plastic state, and back, in several milliseconds. 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 [1,2], suspension of driver seats in goods vehicles [3,4], vibration damping during seismic activity [5,6] or damping of cable bridge vibrations caused by wind and rain [7,8].

A flow curve of MR fluid exhibits Non-Newtonian behavior and is most commonly replaced by the Bingham model of plastic material, alternatively, for a more accurate solution, by so-called biviscous model (Figure 1). If the flow curve is described by the Bingham model, then the resulting shear stress in MR fluid can be described by the following equation:

\[ \tau = \tau_y(H) + \eta \cdot \dot{\gamma} \quad \tau \geq \tau_y, \]  

where \( H \) is the magnetic field intensity, \( \dot{\gamma} \) is shear rate of the fluid, \( \eta \) is the viscosity in the off-state (i.e., viscosity at \( H = 0 \)), \( \tau \) is total shear stress and \( \tau_y \) is yield stress. The total shear stress \( \tau \) in Equation (1) is expressed as a sum of viscous part \( \eta \cdot \dot{\gamma} \) and yield stress \( \tau_y \).

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Although MR fluids have been used for several years, problems occurring during their long-term operation have not yet been satisfactorily resolved. In particular, the effect of temperature, shear stress, shear rate, and the number of cycles on the properties of MR fluids have not been addressed.

Already Carlson et al. [10,11] discovered that the damping force increases with the number of load cycles during long-term loading of magnetorheological damper. They called this phenomenon in-use-thickening (IUT). Since in their experiment the damping force was only sampled at constant speed of pulsator, it was not possible to reconstruct the flow curve from this single point. At that time it was only possible to determine the apparent viscosity. This resulted in a hypothesis that the IUT is demonstrated by viscosity increase. However, the apparent viscosity is not a material constant for Non-Newtonian fluids. It is dependent on shear rate or shear stress. It is therefore necessary to describe the behavior of non-Newtonian fluids by a flow curve in the desired range of shear rates. Data of apparent viscosity (published by Carlson) can serve only for rough comparison of MR fluid consistency and only under identical test conditions. The flow curve is mathematically described by two parameters (yield stress and viscosity) which are constant for given state of MR fluid in a wide interval of shear rates.

Carlson determined oxidation as a source of IUT and this was confirmed by Ulicny [12]. Ulicny performed a durability test, he described oxidation of Fe-particles and he also described the decrease of the power of the MR-clutch, in which the MR fluid was loaded. Figure 2a shows non-oxidized iron particles, Figure 2b shows oxidized particles after intensive loading of the MR fluid. A visible oxidized layer is both hard and brittle. Nanoparticles of oxides are separated from this oxidized layer due to particle interaction during the MR fluid flow. These nanoparticles increase fluid apparent viscosity in the off-state. Sunkara proceeded in his work and he described the dependence of decrease of the yield stress on oxidation [13].

In Figure 3 “the viscosity increase” of MR fluid (according to Carlson) with the number of cycles is shown with the solid line. The dashed lines mark “viscosity” of new MR fluid with the addition of oxide nanoparticles. Although more efficient MR fluids have been developed, fluid durability as a function of temperature, shear stress and shear rate has not been published nor discussed yet. However, it is generally well-known that oxidation intensity grows with increasing temperature.
Likewise, it can be assumed that higher shear rate will result in a more noticeable collision of iron particles and thereby also in creation of oxide particles.

Figure 3. Off-state viscosity with added nanoparticles [10,11].

To date, nobody published complex description of MR fluid during long-term operation. The description of MR fluid behavior with the aid of an apparent viscosity is not appropriate. For complex description of MR fluid behavior, it is necessary to use the mathematical description of the whole flow curve in the wide range of shear rates. The best model for such behavior is probably a Bingham model.

2. Methods and experimental approach

For long-term tests, the special load unit was developed (Figure 4). This unit works like a slit-flow rheometer which allows loading the MR fluid and also measurement of flow curves without any manipulation with the sample.

Figure 4. Cross section of slit-flow rheometer.

The real piston of the proposed rheometer has a specific slit with thickness \( h_1 = 0.75 \text{mm} \) and width \( b = 2\pi r = 88 \text{mm} \) divided into two identical sections of length \( l_1 = 9 \text{mm} \) (Figure 5). Between them, the fluid passes through the slit with length \( l_2 = 19 \text{mm} \) where is much weaker magnetic field with intensity \( H_2 \ll H_1 \). The geometric profile of this slit is also different \( (h_2 >> h_1) \). The hydraulic resistance of this piston part is therefore very small and its influence was included in the correction function that is evaluated during the necessary calibration.
Our load unit was installed to the mechanical pulsator with stroke 50mm (Figure 7). Tested MRF was 140CG by Lord Corporation. Volume of MRF was 100ml. The MR fluid was exposed to the long-term operation in ON-State ($H_1=134$ kA/m) with the maximum shear rate $\gamma'=35,000$ s$^{-1}$. Two durability tests with different temperatures (50 and 70°C) were conducted. The durability tests were conducted in accordance with the diagram in Figure 6. The tests were stopped after specific life dissipation energy $LDE=1.2$ MJcm$^3$.

At each checkpoint of test, the flow curves in off-state and on-state within the temperature range 20 to 80°C were measured using our load and rheometric unit. Flow curves at control points were obtained using the start-up tests (Figure 7). From measured points of velocity and force there were selected only those, where the piston acceleration was close to zero (e.g. points $F_1$ and $v_1$ on Figure 7). This choice eliminated the influence of gas content elasticity of the load unit and inertia forces on the hysteretic nature of the point distribution. This also ensured a stable flow in the unit slit. F-v (Force-velocity) characteristic was obtained from these tests and was transformed into a flow curve using the appropriate mathematical relations. For presented results in OFF-state, an influence of apparent slip wall effect during the evaluation was neglected due to relatively low consistency of MRF.

The behavior change of MR fluid in off-state was evaluated from the Bingham’s model parameters change (viscosity, dynamic yield stress) and the influence of temperature was observed too.

A repeatability of measurement could not be accurately determined due to unequal conditions during test. Especially temperature could not be kept on exactly the same value during temperature unstable start-up test for measuring flow curves. For this reason, the temperature dependence of the monitored parameters was measured in the wide interval 20-75°C. From the measured points of shear stress (at $\gamma'=10,000$ s$^{-1}$) dependence on temperature and dynamic yield stress dependence on temperature (Figure 8), it is possible to assume that the repeatability is on a very good level.
3. Results and discussion
All presented results are valid for the off-state. Figure 9 shows the change of consistence of the MR fluid before and after loading.

Figure 10 shows the significant viscosity decrease (up to 36\%) after dissipation of 90 kJ cm\(^{-3}\). After this initial decrease, the viscosity remained stable. The beginning of the second durability test was monitored more precisely and it was identified that the viscosity decrease came already when LDE = 9±20 kJ cm\(^{-3}\).
\[ \eta(t) = 1.0529e^{-0.0321t} \]

The comparison of viscosity curve during loading with different temperatures (Figure 11) shows that the temperature did not influence the viscosity. Figure 10 shows all measured viscosity values during both tests except the beginning of the loading, where the viscosity decreased.

The second parameter of the Bingham model is a dynamic yield stress. Figure 12 shows the course of the dynamic yield stress curve during durability test at 50°C. There is a significant increase from 1 to 4kPa.

During durability test at 70°C the increase of dynamic yield stress was considerable lower from 1 to 2.5 kPa (Figure 13).
There was also observed a certain dynamic yield stress dependence on the temperature, which was considerably changing during durability test (Figure 14). In the beginning of the MR fluid test, the dynamic yield stress was independent on the temperature. With the increasing number of load cycles (and thus increase of LDE), the dependence on temperature started to be obvious and increasing in time.

4. Conclusion
The significant MR fluid viscosity decrease during the beginning of the durability test was described. After that the viscosity was no more changing. Contrary the dynamic yield stress course had increasing character, which fully corresponds with the published knowledge that the consistence of the MR fluid is increasing because the oxidized layer is separated from the surface due to particles interaction. During the test with higher temperature, the increase of dynamic yield stress is less significant. This phenomenon is caused by lower load of the MR fluid, because the apparent viscosity is lower and thus interactions among particles are less significant.

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