Magnetorheological fluids with two-component dispersed phase

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Abstract. In the paper the results of investigations of rheological properties of magnetorheological fluids with two-component dispersed phase are presented. Normal and tangential components of the mechanical stress in fluids in the magnetic field are determined. It is showed that using of carbonyl iron and chromium oxide as dispersed phase components allows to achieve essential structural response on magnetic influence.

1. Introduction

The currently used methods protection from vibrations, performing important functions, however, due to increasing demands on the protection of technical equipment and precision electronic devices, especially for transport, require upgrades and new solutions for the implementation of a more efficient and directional damping effects of various vibration types [1].

One of the promising methods for targeted reduction of vibration exposure on the object is its vibroisolation, in particular, with the use of viscous damping. This method finds new control features through the use of modern intellectual damping fluids with magnetosensitive nanofillers [2]. In the magnetorheological fluids (MRF) containing non-colloidal particles as the dispersed phase, under the influence of external fields a strong structuring of particles is observed, which is defined substantially by their magnetic properties – magnetic permeability, saturation magnetization, remnant magnetization, coercive force. Thanks to it, MRF exhibits elastic and viscoplastic properties according to the level of external influence. This allows one to control its damping characteristics specifically and reversibly (response time less than $10^{-3}$ s). It is known, that MRF are used as fluids for flow hydraulic systems and fluid dampers, squeeze dampers [3–6], including ground transportation systems and precision instruments. In the present time there is a very urgent task of creating hydraulic multipurpose damping elements on the base of MRF, having improved characteristics. The main difficulties in development of MRFs of new generation are securing the aggregation and sedimentation stability, also increasing of sensitivity of their elastoviscoplastic characteristics to the magnetic field. The stability of such systems can be provided by prevention of spontaneous irreversible coagulation of magnetic owing to the adding of colloid-type substances that form structural-mechanical barriers between particles.

Usually the classical MRF contains a magnetic dispersed phase of the magnetosoft or magnetohard type [7,8]. In the case of magnetosoft many-domain particles, for example, carbonyl iron the MRF structure is distorted even at small shear rate after the field has been turned off. MRF of single-domain

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particles “store” the viscosity change due to the magnetic field even after the field has been turned off. Adding an additional high-dispersed magnetohard powder can be one way for improving the classical MRF consumer characteristics. Its particles form a spatial structure in the carrying medium due to the intrinsic magnetic moment in the absence of the magnetic field, i. e. they serve as an additional stabilizer.

2. Materials and equipment

The aim of this study is to investigate the rheological and damping response to stationary and dynamic influences of different types on MRF containing two-component dispersed phase particles of soft magnetic material – carbonyl iron, as the second – particles of hard magnetic material (chrome dioxide CrO₂ or iron gamma-oxide γ-Fe₂O₃) or non-magnetic particles of aerosil SiO₂, under the influence of the external magnetic field. Mineral oil was dispersion media.

Rheological measurements were performed by means of rheometer Physica MCR 301 by Anton Paar with using of a measuring cell of parallel plate type with diameter of 20 mm and the clearance between them is 0.7 mm. The upper plate can perform a rotary tangential (horizontal) shear. Furthermore, it can be moved in the vertical direction at a constant speed. The values of the induction of the constant magnetic field have been varied up to the value of \(B = 1\) T, the range values of shear stress values is \(0\)–\(128\) kPa.

Experiments were conducted in the following modes of deformations on MRM:

1) tangential shear mode of the top plate at a constant shear rate in the range of \(0.01 – 1000\) s\(^{-1}\);

2) continuous vertical shift mode of the upper plate, wherein the clearance \(d\) during 50 s decreased from 0.7 mm to 0.65 mm with a corresponding relative deformation of the material \(\varepsilon = \Delta d / d\) in the range of values \(0 – 0.07\);

3) continuous vertical movement mode of the upper plate (like to case 2) with a simultaneous tangential shear deformation at a constant shear rate of \(10\) s\(^{-1}\);

4) linear shear stress growth from zero to given value slightly exceeding yield stress of MRF.

Magnetic properties of MRF are defined by the standard technique of measurement of magnetization with two Hall sensors. Magnetization curves are received in the range of magnetic field strength up to 450 kA/m.

In all modes of deformation the values of resistance force in a material to the shift of the upper plate \(F\) (normal \(F_N\) and tangential \(F_T\) components) were recorded. They were determined by pressure sensors on the top measuring plate of the experimental cell at material’s shear. The dependencies are presented in the form of specific values of force \(F_{N,T} / S\), where \(S\) – area of the plate, i.e., normal \(\tau_N\) and tangential \(\tau_T\) values of shear stress on the magnetic field at various modes of deformation.

3. Results and discussion

Firstly, magnetorheological fluids with high volume concentration of the dispersed phase (42 vol. % of carbonyl iron – the first phase – and 2.4 vol. % of the second phase) were studied. Compositions of MRF and their characteristics without magnetic field are listed in Table 1.

### Table 1. Compositions of high-concentrated MRF containing complex dispersed phase.

| MRF | The second phase | \(\tau_0\) at \(B = 0\) | \(\tau_T\) at \(B = 0, 30\) s\(^{-1}\) |
|-----|-----------------|-----------------|-----------------|
| 1   | CrO₂            | 2.78            | 309             |
| 2   | γ-Fe₂O₃         | 1.41            | 291             |
| 3   | SiO₂            | 0.76            | 141             |

Magnetization curves of these MRF are presented in figure 1. Magnetization of MRF-3 containing nonmagnetic silica is smaller than MRFs 1 and 2 containing only magnetosensitive powders. Because
of saturation magnetization values of CrO$_2$ and $\gamma$-Fe$_2$O$_3$ are very close (480 and 440 kA/m correspondingly) their magnetization curves are similar. At the magnetic field strength more than 300 kA/m growth of magnetization reduces, the saturation begins.

Dependences of static yield stress and shear stress at shear rate 10 s$^{-1}$ on magnetic field induction are presented in figures 2 and 3. As particles of magnetohard powders have smaller sizes (long axis is less than 0.7 μm) than ones of carbonyl iron (3–4 μm) they form shells around carbonyl iron particles. In the external magnetic field all ferromagnetic phase are magnetized, at this needle-like particles of $\gamma$-Fe$_2$O$_3$ or CrO$_2$ aspire to align to field with long axis forming on the surface of carbonyl iron particles peculiar brushes. Interactions of such rough formations lead to additional energy dissipation in shear flow.

![Figure 1](image1.png)

**Figure 1.** Magnetization curves of concentrated MRF.

![Figure 2](image2.png)

**Figure 2.** Dependence of static yield stress of MRFs (mode 4) on magnetic field induction.

![Figure 3](image3.png)

**Figure 3.** Dependence of shear stresses of MRFs on magnetic field induction (mode 1), shear rate – 10 s$^{-1}$.

![Figure 4](image4.png)

**Figure 4.** Dependence of shear stresses of MRFs on volume concentration of dispersed phase without magnetic field, shear rate – 11.5 s$^{-1}$.

As it is seen from figures 2 and 3, the MRF-1 shows the greater values of shear stresses in the magnetic field, what can be explained by bigger elongation of chromium dioxide particles as against $\gamma$-Fe$_2$O$_3$ ones and their higher magnetization.

The experiments showed, that MRFs containing general volume concentration of dispersed phase no more than 30% have optimal combination for vibroprotecting devices of low viscosity without magnetic field and essential increment of energy dissipation in the field. For example, in figure 4
dependence of shear stresses of some composition MRFs on volume concentration of dispersed phase without magnetic field is showed.

Therefore for further experiments we have chosen magnetorheological fluid which contains insulating oil and 15.9% of complex filler from iron, chromium oxide $\text{CrO}_2$ and silicon oxide $\text{SiO}_2$ was investigated in different regimes. Dependences of the shear stress $\tau_T$ vs. shear rate for this fluid presented in figure 5 allow us to determine that with increasing the induction of the external magnetic field all the elastic and viscoplastic characteristics of the MRF increase sharply. First of all, limiting shear stresses, increasing which the plastic shear of the material appears, followed by a flow in the gap between the plates. It is characterized by the small range of relative deformations (less than 1%) and the growth of values $\tau_T$ in 3000 times in comparison with those without the field.

![Figure 5](image1.png)

**Figure 5.** Dependence of shear stress of MRE on shear rate in mode 1 at different magnetic field induction.

Normal shear stresses (figure 6) in the continuous deformation mode are practically independent of the shear rate in the range of shear rates about $30 \text{ s}^{-1}$. At high shear rates, they increase in the magnetic field with induction of more than 0.1 T. The normal stresses are approximately equal to the shear stresses in the range of the magnetic field up to 0.25 T. At higher fields the normal stresses exceed the shear stresses, reaching values of 120 kPa.

![Figure 6](image2.png)

**Figure 6.** Dependence of normal and shear stresses of MRE on magnetic field induction in mode 1, shear rate $11.5 \text{ s}^{-1}$; rhombuses $\tau_T$, triangles $\tau_N$.

![Figure 7](image3.png)

**Figure 7.** Dependence of $\tau_N$ on compressive deformation of MRE (mode 2) at different magnetic field induction ($\circ - B=0$, $\square - 0.2$ T, $\star - 0.3$, $\blacksquare - 0.5$, $\times - 1$).

![Figure 8](image4.png)

**Figure 8.** Dependence of normal stress on compressive deformation of MRM (mode 3) at shear rate $10 \text{ s}^{-1}$ at different magnetic field induction ($\circ - B=0$, $\square - 0.2$ T, $\star - 0.3$, $\blacksquare - 0.5$, $\times - 1$).
The dependence of the normal stresses on the strain under compression of MRM according to the mode 2 is shown in figure 7. It is seen that the increase in the normal stresses is the most significant at the beginning of the compression. With the increase in the compressive strain the growth of $\tau_N$ slows down. The higher the intensity of the magnetic field, the smaller compression of the material can be achieved and the higher its resistance to the compression is. Similar relationships are observed for the normal stresses in the vertical compression mode with a continuous simultaneous tangential shear deformation, but $\tau_N$ magnitude is smaller (figure 8). The increase of the shear stress $\tau_T$ at compression is smaller than the increase of $\tau_N$ (figure 9). The shear stresses grow linearly with deformation; they increase at the compression by about 60–70% (mode 3).

4. Conclusion
The rheological properties of magnetorheological fluids with complex dispersed phase in the magnetic field depend not only on magnetic properties, carbonyl iron concentration, but and on material of second component of dispersed phase. It has been experimentally shown that for certain modes of the magnetic field impact on the damping magnetosensitive material one can effectively increase the resistance to the external vibration influence both in the tangential and the normal directions. The use of magnetorheological fluids possessing higher structural response on magnetic influence for these purposes will allow to implement tuning parameters of the damping unit to multidirectional vibrations of broad frequency and amplitude range, arising as a result of the effects of internal and external sources.

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