738. Investigation of magneto-rheological fluid parameters using cantilever-type piezoactuator

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Abstract. There has been a growing interest in the on-line detection of viscosity of magneto-rheological fluids since it is a critical parameter that is sensitive to material property changes caused by chemical reactions, sedimentation process and magnetic field. Online monitoring of viscosity and density offers a powerful means for controlling the quality of magneto-rheological fluids and processes involving fluid environment.

Keywords: magneto-rheological fluid, piezoelectric materials, cantilever, actuator, viscosity, density, measurements, monitoring.

Introduction

A common device for measurements of magneto-rheological (MR) fluid viscosity is a rheometer. It is quite expensive equipment of large size for a wide range of measurements. A new measurement device for fluid viscosity measurements was created using smart materials. A Bingham model is used to characterize the constitutive behavior of the MR fluids subject to an external magnetic field strength. Also, during this research, a new generation of magneto-rheological fluid was developed and tested in a traditional way by using rheometer and in a novel way by using a new construction for it.

New generation magneto-rheological fluid

Magneto-rheological (MR) fluids consist of stable micro-sized suspensions, magnetisable particles dispersed in a carrier medium such as silicon oil or water. When a magnetic field is applied, the polarization induced in suspended particles results in the MR effect of the MR fluids. The MR effect directly influences the mechanical properties of the MR fluids. The suspended particles in the MR fluid become magnetized and align themselves, like chains, with the direction of the magnetic field. The formation of these particle chains restricts the movement of the MR fluid thereby increasing its yield stress.

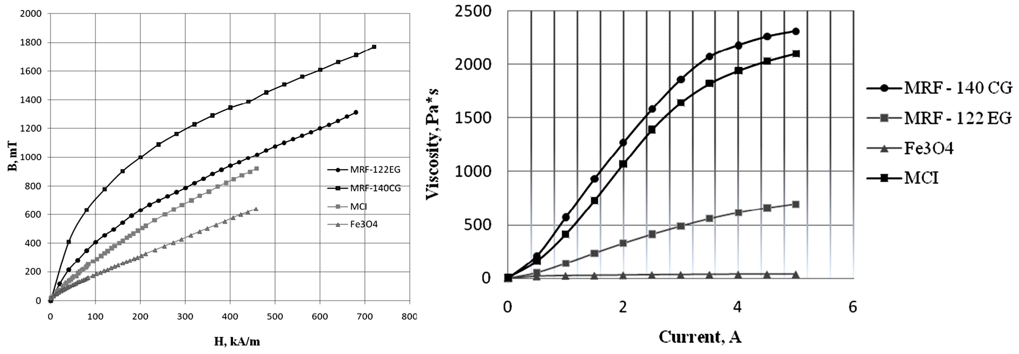
For a wide practical application like direct active process, monitoring of fluid behavior, a viscosity of the magneto-rheological fluid is very important. Three types of magneto-rheological fluids were investigated under fluid viscosity. Magneto-rheological fluid has negative affective phenomenon – sedimentation, also influences practical application. MR fluid flows similarly to the viscous non-Newtonian fluid. The rheological equation corresponding to the Maxwell-type fluid body is [4, 5]:

$$\frac{d\varepsilon}{dt} = \frac{1}{2G_S}\dot{\sigma} + \frac{1}{2\eta}\sigma . \tag{1}$$

Here $\varepsilon = \varepsilon_1 + \varepsilon_2$ is fluid deformation; G_s fluid elastic modulus; σ is fluid stress; η is fluid viscosity. Equation is valid when the shear stress acts between the moving layers of the magneto-rheological fluid, related to each other. The investigation of the fluid movement of normal stress σ_n, equation is expressed as follows [4, 5]:

$$\frac{d\varepsilon}{dt}=\frac{\dot{\sigma}_n}{G_s}+\frac{\sigma_n}{\lambda}. \tag{2}$$

In order to avoid or at least reduce this negative phenomenon a new, improved composition of the magneto-rheological fluid was proposed. New generation fluid was compared with well known MR fluids MRF-122 EG and MRF-140 CG (LORD). Measurements of magneto-rheological fluids viscosity was performed by means of two methods: using "Anton Paar" rheometer and a the developed novel device for measurements - a cantilever-type actuator (Fig. 1). In the direct process or fluid state observation a fluid parameters sensor is an important device. The model parameters are obtained from measurements with well-known sample liquids by a curve fitting procedure. Finally, the measurements results with cantilever-type actuator are presented. Values of viscosity and shear show the viability of the model. During scientific research of sedimentation the solution was developed resulting in a new generation magneto-rheological fluid. Differently sized magnetic particles were mixed in this new fluid. The reason of it is to overcome the gravitational forces and reduce extent of sedimentation. Mixed particles partly undergo Brownian motion and reduce gravitation force. The main idea of the production process is mixing nano-scale (Fe_3O_4) and micro-scale (Carbonyl iron) particles. Such improvement generates Brownian motion inside the fluid. Magnetic particles suspended in a liquid tend to move in pseudo-random or stochastic paths through the liquid, even if the liquid in question is at rest and the process of sedimentation is significantly reduced.



a) b)

Fig. 1. a) Dependence of magnetic induction on magnetic field strength, four different fluids are measured: two types from LORD (MRF – 122EG and MRF – 140CG) and two different stages of the produced liquid; b) dependence of viscosity on current (three different magneto-rheological fluids were measured and one magnetic fluid)

Magneto-rheological fluid measurements

Many practical applications in real structures require accurate fluid properties. It calls for an efficient operation. For magneto-rheological effect one of the most important physical fluid properties is objective and adequate viscosity of active and non-active MR fluid. Several methods are designed to measure the viscosity of liquids. Investigated and the proposed method is based on interaction between the liquid and the oscillating piezoelectric cantilever. Prior to completion of this research methodology, several measurements were performed with rheometer. The results indicate that the developed magneto-rheological fluid MCI is fairly strong in comparison to MR fluids LORD MRF-140 CG and MRF-122 EG. It means that MR controlling range is practical from application point of view. The mathematical expressions of experiment are shown in equations (5), (6), (7). This calculation refers the representative radius R_{max} according to DIN53018 [4]:

$$\dot{\gamma}_{\max} = \frac{\omega \cdot R}{H}, \tag{3}$$

$$\tau_{\max} = \frac{2 \cdot M}{\pi \cdot R^3}, \tag{4}$$

$$\gamma_{\max} = \frac{R \cdot \phi}{H}, \tag{5}$$

where mean values in equation (5), (6), (7) are: $\dot{\gamma}$ - shear rate, ω - angular velocity, R - plate radius, H - gap, τ - shear stress, M - torque, ϕ - deflection angle.

Piezoelectric actuator for viscosity measurements

The vibration behavior of the piezoelectric bending actuator is described by the Euler-Bernoulli beam equation:

$$EI\frac{\partial^4 \Psi(x,t)}{\partial^4 x^4} + \mu \frac{\partial^2 \Psi(x,t)}{\partial t^2} = \frac{\partial^2 M_p(x,t)}{\partial x^2}, \tag{6}$$

where EI and μ are the effective bending stiffness and the effective mass per unit length of the composite beam, $\Psi(x, t)$ is the beam deflection in z-direction (Fig. 4), and M_p is the actuating moment due to the piezoelectric effect. Since M_p is considered to be a constant moment along the entire beam, $\partial^2 M_p/\partial x^2 = 0$. Consequently, the boundary conditions for the clamped-free beam are:

$$\begin{aligned} &\Psi(0,t) = 0, \\ &\frac{\delta \Psi(0,t)}{\delta x} = 0, \\ &\frac{\delta^2 \Psi(L,t)}{\delta x^2} = \frac{1}{EI} M_p, \\ &\frac{\delta^3 \Psi(L,t)}{\delta x^3} = -\frac{1}{EI} F, \end{aligned} \tag{7}$$

where L is the length of the beam and F is the force acting on the tip due to the interaction with the surrounding liquid. The actuating moment M_p is given by [7]:

$$M_p = \int_{A_p} Y_p d_{31} E_z z dA = w_b Y_p d_{31} V_d z_m, \tag{8}$$

where A_p, Y_p, and d_{31} are the cross-sectional area, Young’s modulus, and the piezoelectric modulus of the actuating layer and E_z is the electric field in this layer in z-direction, w_b is the width of the bending actuator, z_m is the mean distance of the actuating layer from the beam center, and V_d is the excitation voltage (Fig. 2).

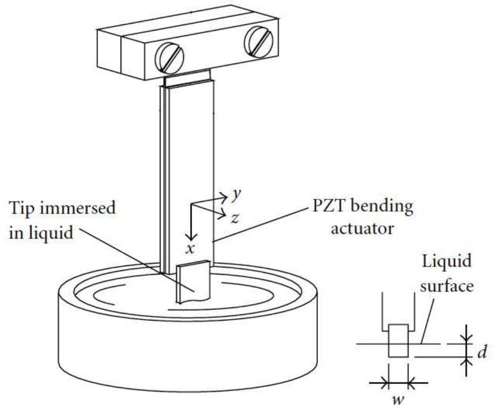


Fig. 2. PZT bending actuator is rigidly clamped at one end. To the free end of the cantilever, a tip of well defined geometry (width *w*) is attached and immersed in the sample liquid (dipping depth *d*). The interaction of the cantilever tip and the liquid changes the frequency characteristics [6]

The measured voltage V_s is calculated by applying:

$$\begin{aligned} D_z &= d_{31}T_{xx} + \varepsilon E_z, \\ T_{xx} &= \frac{1}{K_{11}}\left(S_{xx} - d_{31}E_z\right), \end{aligned} \tag{9}$$

to the sensing PZT layer, where D_z, T_{xx}, and S_{xx} are electric displacement, stress, and strain, ε and K_{11} are the permittivity and the compliance of the PZT layer. The cantilever deflection $z(t)$ can then be determined by solving the differential equation for a one-dimensional forced harmonic oscillator:

$$\ddot{z}(t) + \frac{b_{eff}}{m}\dot{z}(t) + \frac{k_{eff}}{m}z(t) = \frac{F_p(t)}{m}, \tag{10}$$

where $b_{eff} = b_e + b_m$ – total effective damping of the system; $k_{eff} = k_b + k_{mag}$ – total effective stiffness of the system, F_p – piezoelectric force.

Experimental setup

The purpose of this research work was to determine the coefficient of viscosity of a magneto-rheological fluid for different values of the magnetic field. Method of indirect measurement was implemented using a reference fluid with known properties. A test stand with a piezoelectric cantilever-type viscometer is shown in Fig. 3. The measurements revealed that the viscosity of the magneto-rheological fluid was linearly dependent in a wide range of values of the magnetic induction. Piezoelectric actuator is rigidly fixed at one end. The tip is immersed into the magneto-rheological fluid and is fixed to the free end of the actuator. The interaction between the actuator tip bending and fluid resistance forces are measured by tracking bending amplitudes. Experiment results are widely controlled by changing MR fluid viscosity. Voltage supplied to electromagnetic coil is from 10 to 30 V, when the cantilever oscillates at a frequency of 20 Hz [1-3].

Four fluids were tested during the experiment. One of them was ferromagnetic, other two - LORD MR fluids and the last one - developed by the authors.

The cantilever sensor used in this experiment is Noliac ceramic multilayer bender CMBP09 (Table 1). The bending actuator has two different types of tip position (Fig. 5). Also, results are dependant on the type of piezoelectric cantilever actuator tip.

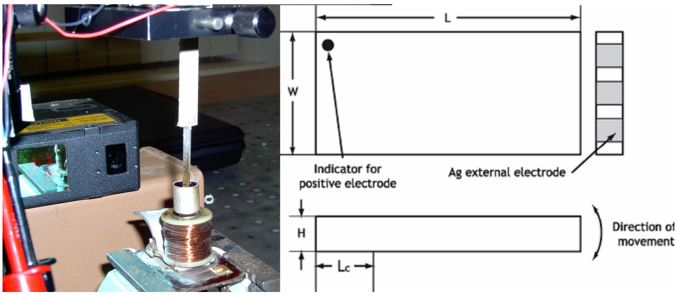


Fig. 3. Diagram of the piezoelectric actuator and photo of experimental setup

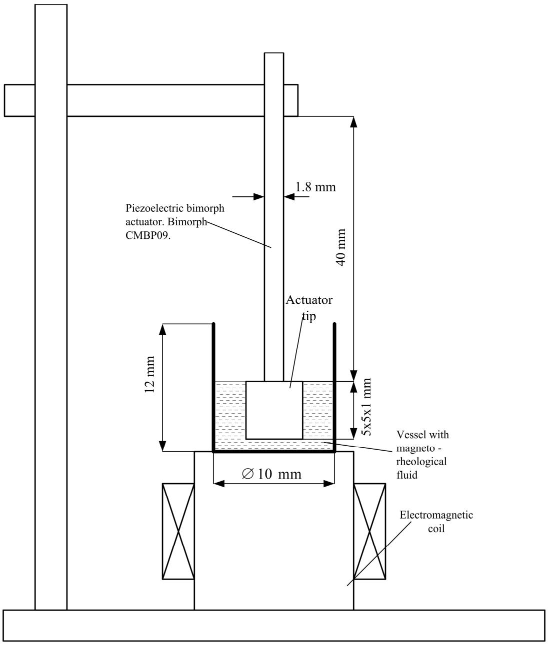
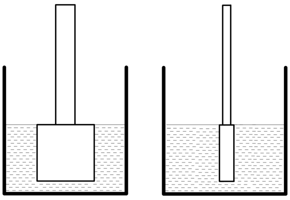


Fig. 4. Measurement setup

The analytical model is based on an approximation of the immersed cantilever as an oscillating sphere comprising the effective mass and the intrinsic damping of the cantilever and additional mass and damping due to the liquid loading. The model parameters are obtained from measurements with well-known sample liquids by a curve fitting procedure.



a) b)

Fig. 5. Two types of piezoelectric actuator tip: a) entire area of the tip operation; b) shear mode operation

Research purpose is to develop an experimental device for measurement of characteristics of the magneto-rheological fluids. Fig. 6 illustrates experimental setup assembled for measurement of magneto-rheological fluid characteristics: fluids shear and viscosity. Registered experimental results are dependent on magnetic induction. A crucial performance metric is the sensitivity of a measurement device. At the end of Noliac cantilever two tip types were used for good device sensitivity. Noliac ceramic multilayer bender was used for device measurement accuracy. This bender has a very good amplitude characteristic, low voltage and multilayer ceramic composition.

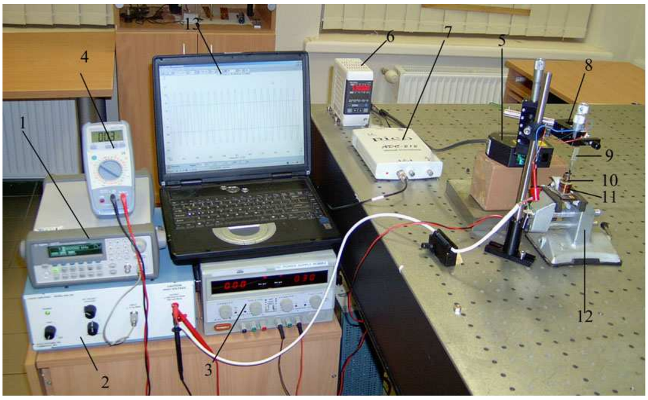
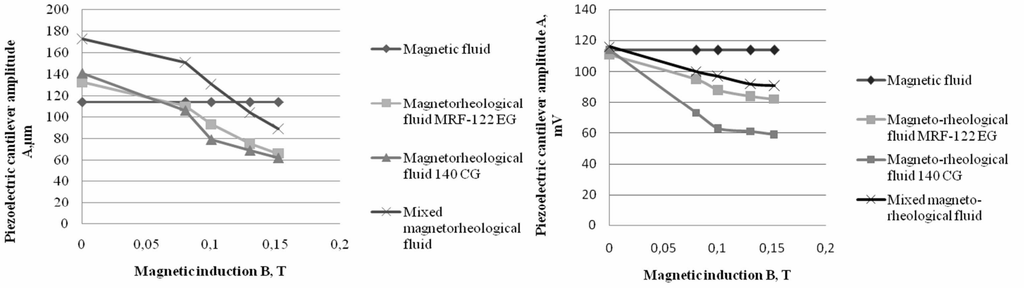


Fig. 6. The experimental setup: 1 – signal generator Agilent 33220A; 2 – power amplifier EPA-104; 3 – DC supply 4 – multimeter MS8201H; 5 – laser displacement sensor LK-G82; 6 – laser sensor controller LK-G3001PV; 7 – analog-digital converter PICO ADC-212; 8 – holder for the piezoactuator with micrometer screw; 9 – piezoelectric bimorph actuator; 10 – vessel with MRF; 11 – electromagnet; 12 – holder for the electromagnet; 13 – computer



a) b)

Fig. 7. a) Dependence of piezoelectric cantilever amplitude on voltage for different fluids. Magnetic fluid is not rheological and magnetic field does not affect viscosity of the fluid, so cantilever oscillating amplitude is stable, when the magnetic field varies. Experiment with the tip operating in shear mode; b) Dependence of piezoelectric cantilever amplitude on voltage for different fluids. Magnetic fluid is not rheological and magnetic field does not affect viscosity of the fluid, so cantilever oscillating amplitude is stable when the magnetic field varies. Experiment with the tip operating in entire area

Piezoelectric materials have direct and inverse effect. When piezoelectric cantilever-type actuator works in an inverse mode harmonic flexural oscillations are generated. At the same time another phenomenon occurs: variable viscosity of the magneto-rheological fluid reduces cantilever oscillation amplitude. Very important factory of measurements device is sensitivity, which depends on various factors: magneto-rheological fluid type, ingredients, working temperature, rheological effect strength, actuator geometry and type. In this case sensitivity range is 1.5 – 2.5.

Conclusions

Piezoelectric cantilever changes bending amplitude. The changes depend on viscosity of the magneto-rheological fluid (also magnetic field strength changes). These results allow determination of the physical properties of the liquid. Two different tip positioning types are attached at the cantilever end and immersed into three different magneto-rheological fluids samples as well as one sample of magnetic fluid. Analytical model is needed to determine magneto-rheological fluid parameters depending on magnetic field strength and piezoelectric cantilever. Further tasks include improvement of the developed device including determination of calibration curves for the enhanced measurement accuracy.

Acknowledgements

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