Positioning magnetorheological actuator

Valery Mikhailov\textsuperscript{1}, Dmitry Borin\textsuperscript{2}, Alexey Bazinenkov\textsuperscript{1} and Igor Akimov\textsuperscript{1}

\textsuperscript{1} Bauman Moscow State Technical University, 2-nd Baumanskaia st. 5, MT-11, 105005, Moscow, Russia

\textsuperscript{2} Technische Universität Dresden, Chair of Magnetofluiddynamics, 01062, Dresden, Germany

E-mail: mikhailov@bmstu.ru

Abstract. In this work we consider a construction of a positioning magnetorheological actuator based on bellow units, as well as dynamical model, which include such elements as a magnetically hysteresis, pressure loses in hydraulic system, nonlinearity of rheological behaviour of working fluid. Two operating modes of positioning actuator are taken into account and transients are presented. Dynamical modelling shows possibility for the improvement of a real control system and ensure of submicron precision of positioning with millisecond time of response.

1. Introduction

Rapid response of magnetorheological (MR) fluids to an applied magnetic field, as well as precisely controllable yield stress, allows to use MR fluids in engineering applications such as semi-active dampers, clutches etc [1-3]. Studies on MR hydraulic power system has been performed in [4,5]. Besides, for more than ten years the use of MR effect for the control of hydraulic actuating systems in vacuum technological equipment [6, 7] and astronomical telescopes [8] is being proposed. In this work we briefly describe an actuator developed recently by us and its dynamical model which allow improvements of the positioning system’s parameters.

2. Construction of the actuator

The principle idea of proposed actuator is in the use of bellow units, as a pressure chambers, and MR valves system based on Wheatstone bridge hydraulic power circuit. MR fluid is pumped from the pump to the bellow units through the input MR-valves and than pumped out through output MR valves. Objects moves relatively to the base of elastic membrane because of pressure difference in opposite hydrocylinders. Control of pressure drop is carried out due to adjustment of the magnetic field applied to MR fluid in MR valves. By means of bellow units it is possible to realize not only the linear actuating but a multicoordinate positioning system as well. The scheme of the linear actuator is shown in figure 1.
3. Parameters of actuator
Experiments on actuators prototype have been performed with a control system analogous to one used in [8]. Figure 2 shows response of the actuator (red curve) on step signal (green curve). Actuator was loaded with 70 kg of external mass in direction of moving, a spherical bearing was used as a guide and measurements were made with contact inductive sensor. The set position (2 µm shift relative to initial coordinate) is achieved in 250 ms with precision of ΔX=0.25 µm which is limited by sensor resolution, resistance force of guide and used control algorithms. A new control system should be developed to ensure of the actuators characteristics improvement.

4. Dynamical model of the actuator
The most important instrument for the control system analysis and synthesis is a dynamical modelling of the considered device. To define the elements of the dynamical model, one needs to find an influence of rheological and dynamical properties of MR fluid on the pressure drop on the working channel of the MR valve. Various models for some types of MR devices are already known e.g. see in [10, 11]. In [11], among others, the magnetic hysteresis effect is included in the model, as well as in a model for the valve of the MR positioning actuator [12].

Generalized functional scheme of proposed model for the case of one coordinate positioning is shown in figure 3 and consists of such elements as input and output MR valves (which are considered in model including magnetic and rheological effects), pump line, positioning object and measuring system.
To describe a rheological behavior of MR fluid in working elements of MR valves, the Bingham plastic model is usually used [13, 14]. However, in the case of positioning actuator with MR control, the different operating modes must be considered. In advance positioning mode (acceleration and rapid moving) the MR fluid is a viscous medium, because of the not high magnetic field strength and high shear rates, and the Bingham model is applicable.

In adjustment positioning mode there are two regimes, namely preliminary adjustment and precise regimes. In preliminary adjustment regime, the shear rates are usually higher than 1 s\(^{-1}\) and the Bingham model is still applicable, even under action of high field strength, although the behavior of fluid is viscoplastic. In precise adjustment regime, shear rates are less than 0.1 s\(^{-1}\) and because of the strong viscoplastic behavior of MR fluid and correspondingly non-linearity of flow curves one must use a better model for the behavior of the MR fluids. In this case the fit for flow curves for the used by us self prepared MR fluid (20 vol. % of 5 \(\mu\)m particles in organic oil) can be obtained with the so-called Casson equation [15]:

\[
\tau^2 = \tau_y^2 + (\eta \cdot \dot{\gamma})^2
\]

where \(\tau\) is the shear stress, \(\tau_y\) is the yield stress, \(\eta\) is the viscosity and \(\dot{\gamma}\) is the shear rate.

In case of other MR fluids optimal fit have to be found, e.g. see [16] for the Lord Corp. fluids.

Besides, the time of aggregation of MR fluids at low shear rates must be taken into account in the model as an important element, which has a remarkable influence on dynamics of control system. Relaxation and cluster formation in MR fluids under action of magnetic field can be described with the so-called method of mechanical analogies. Namely, for the adjustment positioning mode, when fluid has viscoplastic behavior, one can consider the elements of Voigt model, where the elastic element with elasticity modulus \(E\) oscillates in viscous medium with viscosity \(\eta\) and the time of transient is defined as \(t = \eta / E\), there both variables are magnet field and therefore control signal dependent.

5. Results of simulations
Simulation was performed by means of Simulink application of MathLab software package. We considered two operating modes separately and results of transients are presented in figures 4 and 5 for
the advance positioning and adjustment positioning mode respectively. Two various regulators were chosen for each mode to ensure the stability of transients. In case of advance positioning the proportional-integral-differential and for the adjustment positioning mode the proportional-differential regulator was used. Time of response for both considered modes is 85 ms and 5 ms which are chosen for the accuracy of the positioning of 5 mm and 50 nm respectively.

![Figure 4. Transient of model for the advance positioning mode](image1)

![Figure 5. Transient of model for the adjustment positioning mode](image2)

6. Summary and outlooks
Construction of a positioning magnetorheological actuator based on bellow units and its dynamical model are presented. In the dynamical model of MR actuator for the analysis and synthesis of control laws two operating modes are considered. For the precise adjustment regime a non-linear model of MR behaviour must be implemented. To take into account the dynamics of structure formation in MR fluids, the Voigt mechanical model of fluid behaviour is used. Dynamical modelling shows possibility for the improvement of a real control system and ensure of submicron precision of positioning with millisecond time of response. A question of a switching between two regimes should to be at the centre of attention during the development of a program and electronic part of the control system. Results of modelling have to be experimentally verified.

References
[1] Carlson J D (2005) Int J Mod Phys B 19(7-9), 1463
[2] Lee U, Kim D, Hur N and Jeon D (1999) J Intell Mater Syst Struct 10(9), 701
[3] Gordaninejad F and Kelso S P (2000) J Intell Mater Syst Struct 11(5), 395
[4] Yoo J-H, Sirohi J and Wereley N M (2001) Proc. of SPIE 4327(22) 148
[5] Yoo J-H and Wereley N M (2004) J Intell Mater Syst Struct 15(11), 847
[6] Anisimov V V, Deulin E A, Khramtsov S V and Mikhailov V P (1996) Vacuum 47 (10), 1163
[7] Borin D, Mikhailov V, Deulin E and Zobov I (2007) Vacuum technique and technology 17(2),141 (in russian)
[8] Deulin E A, Mikhailov V P, Eliseev O N and Sychev V V (2000) Proc. of SPIE, 4003, 303
[9] Lord Corporation Engineering Note: Designing with MR Fluids (online http://www.lord.com)
[10] Jolly M R, Carlson J D and Munoz B C (1996) J Smart Mater Struct 5, 607
[11] Jinung An and Dong–Soo Kwon (2002) J Intell Mater Syst Struct 14(9), 541
[12] Borin D, Mikhailov V and Bazinenkov A (2007) Conversation in machine buildings of Russia 3, 37 (in russian)
[13] Wereley N (2008) J Intell Mater Syst Struct 19(3), 257
[14] Gordaninejad F (1999) J Intell Mater Syst Struct 10(8), 601
[15] Casson N (1959) in Rheology of Disperse Systems, ed. Mill C (London, Pergamon)
[16] Carlson J D (1997) Proc. Of Int. Conf. on ERS and MRF, 112