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The investigation of the work-fluid characteristics of precision hydraulic active vibration control module

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Abstract

Vibration control in the systems of precise positioning is an important problem that nanotechnology sector is facing. This problem challenges the engineers to develop advance positioning mechanisms such as hydraulic magnetorheological (MR) actuators or MR modules. These modules combine the characteristics of hydraulic systems and electromagnetic control because of the use of magnetorheological fluids instead of traditional hydraulic fluid. This allows to avoid using inertial valves that results in higher accuracy and dynamic characteristics as compared with conventional systems. The main element of a MR valve is a solenoid that creates a magnetic field to control viscosity and rheological behavior of the fluid due to structuring of the disperse phase of magnetic particles in magnetic field.

The positioning error of the MR module depends, to great extent, on the minimum current which should be applied to the coil to start the motion. This work is aimed at the experimental study of the response of the MR module on the applied current. The response was measured as the pressure drop in the fluid at the exit of the MR module.

It was found that the maximum magnetic field in the working gap of the module of 0.04 T corresponded to the pressure drop 0.12 MPa. The results form the base for design of MR modules of automatic control systems operating under semi-active and active vibration control modes.

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1. Introduction

Vibrations from different sources such as neighboring equipment and road transport is a serious problem for precise technological equipment in various sectors including microelectronics and nanotechnology [6]. Vibration amplitude in buildings can be as high as 200 μm [7] in the frequency range from 0.2 to 200 Hz [10] while the required positioning accuracy is in nanometer range. This problem challenges the engineers to find a radical advancement in vibration suppression by using different principles and phenomena.

Vibration control can be classified into three groups: passive, semi-active and active [8]. In semi-active vibration control systems a damper changes the vibration absorption properties (damping properties) according to the characteristics of external vibrations. An example of such system is a car shock absorber with magnetorheological fluid (MRF) [3,9]. Active vibration control systems are most effective at low frequencies and large amplitudes of vibrations. The active vibration control systems reduce and compensate disturbing force (or vibration displacement) by the additional energy source (or actuator). These systems are usually used positioning mechanisms (actuators). These actuators compensate vibration displacement due to closed-loop control system with feedback. For stationary technological equipment the effective vibration damping can be achieved through combination of passive and active systems.

Among various types of actuators which can potentially be used for active vibration isolation [10] the systems based smart-materials including piezoelectric, magnetostrictive, shape memory alloys materials, MRF, elecrorheological (ER) fluids (ERF), MR elastomers and ER elastomers [13] are the most promising.

A MR actuator is a hydraulic actuator in which MRF is used instead of hydraulic fluid. MRF properties are controlled by external magnetic field [5,12] that changes the properties of MRF directly without any moving inertial elements [2]. MR actuator has low object positioning error (<0.1 μm) and low response time (<200 ms) [11]. It can perform vibration control in the frequency range from 0.2 to 5 Hz. MRF is a suspension in the carrier fluid like organic mineral oil of magnetic particles of reduced iron, pure iron, cobalt, carbonyl iron, nickel, chromium dioxide, etc., 10...30 μm in size .

MR elastomer is a solid-state analog of the MRF [10]. It consists of magnetic particles distributed in silicone rubber. Magnetic powder is usually magnetite (Fe_3O_4) with a particle size of 0.2...0.3 μm and iron with a particle size of 1...5 μm. The elastomer may include both soft and hard magnetic particles [14].

In this work a three-coordinate hydraulic positioning actuator with MR control (or MR module) [12] was studied. The main control element of MR module is a MR valve. And the main element of a MR valve is a solenoid that creates a magnetic field to control viscosity and rheological behavior of the fluid in work gap of the valve due to structuring of the disperse phase of magnetic particles in external magnetic field.

According to [4,15] the positioning error of the MR module depends, to great extent, on the minimum current which should be applied to the coil to start the motion ("pickup current"). This current determines the magnitude of external magnetic field applied to the MRF, and the strength of the structure of the disperse phase of magnetic particles formed in the gap of the MR valve. The higher strength of the structure, the greater pressure drop valve is held.

Using the [16], in the case of MR valve with cylindrical work gap the differential pressure is determined as follows:

$$\Delta P = \frac{9.21\varphi\mu_0 M_s^{1/2} H^{3/2} D_{mid} L}{(\mathrm{D}_{out}^2 - \mathrm{D}_{in}^2)} , \tag{1}$$

where φ - volume concentration disperse phase of magnetic particles in MRF, M_s - magnetic particles saturation magnetization, H - magnetic field, L - work gap length, D_{mid} , D_{out} , D_{in} - middle, outer, inner diameter of cylindrical MR valve work gap respectively.

This work is aimed at the experimental study of the response of the MR valve on the applied current. The response was measured as the pressure drop in the fluid at the work gap of the MR valve.

2. Experimental details

The main control element of MR module is a MR valve (Fig. 1). It controls MRF flow on the module channels. MR valve is made of a soft magnetic material for magnetic circuit consisting of several sections (2), (3), (4), an electromagnetic coil (1) and a working gap with MRF (5). The magnetic field in the MR valve gap increases with increasing the coil electric current. The flow rate of the fluid through the gap depends on the applied magnetic field due to the MR effect [5].

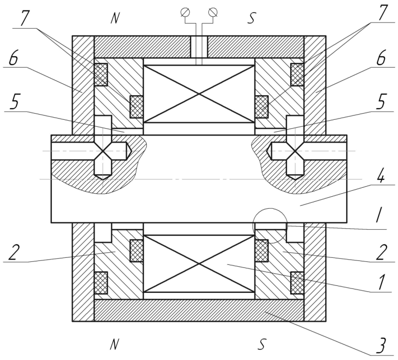

Fig. 1. MR valve: 1 - electromagnetic coil, 2-4 – parts of magnetic circuit, 5 - working MRF gap, 6 – MR valve body, 7 - seals

MR module [1] is shown schematically in Fig. 2. The module is mounted on the base (4). It includes five hydraulic cylinders (2) (one pair of the hydraulic cylinders is not shown). A bellow unit (6) is used for sealing the cylinders and as an elastic guide of a moving rod (1). The pump (3) generates a continuous flow of MRF through the channels. The MR valves (5) control MRF flow rate in the channels. The cylinders are connected to each axis by a hydraulic bridge circuit. The moving rod starts to move when certain pressure difference at the cylinders of one axis is applied. The rods of all cylinders (1) are rigidly fixed to the movable body.

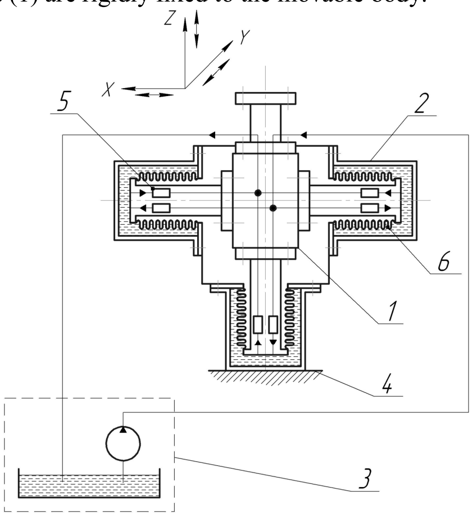

Fig. 2. The MR module scheme: 1 - moving rod, 2 – hydraulic cylinder, 3 - pump, 4 - base 5 – MR valve, 6 - bellow unit

The experimental tool (fig. 3) is designed to study the response of MRF in the work gap of MR valve on the applied magnetic field. The experimental setup consists of two bodies (4), an electromagnetic coil (3), a magnetic circuit (1) with poles (2), a working gap between the poles (5), two burettes (6) and a pressure gauge (8).

MRF flows from one burette to another (6) through the holes in the tool bodies (4) and the working gap (5). The working gap situates in the magnetic circuit (1) between the poles (2). A compressed air pipe (7) generates the required pressure difference between the burettes. The pressure gauge (8) is used to control the pressure difference.

The custom-made MRF with average carbonyl iron particle size 15 μm and volume concentration 0.3 was used.

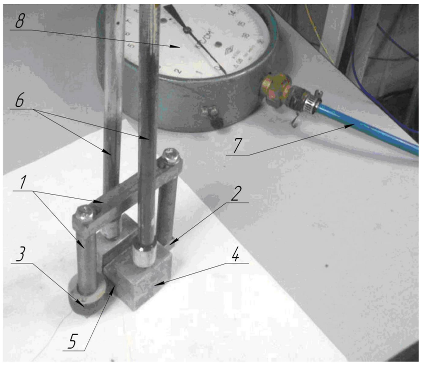

Fig. 3. The experimental tool for investigation of moving current of MRF: 1 – parts of magnetic circuit, 2 – pole pieces of magnetic circuit, 3 – electromagnetic coil, 4 – bodies, 5 – working gap, 6 – burettes, 7 – pneumatic hose, 8 - air gauge

3. Experimental results

The dependence of the pressure drop on the working gap on electric current passing through the coil was measured in this experiment. The magnetic field in the gap was calculated using finite element method. The dependence of the pressure drop on the applied magnetic field is plotted in Fig. 4.

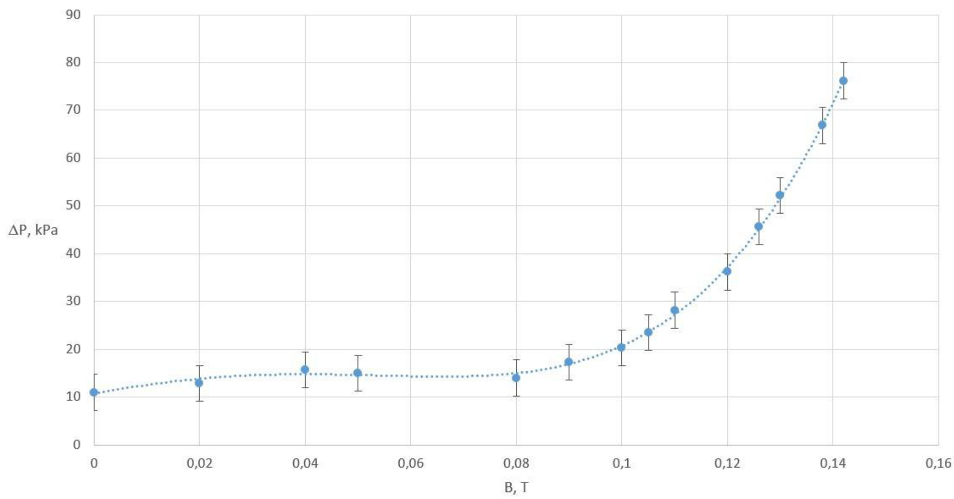

Fig. 4. Experimental diagram of the pressure drop (ΔP) vs magnetic field (B) in the working gap (the dotted line is a guide to an eye)

It was found that the obtained dependence is nonlinear. This can be related with the nonlinear magnetization curve of the magnetic circuit material and MRF in the working gap. The flow of MRF could not be completely stopped by the applied magnetic field. The maximum pressure drop was 75 kPa at the magnetic field in the gap 0.14 T.

4. Conclusions

The use of active and semi-active vibration isolation based on MRF can improve the efficiency of the precise equipment vibration protection.

The results obtained in this work allow to determine the current that should be applied to the coil in order to obtain the required pressure drop. The maximum pressure drop on the MR valve work gap is 75 kPa at the magnetic field in the gap 0.14 T. In the proposed MR module design the maximum value of the magnetic field of 0.14 T can be provided at the coil control current 2 A.

The most effective MR valve control is achieved at the work gap magnetic field up to 0.08 T. MR module with the closed-loop control system with feedback is capable to provide object position error 0.2 μm at the vibration disturbance at a frequency of 5 Hz with an amplitude up to 3 mm.

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