Simulation of Performance Characteristics of a Magnetorheological Shock-Absorber at the Dependence of Rheological Properties from the Magnetic Field

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Abstract. The mathematical model of a magnetorheological shock-absorber taking into account of the dependence of rheological properties from the magnetic field is developed. Performance characteristics of the MR shock-absorber (dependences of force on value of control electric signal taking into account of shock-absorber geometry, rod displacement, rheological properties of MR fluid) are calculated. The analysis of influence of control electric signal value on MR shock-absorber performance characteristics depending on amplitudes and frequencies of piston movement is carried out.

1. Introduction

Now active development of new compositions of magnetorheological (MR) fluids, theoretical and experimental research of their rheological properties and search of their practical application in the technician are conducted [1-3]. The most demanded application area of MR fluid is the machinery construction [3, 4]. In the scientific and technical literature various variants of active and semi-active cushion systems are considered [1, 3, 4]. In such systems one of the main elements is the controlled shock-absorber with a MR fluid, named MR shock-absorber. Last years necessity of development of MR shock-absorber mathematical models and numerical estimation of its performance characteristics increases by reason of occurrence of large quantity of MR fluid compositions with various rheological properties [1, 2, 4]. By development of controlled cushion systems of the concrete vehicle is required the designing of new geometry of a MR shock-absorber and its elements [4, 5].

The purpose of this work is simulation and analysis of performance characteristics of the designed MR shock-absorber taking into account rheological properties of the MR fluid, influence of the magnetic field and such as modes of dynamic rod load under the harmonic law.

2. Problem statement

In this work, performance characteristics of the magnetorheological shock-absorber, which is used for a controlled vibroprotective system, are modelled and numerically evaluated. Figure 1 shows the scheme of the magnetorheological shock-absorber and its basic elements. Hydraulic resistance is created in the annular channels 5 (Figure 1), thus the area 3 of the channels 5 defines a regulation zone of MR fluid viscosity at influence by the magnetic field (Figure 2). At electric current, giving on the solenoid (the inductance coil) 6, creates the magnetic field with the flux 7 passing through the core which represents the piston 4 rigidly connected with the rod 8 and located in the shock-absorber cylinder 1.

Resistance force of the telescopic MR shock-absorber, depending on time t, is defined from the equation system [5]:

$$F_{mra}(t,B) = F_{fr}(t,B) + F_{gas}(t) + F_f(t,B) \tag{1}$$

where

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$$F_{fr}(t,B) = (F_0 + c_1 \cdot \Delta P(t,B)) sgn(v_p(t)) \tag{2}$$

$$F_{gas}(t) = P_0 \left[V_0 / \left(V_0 - S_r \left(l_r - z(t) \right) \right) \right]^m \cdot S_r \tag{3}$$

$$F_f(t,B) = \left(S_p - S_r \right) \Delta P(t,B) \tag{4}$$

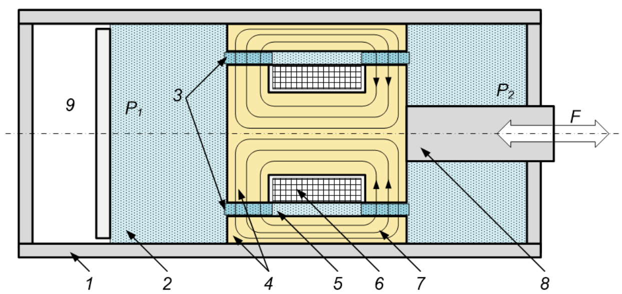


Figure 1. The scheme of the MR shock-absorber: 1 – the cylinder; 2 – a MR fluid without the magnetic field; 3 – a MR fluid in the magnetic field; 4 – the piston; 5 – the annular channel; 6 – the solenoid; 7 – the magnetic field lines; 8 – the rod; 9 – the pneumatic camera with a gas.

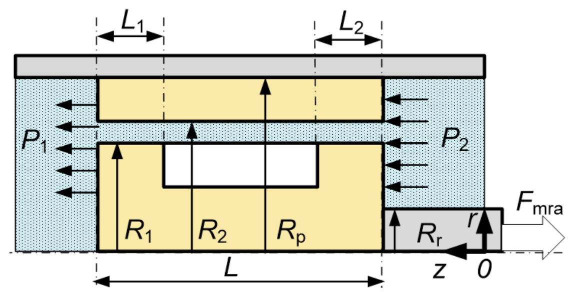


Figure 2. The geometry of the annular channel of the piston of the controlled shock-absorber with a MR fluid in the cylindrical coordinate system.

F_{fr}, F_{gas}, F_f – the forces of dry friction, gas friction in a pneumatic camera and hydraulic resistance of MR fluid in an annular channel. The inertia force of a MR shock-absorber piston is neglected [4, 5]; S_p and S_r – the area of cross-section section of a piston and a rod accordingly; F_0 and c_1 – the parameters, which define dry force from an experiment; m – the index of power; t – the time; $\Delta P = P_1 - P_2$ – the pressure drop; v_p – the piston velocity; z, r – the coordinates; R_p, R_r – the piston and rod radii; R_1, R_2 – the internal and external radii of a channel; l_r – the initial piston position; B – the magnetic flux density.

Let's define the pressure drop in an orifice channel of the piston. A flow of an incompressible viscoplastic MR fluid in the annular channel at the cylindrical coordinate system is described by the equation system, which contains movement equation, rheological equation and continuity equation:

$$\rho \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\eta \frac{\partial u}{\partial r} \right), \eta(B,r,z) = \frac{\tau_0(B)}{|\partial u / \partial r|} + \mu(B)\left(\frac{\partial u}{\partial r} \right)^{n(B)-1}, 2\pi \int_{R_1}^{R_2} u(r,t)\, r\, dr = Q(t) = \dot{V}(t) \tag{5}$$

where η – the apparent viscosity; u – the velocity; p – the pressure; ρ – the density of MR fluid; Q – the volume flow. Volume flow of MR fluid in the channel is defined [4] from the sinusoidal law of piston displacement $x(t) = A_m \cdot \sin(2\pi ft)$ with defined values of frequency f and amplitude A_m:

$$Q(t) = \left(S_\text{p} - S_\text{r} \right) \dot{x}(t) = 2\pi^2 \left(R_\text{p}^2 - R_\text{r}^2 \right) f A_m \cos(2\pi ft) \tag{6}$$

We use net method [6] for calculation of equation system (5).

The MR fluid is considered motionless, and no-slip conditions are set on walls of an annular channel:

$$u(r, t=0) = 0 \text{ and } u(r = R_1, t) = 0,\ u(r = R_2, t) = 0 \tag{7}$$

MR fluid has been developed in A.V. Luikov Heat and mass transfer institute of the National academy of sciences of Belarus [2]. Measurements of rheological properties of the MR fluid have been executed in a range of shear rates 0.01–1000s^{-1} on Rheometer "Physica MCR 301" of manufacturer "Anton Paar" with a measuring cell "MRD70".

3. Results and discussion

Rheological curves are constructed for the experiments at various values of magnetic flux density (Figure 3). All of them can be described by viscoplastic model Herschel-Bulkley (Figure 3 and 4):

$$\tau(B,\dot{\gamma}) = \tau_0(B) + \mu(B)\cdot\dot{\gamma}^{n(B)} \quad (8)$$

where parameters of dynamic yield stress τ_0, plastic viscosity μ and index of power n depend on magnetic flux density B [in scale of mT] accordingly:

$$\tau_0(B) = 140.0 + 19.273B + 0.1023B^2, \text{ [Pa]} \quad (9)$$

$$\mu(B) = 200.1 + 8.5611\cdot B + 0.1146\cdot B^2, \text{ [Pa·s]} \quad (10)$$

$$n(B) = 0.3/(1 + 0.00216\cdot B) \quad (11)$$

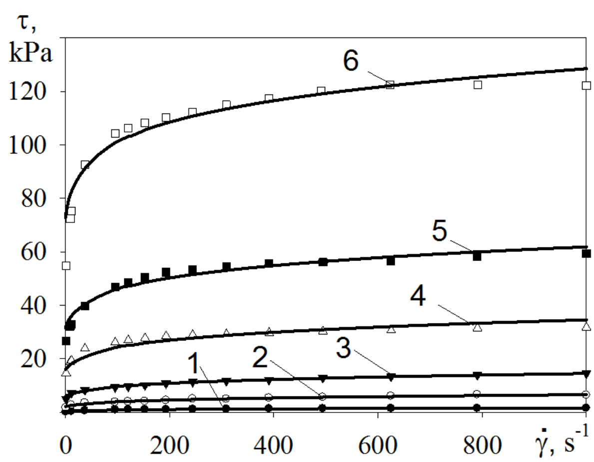


Figure 3. The dependence of shear stress τ of the MR fluid on shear rate $\dot{\gamma}$ at different values of magnetic flux density B:
1 – B=0mT; 2 – 50; 3 – 100; 4 – 200; 5 – 300; 6 – 500. Points – experiment; lines – the model (8).

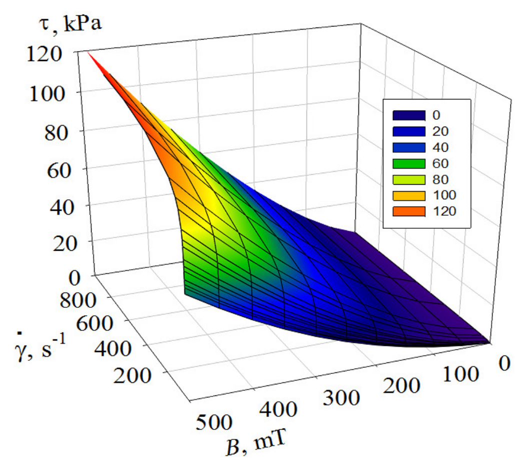
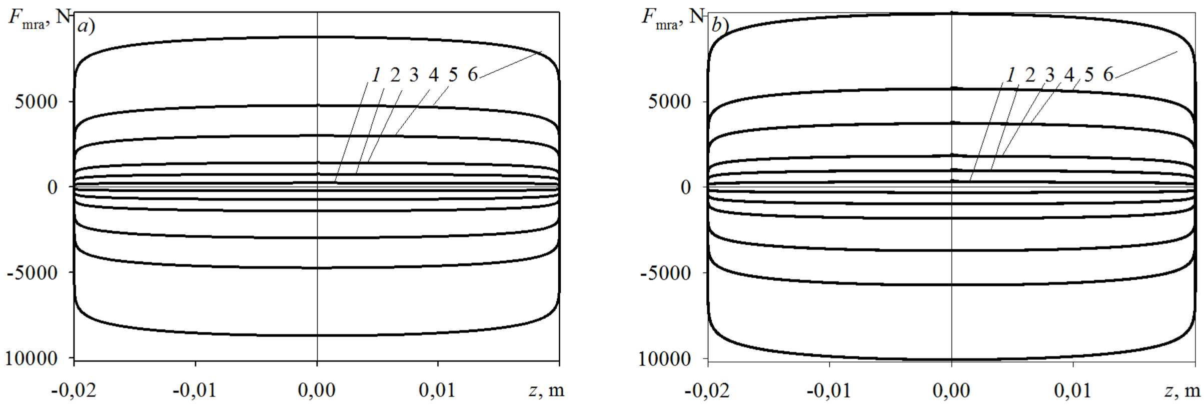


Figure 4. The dependence of shear stress τ of the MR fluid on shear rate $\dot{\gamma}$ and different values of magnetic flux density B by the model (8).

Overall relative variation coefficient of Herschel-Bulkley model is equal 9.8%, that precisely enough describes viscoplastic behaviour of the MR fluid at different magnetic flux density B in the range 0–500mT (Figure 3). As a result, this model (8)–(11) allows to define the general calculated dependence of shear stress on shear rate and magnetic flux density (Figure 4). Having defined rheological state equation in a form of Herschel-Bulkley model and dependences its parameters (yield stress, plastic viscosity, index of power) on magnetic flux density, the problem of MR fluid flow in the annular channel of the controlled shock-absorber taking into account construction geometry, external influence of a magnetic field and conditions of dynamic loading of rod can be solved.

For calculation of performance characteristics of the MR shock-absorber we use following data: R_r=0.008m; R_p=0.02m; R_1=0.016m; R_2=0.017m; L=0.02m; L_1=L_2=0.01m; P_0=10MPa; V_0=0.00009m^3; ρ=2600kg/m^3; F_0=60H; c_1=3·10^{-6}N/Pa; l_r=0.08m.

Results of numerical modelling of MR shock-absorber force are resulted in Figure 5 at rod motion under the harmonic law with amplitude of 20mm, frequency of 1 and 3Hz. For the purpose of simplification it is admissible that the force component F_{gas} is equal to zero.



a) A_m=20mm, f=1 Hz; b) A_m=20mm, f=3Hz.

Figure 5. The dependence of MR shock-absorber force from rod displacement z at different values of magnetic flux density B: 1 – B=0 mT; 2 – 50; 3 – 100; 4 – 200; 5 – 300; 6 – 500.

The force F_{mra} increases with growth of magnetic flux density: F_{mra}=263N (Figure 5-*a*) and F_{mra}=395N (Figure 5-*b*) at the absence of a magnetic field, F_{mra}=8781N (Figure 5-*a*) and F_{mra}=10198N (Figure 5-*b*) at magnetic flux density B=500mT. Thus, relative increase of force is equal 33.4 (Figure 5-*a*) and 25.8 times (Figure 5-*b*).

4. Conclusions

Thus, the mathematical model of a MR shock-absorber taking into account dependence rheological properties of the MR fluid on shear rate and magnetic flux density is developed. Performance characteristics of the MR shock-absorber (dependence of force on rod displacement taking into account shock-absorber geometry, rheological properties of the MR fluid, magnetic flux density) are calculated. The analysis of performance characteristics is made for different loading conditions. Dependences of MR shock-absorber resistance force on magnetic flux density are defined. These dependences can be used by development of control algorithm of shock-absorber performance characteristics for electronic control units.

Acknowledgments

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