Estimation of performance characteristics of a controlled shock-absorber affected by the magnetic field and temperature on rheological properties of the magnetorheological fluid

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Abstract. The mathematical model of MR fluid flow in an annular channel of the MR shock-absorber taking into account forces of dry friction and gas friction in a pneumatic camera, dependence rheological properties of the MR fluid on shear rate, temperature and magnetic flux density 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, temperature) are calculated. The analysis of influence of the magnetic field and temperature values on the MR shock-absorber performance characteristics depending on amplitudes and frequencies of piston movement is carried out. The resistance force with growth of magnetic flux density increases 40 times. But the resistance force with growth of temperature from 20°C to 80°C decreases 7 times, in an magnetic field ($B = 500$ mT), and 2 times, without a field ($B = 0$ mT).

Keywords: magnetorheological fluid, rheological properties, temperature, magnetic flux density, shock-absorber, mathematical model, simulation, performance characteristics, force.

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 fluids 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 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].

Temperature factor has significant influence on rheological properties of a MR fluid, but we were not found sufficient information to describe performances characteristics of controllable shock-absorbers and any control algorithm for electronic control units taking into account of temperature. The designing of new geometry of MR shock-absorber and its elements by development of controlled cushion systems of the concrete vehicle is usually required [4, 5].

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

2. Problem statement

Fig. 1 shows the scheme of the magnetorheological shock-absorber and its basic elements.

Hydraulic resistance is created in the annular channels 5 (Fig. 1), thus the area 3 of the channels 5 defines a regulation zone of MR fluid viscosity at influence by the magnetic field.

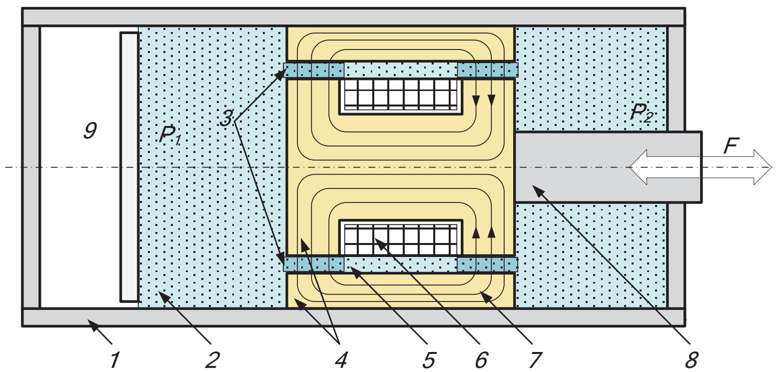


Fig. 1. The scheme of the MR shock-absorber: 1 – the cylinder; 2 – a MR fluid without a magnetic field; 3 – a MR fluid in the magnetic field; 4 – the piston; 5 – the annular channel; 6 – the solenoid; 7 – magnetic field lines; 8 – the rod; 9 – the pneumatic camera with a gas

At electric current, giving on the solenoid 6 (Fig. 1), 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 a telescopic MR shock-absorber, depending on time t, is defined from the equation system [5]:

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

where:

$$F_{fr}(t,B,T) = \left(F_0 + c_1 \cdot \Delta P(t,B,T)\right)\text{sgn}\left(v_p(t)\right), \quad (2)$$

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

$$F_f(t,B,T) = (S_p - S_r)\Delta P(t,B,T), \quad (4)$$

where F_{fr}, F_{gas}, F_f is 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 is the area of cross-section section of a piston and a rod accordingly; F_0 and c_1 is the parameters, which define dry force from an experiment; m is the index of power; t is the time; $\Delta P = P_1 - P_2$ is the pressure drop; v_p is the piston velocity; z, r is the coordinates; R_p, R_r is the piston and rod radii; R_1, R_2 is the internal and external radii of a channel; l_r is the initial piston position; B is the magnetic flux density; T is the temperature.

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:

$$\rho\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial u}{\partial r}\right), \quad (5)$$

$$\eta(B,T,r,z) = -\frac{\tau_0(B,T)}{\left|\frac{\partial u}{\partial r}\right|} + \mu(B,T)\left(\frac{\partial u}{\partial r}\right)^{n(B)-1}, \quad (6)$$

$$2\pi \int_{R_1}^{R_2} u(r,t) r dr = Q(t), \quad (7)$$

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

$$Q(t) = (S_p - S_r)\dot{x}(t) = 2\pi^2 (S_p - S_r) f A_m \cos(2\pi f t). \quad (8)$$

We use net method [6] for calculation of Eq. (5)–(7).

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

$$u(r, t = 0) = 0, \quad (9)$$
$$u(r = R_1, t) = 0, \;\; u(r = R_2, t) = 0. \quad (10)$$

The 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 0.01-1000 s^{-1} on Rheometer “Physica MCR 301” of manufacturer “Anton Paar” with a measuring cell “MRD70”.

3. Results and discussion

In this work, performance characteristics of the magnetorheological shock-absorber, which is used for a controlled vibroprotective system, are modelled and numerically evaluated.

Rheological curves are constructed for the experiments at various values of magnetic flux density [2]. All of them can be described by viscoplastic model Herschel-Bulkley:

$$\tau(B,T,\dot{\gamma}) = \tau_0(B,T) + \mu(B,T)\dot{\gamma}^{n(B)}, \quad (11)$$

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] and temperature T accordingly:

$$\tau_0(B,T) = (272.503 + 37.514 \cdot B + 0.1991 \cdot B^2)\exp(-0.0333 \cdot T), \;\; [\text{Pa} \cdot \text{s}], \quad (12)$$
$$\mu(B,T) = (389.4846 + 16.664 \cdot B + 0.2231 \cdot B^2)\exp(-0.0333 \cdot T), \;\; [\text{Pa} \cdot \text{s}^{-n}], \quad (13)$$
$$n(B) = \frac{0.3}{1 + 0.00216 \cdot B}. \quad (14)$$

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 0-500 mT and temperature $T = 20$°C [7]. The temperature dependence of yield stress τ_0 and plastic viscosity μ was defined as an approximation of rheological curves of dispersion media of MR fluid from temperature. As a result, this rheological model (see Eqs. (11–14)) allows to define the general calculated dependence of shear stress on shear rate, temperature and magnetic flux density (Fig. 2).

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 an annular channel of a controlled shock-absorber taking into account construction geometry, external influence of the magnetic field and conditions of dynamic rod loading can be solved.

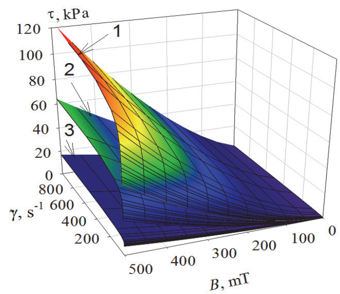
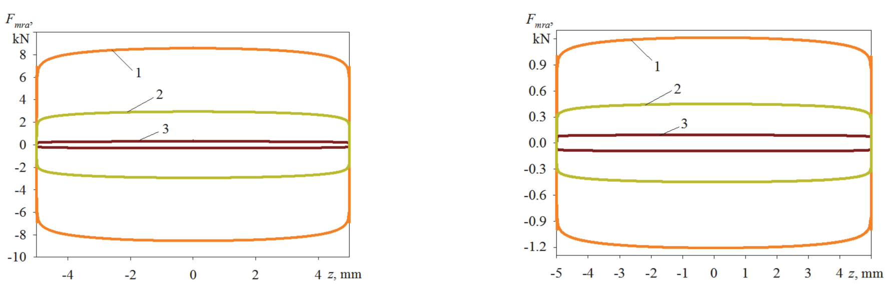


Fig. 2. The dependence of shear stress τ of the MR fluid on shear rate and different values of magnetic flux density: 1 – T = 20°C; 2 – T = 40°C; 2 – T = 80°C



a) A_m = 5 mm, f = 1 Hz, T = 20°C b) A_m = 5 mm, f = 1 Hz, T = 80°C

Fig. 3. The dependence of MR shock-absorber force from rod displacement z at different values of magnetic flux density B and temperature T: 1 – B = 0 mT; 2 – 200; 3 – 500

For calculation of performance characteristics of the MR shock-absorber we use following data: R_r = 0,008 m; R_p = 0,02 m; R_1 = 0,016 m; R_2 = 0,017 m; L = 0,03 m; $L_1 = L_2$ = 0,01 m; P_0 = 10 MPa; v_0 = 0,00009 m^3; ρ = 2600 kg/m^3; F_0 = 60 H; $c_1 = 3\cdot10^{-6}$ N/Pa; l_r = 0,08 m.

Results of numerical modelling of MR shock-absorber force are resulted in Fig. 3 at rod motion under the harmonic law with amplitude of 1, 5 and 40 mm, frequency of 0.5, 1 and 3 Hz, temperature of 20 and 80°C, magnetic flux density of 0, 200 and 500 mT. For the purpose of simplification it is admissible that the force component F_{gas} is equal to zero.

Estimation of the maximum resistance force on the rod was realized in the rebound stroke of the MR shock-absorber due to the fact that the resistance force F_{mra} acting on the rod in the compression stroke for this shock-absorber design is equal the resistance force F_{mra} acting on the rod in the rebound stroke. The result of experimental data processing is shown in Fig. 4 as the dependences of the maximum resistance force of the MR shock-absorber (at rebound stroke) on the magnetic flux density B and temperature T by the harmonical law $v_p = 2\pi A_m f \cos(2\pi f t)$, where A_m is the amplitude of displacement, f is the frequency, and t is the time. Fig. 4 shows, that that resistance force grows with the magnetic flux density at different piston velocities v_p. So, the force at the velocity v_p = 0.0314 m/s in an magnetic field (E = 500 mT) and without a field (B = 0 mT) increases 32 times, when T = 20°C, and at T = 80°C, 13 times.

The force F_{mra} increases with growth of magnetic flux density (see Table 1), for example: F_{mra} = 196 N (at f = 0.5 Hz) and F_{mra} = 302 N (at f = 3 Hz) at the absence of a magnetic field, F_{mra} = 6846 N (at f = 0.5 Hz) and F_{mra} = 8577 N (at f = 3 Hz) at magnetic flux density B = 500 mT and amplitude A_m = 5 mm. The force F_{mra} decreases with growth of temperature (see Table 2), for example: $F_{mra} = 263$ N and $F_{mra} = 395$ N at the absence of a magnetic field, $F_{mra} = 8781$ N and $F_{mra} = 10198$ N at magnetic flux density $B = 500$ mT and amplitude $A_m = 20$ mm. Similar result was obtained for the case, when A_m is equal 1, 5, 40 mm.

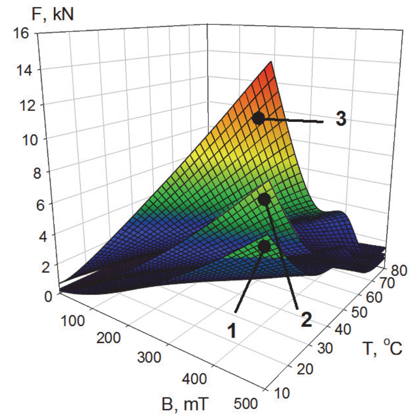


Fig. 4. The dependence of the MR shock-absorber force on magnetic flux density B and temperature T at different values of piston velocity v_p: $1 - v_p = 0.0031$ m/s; 2 – 0.0314; 3 – 0.6283

Table 1. Estimation of the performance characteristics of the controlled MR shock-absorber at magnetic flux density $B = 0$ and 500 mT (temperature $T = 20$°C)

A_m, mm	f, Hz	F_{mra}, N		$\frac{F_{mra}(B = 500\text{ mT})}{F_{mra}(B = 0\text{ mT})}$
		at $B = 0$ mT	at $B = 500$ mT	
1	0.5	141	5669	40.1
	3	204	6999	34.2
5	0.5	196	6846	34.9
	3	302	8577	28.4
40	0.5	325	8907	27.4
	3	531	11346	21.3

Thus, the coefficient of relative increase of force $F_{mra}(B = 500\text{ mT})/F_{mra}(B = 500\text{ mT})$ is equal 40.1 and 21,3 times for different loading conditions (Table 1). Controllable characteristics of the shock-absorber have more wide changing range of resistance force at low piston velocity, when magnetic flux density varies in a range from 0 to 500 mT. Therefore, any controlled shock-absorber is necessary for developing with the annular gap, where as far as possible an average speed of MR fluid flow will be minimum.

The coefficient of relative increase of force $F_{mra}(T = 20°\text{C})/F_{mra}(T = 80°\text{C})$ is equal 2 and 7.1 times for different loading conditions (Table 2). Therefore, it is very important to take into account this temperature factor whereas dependences of the performance characteristics of the MR shock-absorber on temperature strongly influence on an active vibroisolation of vehicles.

Table 2. Estimation of the performance characteristics of the controlled MR shock-absorber at temperature $T = 20$ and 80°C

A_m, mm	f, Hz	F_{mra}, N		$\frac{F_{mra}(T = 20°\text{C})}{F_{mra}(T = 80°\text{C})}$
		$T = 20$°C	$T = 80$°C	
		at $B = 0$ mT		
1	0.5	141	71	2.0
	3	204	80	2.6
40	0.5	325	96	3.4
	3	531	128	4.2
		at $B = 500$ mT		

1	0.5	5669	821	6.9
	3	6999	1001	7.0
40	0.5	8907	1259	7.1
	3	11346	1592	7.1

4. Conclusions

Thereby, the mathematical model of MR fluid flow in an annular channel of the MR shock-absorber taking into account forces of dry friction and gas friction in a pneumatic camera, dependence rheological properties of the MR fluid on shear rate, temperature 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, temperature) are calculated. The analysis of performance characteristics is made for different loading conditions. The resistance force with growth of magnetic flux density increases 40 times. But the resistance force with growth of temperature from 20°C to 80°C decreases 7 times, in an magnetic field ($B = 500$ mT), and 2 times, without a field ($B = 0$ mT). These temperature dependences can be used by development of a control algorithm of shock-absorber performance characteristics for electronic control units.

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