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DYNAMIC CHARACTERISTICS OF HYDRAULIC BRAKE DEVICES WITH MAGNETORHEOLOGICAL CONTROL

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Consideration is given to the magnetorheological principle of control of an electrohydraulic brake device. The level of dissipation losses in the channel of the control unit, which determines the braking force in such systems, is regulated by a magnetic field adjusting a magnetosensitive pressure fluid to a prescribed effective viscosity. In an experiment, control of the main parameters characterizing the force and frequency characteristics of the device has been accomplished. It is found that the characteristic time of developing a braking force is 10^{-3} *sec, and the speed of response of the system is mainly limited by the frequency characteristics of the inductor of the magnetic field of the magnetorheological throttling valve.*

Introduction. Hydraulic dampers are widely used to suppress the velocity and absorb shocks of displaced masses in drives and actuators, robotic systems, vehicle suspensions, etc., [1]. Their main feature is the dissipative character of a developed braking force. Here, the kinetic energy of a displaced object is irreversibly transformed into thermal energy, followed by its scattering into the surrounding medium. The elastic forces of resistance of hydraulic dampers are negligible, and the accumulation of potential energy is minimal, which allows implementation of an aperiodic law of braking.

The element mating the electric controlling and hydraulic actuating components in such systems is an electromechanical converter. Its adjustment to a prescribed braking force is accomplished by changing the flow area or the length of the channel. The presence of movable parts restricts the frequency characteristics of electromechanical regulators, they are complicated in construction, expensive, and their service life is short.

Improvement of hydraulic brake devices and an increase in the speed of their response can be achieved by means of magnetorheological technologies [2]. The latter are based on the possibility of control of a magnetic field by the rheological characteristics (viscosity, plasticity) of magnetorheological suspensions (MRS) [3].

The MRS are freely dispersed microheterogeneous systems. They represent suspensions of magnetic particles of micron size. The disperse medium of hydraulic MRS is a low-viscosity synthetic, mineral, or organic oil to which surfactants and stabilizing agents imparting sedimentation and aggregation stability to the suspension are added. Without a magnetic field, the rheological properties of an MRS with a volume concentration of the disperse phase of up to 10–15% are commonly almost the same as those of the Newtonian ones (Fig. 1).

In a magnetic field, particles of the magnetic phase of an MRS are polarized (magnetized), interact with each other, and, possessing spatial degrees of freedom, form elongated aggregates in the disperse medium, which are aligned along the magnetic lines of force. A structure induced by an applied magnetic field radically changes the rheological characteristics of the MRS. Its effective viscosity η increases by several orders of magnitude, the suspension acquires viscoplastic properties, and the yield strength of the MRS τ_0 can attain 10^4-10^5 Pa. The electrorheological effect is fully reversible. After switching the field off, the MRS acquires the initial rheological parameters [2]. The characteristic times for increasing or decreasing the viscous stresses in the MRS are less than 10^{-3} sec [4, 5].

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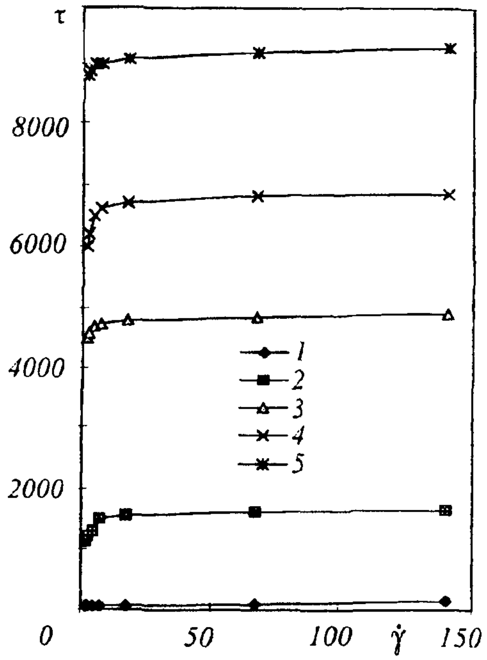


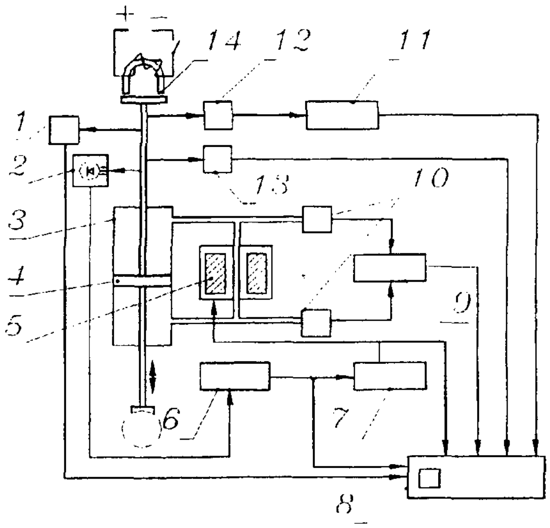


Fig. 1. Rheological curves of MRS pressure flow in external magnetic fields of different intensity H. 1) $H = 0$ kA/m; 2) 63.5; 3) 127; 4) 190; 5) 254. τ, Pa; $\dot{\gamma}$, sec^{-1}.

Fig. 2. Diagram of experimental setup.

Thus, the use of an MRS as a working fluid of controlled hydraulic systems allows control of their force characteristics by direct action of electrical signals with fast response. The control unit in such systems is a magnetorheological throttling valve (MRTV), which regulates MRS flow dissipation in a contactless manner by adjusting the medium to the required effective viscosity.

Experimental Setup. The force and frequency characteristics of the magnetorheological brake device were investigated on a test bench shown schematically in Fig. 2.

The magnetorheological brake device consists of a hydrocylinder 3 equipped with a piston 4 having two rods. The internal cavities of the hydrocylinder are filled with a preevacuated MRS, the composition and the procedure for preparation of which are described in [6]. The spaces in front of the hydrocylinder and behind it are connected with a short hydraulic main, in which an MRTV-5 is mounted. The hydrocylinder is held in an upright position. Its lower rod is equipped with a clamp to fasten the load to it.

The test bench is equipped with a pulsed current source 7 to energize the MRTV winding, with transducers of velocity 13, position 1, and acceleration 12 of the rod, with MRTV differential pressure pickups 10 connected to differential amplifier 9, a system for recording current changes in the MRTV winding.

The measuring system consists of a recording device (multichannel storage oscillograph) 8, pulse generator 6, amplifiers with high-impedance inputs 9 and 11 providing the necessary frequency range of operation of the piezoelectric pressure and acceleration transducers. An electromagnetic device 14 serves for fixing the hydrocylinder rod in its extreme upright position.

The test bench is operated as follows. The hydrocylinder rod is transferred to the extreme upright position and fixed by electromagnetic device 14. A load of a prescribed mass is fastened to the lower end of the rod. By a command, the winding of the electromagnetic clamping device is deenergized and the hydrocylinder rod is displaced by gravity to the lower position. As the rod reaches the prescribed position on the trajectory of motion, photodiode 2 initiates a signal that causes generator 6 to operate. A square voltage pulse is sent to amplifier 7, producing a current pulse of prescribed duration, which supplies power to MRTV winding 5. Simultaneously, a sync pulse of the generator initiates time scanning of multichannel oscillograph 8. Signals of transducers of MRTV differential pressure 10, position 1, velocity 13, and acceleration 12 as well as current in the MRTV winding are sent to the oscillograph inputs.

MRTV Construction and Design. The MRTV used in the experiments was designed proceeding from the following requirements: the characteristic time of field build-up in its working gap must not exceed $5 \cdot 10^{-3}$ sec and the differential pressure across the MRTV must provide a braking force of 500 N. In the experimental setup, use was made of a hydrocylinder with a working area of the piston of $8.8 \cdot 10^{-4}$ m^2. Thus, the differential pressure across the MRTV must be not less than $6 \cdot 10^5$ N/m^2.

Let us consider some features of MRTV construction which must be implemented to obtain the prescribed speed of response and necessary force characteristics of the MR-braking device.

The MRTV incorporates a winding and a magnetic core with a sealed plane gap (a hydraulic channel), the cross section of which is equal to the core's. The hydraulic channel of the MRTV connected to hydrocylinder cavities via rigid fluid mains.

In designing an MRTV it is necessary to take into consideration some factors influencing the efficiency of its operation. The magnetic intensity vector must be perpendicular to the velocity vector of MRS flow in the channel. The channel walls of the MRTV must be made of a magnetic material. The highest effect is achieved when the poles of the MRTV inductor serve as channel walls, i.e., the magnetic circuit of the MRTV is closed by the MRS circulating in the channel [7].

A considerable increment of viscous stresses in the MRS could be caused by the induction of 300–400 mT in the hydraulic gap of the MRTV [3]. Therefore, the magnetic core used in the MRTV is made of a material with high magnetic permeability μ_1, which minimizes a hydraulic gap h. However, a decrease in the gap causes an increase in the parasitic hydraulic resistance of the throttling valve in the absence of a control signal in its winding and, as a consequence, a narrowing of the control range. On the other hand, an increase in the hydraulic gap entails an increase in the resistance of the magnetic circuit of the throttling valve and requires an increase in the magnetization force of the winding wI (w is the number of turns, I is current).

The design of the magnetic circuit of the throttling valve is based on Ampere's law. With regard for the cross-sectional constancy of the magnetic circuit of the MRTV, the magnetic intensity H_2 in the hydraulic gap h is determined by the relation

$$H_2 = \mu_1 wI/(z\mu_2 + h\mu_1) , \tag{1}$$

where z is the length of the magnetic core; μ_2 is the magnetic permeability of the MRS. In the MRTV under consideration $z = 28 \cdot 10^{-2}$ m, $h = 3.5 \cdot 10^{-3}$ m. If $\mu_1 >> \mu_2$, then (1) acquires the form

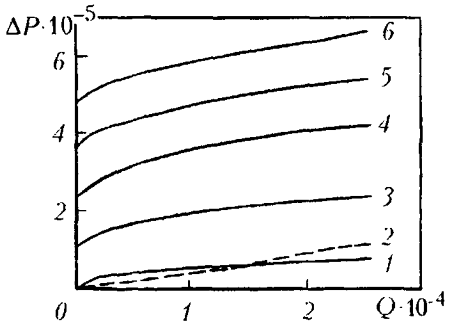
$$H_2 = wI/h . \tag{1'}$$

Such a situation occurs in an MRTV channel not filled with an MRS ($\mu_2 = \mu_0$).

Magnetometric measurements show that in a field with an intensity of 60 kA/m, the magnetic permeability of the MRS is $\mu_2 \sim 1.86$. Then $\mu_1 \sim 1000$ and with a current of 1 A in the MRTV winding (the number of turns in the winding is $w = 240$) the intensity of the field in a channel filled with an MRS will be equal to 60 kA/m. If the channel is not filled with an MRS, then H_2 = 68.6 kA/m (magnetic field dissipation is not accounted for in the estimations). The measured field intensity is 63.5 kA/m. Note that the experimental dependence $H_2 = f(I)$ is linear within the current range of 0–11 A.

The force parameters of the MRTV are described by static flow rate characteristics which relate the differential pressure ΔP to the flow rate Q of the MRS at different H_2. For their determination we used the test bench shown schematically in Fig. 2. In this case, the difference signal of the pressure transducers was applied to oscillograph input Y, while the signal of the velocity transducer determining the fluid flow rate in this case was sent to input X. The MRTV was energized by a d.c. current of the prescribed value and an external force moves the piston rod, thus initiating flow through the throttling valve.

A family of static flow rate characteristics of the MRTV is shown in Fig. 3.



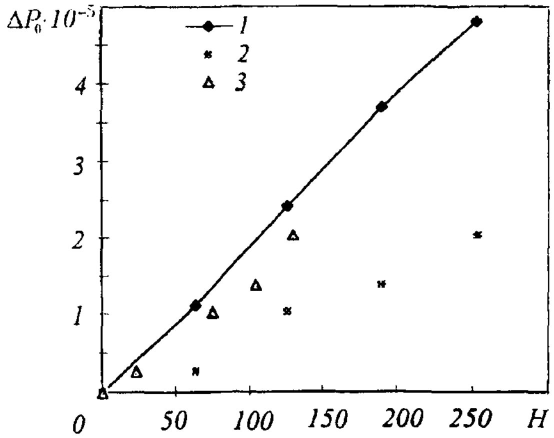


Fig. 3. Static pressure-flow rate characteristics of MRTV: 1) $H = 0$ kA/m (experiment); 2) $H = 0$ (calculation); 3) 63.5; 4) 127; 5) 190; 6) 254. ΔP, Pa; Q, m^3/sec.

Fig. 4. Differential pressure ΔP_0 in MRTV channel at $Q \to 0$ vs. magnetic-field intensity H: 1) experiment; 2, 3) calculation without and with allowance for a demagnetizing field. ΔP_0, Pa; H, kA/m.

For laminar Newtonian fluid flow in a narrow plane channel, its hydraulic resistance can be determined from the relation

$$\Delta P = 12\eta l Q / h^3 b, \tag{2}$$

where l is the channel length; b is its width (in the MRTV under consideration it is $40 \cdot 10^{-3}$ m and $28 \cdot 10^{-3}$ m, respectively). This relation fits well the experimental dependence $\Delta P = f(Q)$ at $H = 0$ (the dashed curve in Fig. 3). It should be noted that the rheological properties of the MRS at $H = 0$ differ slightly from the Newtonian characteristics and at low shear rates its effective viscosity exceeds the value used in the calculations ($\eta = 1.1$ Pa·sec), which is manifested by the MRS at high shear rates.

For a viscoplastic fluid flow (an MRS in a magnetic field) in a slotted channel the differential pressure can be determined by the formula [8]

$$\Delta P = 2\tau l / h, \tag{3}$$

where τ is the shear stress of the MRS on the channel wall.

Application of this relation to calculation of the static flow rate characteristics of the MRTV is limited by a number of objective factors. A change in the channel configuration and its narrowing, a hydraulic channel length insufficient for implementation of the developed dynamic flow, and the effects of near-wall slip and hydrodynamic demagnetization of the MRS can lead to discrepancies between the experimental and calculated results. Therefore, we restrict ourselves to a comparison of calculated and experimental results only for the case of $Q \to 0$, when the influence of the factors mentioned above is minimized. In this case, formula (3) acquires the form

$$\Delta P_0 = 2\tau_0 l / h, \tag{4}$$

where τ_0 is the yield strength of the MRS.

To determine τ_0, we employ curves of MRS flow in magnetic fields of different intensities (see Fig. 1) obtained on a disk-type rotary magnetorheometer [2].

Experimental ΔP_0 values and those calculated by formula (4) are shown as a function of the applied-field intensity in Fig. 4(1 and 2, respectively). Though in the calculations the dynamic yield strength [8] is used, the value of which slightly exceeds its true value, the experimental data of $\Delta P_0 = f(H)$ exceed the calculated ones.

Unlike the MRTV, the rotary magnetorheometer employed an electromagnetic system with an open magnetic circuit. Such conditions can radically change the mode of magnetization of the MRS sample investigated, which acquires a plane form in the measuring cell of the magnetorheometer.

The internal field H_{int} in the sample will be considerably smaller than the external one H_{ext} which was recorded when measuring the MRS rheological characteristics represented in Fig. 1.

For a plane sample perpendicular to the field direction, H_{int} can be determined from the relation

$$H_{\text{int}} = H_{\text{ext}} - NJ ,$$

where N is the demagnetization factor (for a plane layer perpendicular to the field, $N = 1$); J is the MRS magnetization. An analysis using the static magnetization curve of the MRS under consideration shows that with allowance for the demagnetizing field the calculated ΔP_0 approach the experimental values (3 in Fig. 4).

In order to gain insight into the dynamics of increasing the differential pressure in the MRTV, we will consider the sequence of processes occurring in the MRTV channel after the arrival of a control signal at its winding. The time constant of current build-up δ in the throttling valve circuit is determined by the ratio $\delta = L/R$, where R is the resistance of all elements in the throttling valve circuit ($R = 12.5\ \Omega$); L is its inductance ($L = 59 \cdot 10^{-3}$ G) and is $\approx 5\ \mu$sec.

The magnetic viscosity and eddy currents exert an adverse influence on the rate of induction build-up in the magnetic core. In the frequency range discussed they make the main contribution to the gap in the trajectories of build-up of the winding current and the magnetic core induction, so the MRTV core is assembled of sheets of electrical steel of grade É31.

With build-up of the field, the easily magnetized particles of the disperse phase of the MRS become magnetized and acquire magnetic moments oriented along the field. The characteristic time of this process is $10^{-6}-10^{-7}$ sec.

The dipole-dipole interaction of particles causes structure formation in the MRS (the characteristic time of the process is $10^{-3}-10^{-4}$ sec [4, 5]) and impacts the viscoplastic properties to the MRS. As a result, the profile of MRS flow in the MRTV channel undergoes reconstruction with the formation of a quasisolid core, which is typical of viscoplastic media flows in channels.

The equation of motion of braked mass m, including the mass of the load, piston, rods, and the MRS mass attached to the piston, assuming that the total hydraulic resistance is concentrated in the MRTV channel, has the form

$$md^2x/dt^2 = mg - F_{\text{fr}} - F_{\text{hydr}}(t) .$$

Since the speed of response of the magnetic-field inductor is $5 \cdot 10^{-3}$ sec, it is right to assume that the time scale of developing the braking force $F_{\text{hydr}}(t)$ is fully determined by transient electromagnetic processes in the MRTV and calculation of the device parameters in the braking phase can be considered in a quasistationary approximation by employing the static flow rate characteristics of the MRTV and the relation $H_2 = f(I)$.

In the calculations, the change in the MRS mass attached to the piston with time (the change is not more than 0.04% of m) was not taken into consideration, and the Coulomb friction force F_{fr} was found experimentally to be not more than 20–30 N.

Experimental Results. Figure 5 shows oscillograms of the recorded main parameters of load braking (m = 16 kg), which prior to braking moved uniformly with $V = 0.24$ m/sec. Braking was accomplished by sending a square current pulse with a duration of 40 msec to the MRTV winding. Here, curve 1 reflects the process of current variation, and curves 2, 3, 4 illustrate the change in the load position, its velocity, and acceleration of braking, respectively. Curve 5 characterizes the change in the differential pressure across the MRTV. The scales are $10 \cdot 10^{-3}$ sec for time, for $2.4 \cdot 10^{-3}$ m for position, 0.17 m/sec for velocity (V), 10 m/sec^2 for acceleration (a), 1 A for current, and the differential pressure across the MRTV is $1.2 \cdot 10^5$ N/m^2.

It is seen that current build-up in the MRTV winding occurs with a characteristic time of $5 \cdot 10^{-3}$ sec. As one would expect, the kinetics of the process of structure formation in the MRS and the hydraulic processes in the

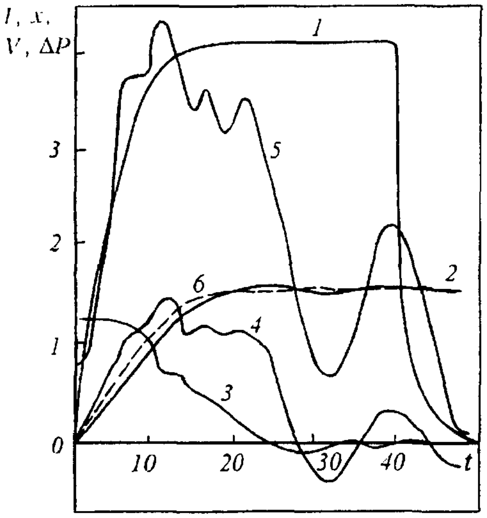


Fig. 5. Oscillograms of the recorded main parameters of the process of load braking: 1) $I(t)$; 2) $x(t)$; 3) $V(t)$; 4) $a(t)$; 5) $\Delta P(t)$; 6) $x(t)$; calculation. t, msec.

MRTV channel, proceeding with smaller characteristic times, do not influence the kinetics of pressure growth in the MRTV channel. After closing the circuit, the differential pressure, determining the braking force, increases with the characteristic time, which coincides with the rise time of a current pulse in the MRTV winding. Only a small delay is observed at the level of $1\text{–}2 \cdot 10^{-3}$ sec, which is determined by the characteristic time of structure formation in the MRS or by the change in the hydrodynamic situation in the MRTV channel. This time scale is the upper bound restricting the frequency characteristic of control of the process of braking in the device under consideration.

The calculated curve of the load position during braking, obtained from the static flow rate characteristics of the MRTV and the relation $H_2 = f(I)$, is represented by the dashed line in Fig. 5. It fits the experimental data sufficiently reliably.

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