Journal of Engineering Physics and Thermophysics, Vol. 78, No. 5, 2005

USE OF ELECTRO-RHEOLOGICAL FLUIDS IN A DAMPING DEVICE

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UDC 629.113:532.135

This paper presents results of experimental studies of an electro-rheological shock absorber based on a controlled hydrosuspension designed to damp a wheeled tractor driver's cab accommodating not only the operator but also complex electronic equipment by regulating the rheological characteristics of the working fluid by means of an external electric field. The characteristics and dependences of the operating conditions of the electro-rheological shock absorber are presented. The dissipative processes have been estimated.

In the past century, a large number of papers devoted to the investigation of electro-rheological fluids (ERFs) aimed at their possible use in various devices have been published [1–10]. On the basis of the scientific results obtained, which made it possible to reveal and describe the mechanism of the electro-structural effect [5, 6], new formulations of highly sensitive electro-rheological materials [7] and radically new technologies have been developed. The latter have been used to create prototypes of new facilities at enterprises and in institutions of many countries: Great Britain, Belarus, the USA, Japan, Korea, etc.

At present, ERFs are used in such devices as hydraulic actuators of robots and robotics components, brake elements, clutches, vibration dampers and suppressors, measuring devices, machine tooling for mechanical treatment, etc. [7–10].

The urgency of developing means for vibration-isolation of massive precision equipment is determined by the more stringent requirements imposed upon the accuracy and, at the same time, upon the universalization of production, because of which high-precision instruments are often placed in the immediate vicinity of vibroactive systems and on moving and vibration-dependent objects.

The demand for a more efficient use of automobiles has led to the necessity of increasing the service speed, which increases the significance of solving the problem of vibration-isolation of the driver's seat, since his perception of the level of smoothness of motion is a "natural limit" controlling the maximum speed in accordance with OST 37.001.291-84 and GOST 12.1.012-90. Vibration-isolation should thereby be provided with the preservation of both the softness of the springs and dampers, which is preferable in driving, and the rigidity needed in maneuvering.

Modern motor-transport means should combine an improved rideability with ease of maneuvering and isolation of the driver from noise, vibration, and shocks to create comfortable conditions. By ease of maneuvering is meant, in particular, smooth operations in turning, accelerating, and braking that do not annoy the driver.

To provide the necessary working conditions, various systems of "secondary cushioning," i.e., systems of cushioning of the driver's cab or the driver's seat are used. At the same time, it is difficult to make the characteristics of the secondary cushioning system consistent with those of the automobile wheel suspension. To solve this problem, it is expedient to use in the secondary cushioning system elastic elements with a variable rigidity. However, the development of elements with a rigidity regulated over a fairly wide range is also a difficult problem, which in turn leads to a greater difficulty in making the construction because of the introduction of valves or throttles with a regulated flow section. An alternative way of changing the characteristics of the secondary cushioning system is the application of shock absorbers with a regulated characteristic, in particular, those based on "intelligent" materials. The numerous advantages of such materials can be used successfully in the automotive industry, especially for damping the vibrations of the driver's cabs of trucks and creating vibration isolation in engine mountings, controlled, in particular, by an elec-

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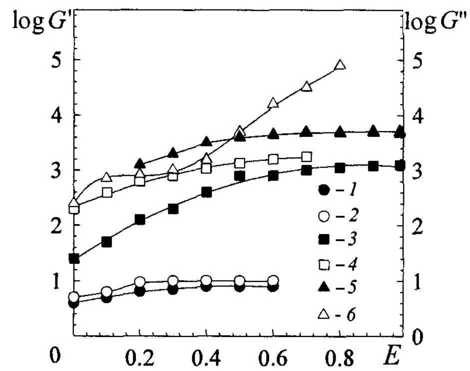


Fig. 1. Loss modulus G'' (1, 3, 5) and elastic modulus G' (2, 4, 6) versus external electric-field strength: 1, 2) C = 10%; 3, 4) 20%; 5, 6) 60% [1) at decreasing strength]. E, kV/mm.

tric signal, as well as of driver's seats. In automobiles, small engine starters, positioning devices for the doors, and optical switches and displacement transducers containing "clever" components can also be used.

This paper presents the results of the experimental study of ERFs in the electro-rheological (ER) shock absorber with a new geometry of the controlled hydrosuspension channel, which represents a double circular channel.

The aim of this work is to explore the possibility of damping the driver's cab of a wheeled tractor accommodating not only the operator, but also sophisticated electronic equipment, with the aid of a hydrosuspension controlled by regulating the rheological characteristics of the working fluid with the help of an external electric field.

Theory. The multiaspect investigation of the rheological characteristics has revealed a complex classification of ERFs [5]. Theoretical and experimental studies of the rheological characteristics of ERFs [7, 10] depending on the concentration and type of ingredients with their fixed set have made it possible to distinguish three characteristic structural-rheological groups according to the type of mechanical behavior of the ERFs:

1. Low-concentration ERFs ($C < 10$ mass %) having in the shear flow almost not interconnected structures moving relative to the dispersion medium. They exhibit properties close to Newtonian fluid. To each level of electrical actions there correspond the respective values of viscosity, and anomalous effects practically do not manifest themselves.

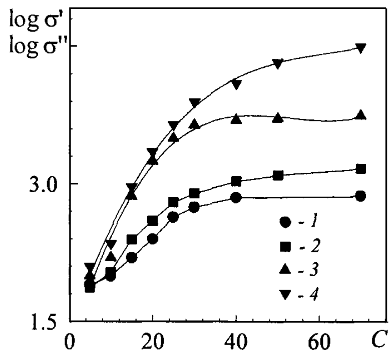
2. ERFs of medium concentrations (C = 10–50 mass %) having a dynamic frame formed by spatially connected structures. These are characterized by Newtonian properties and an effective viscosity of the system in electric fields several times higher. Under small-amplitude deformations not leading to an intensive breakage of the structure such suspensions exhibit elastic properties.

3. High-concentration ERFs ($C > 50$ mass %). These are distinguished by the presence of a completed structural frame providing the largest increase in the effective viscosity and exhibiting marked elastic properties in shear in the reversible deformation zone, as well as in the creep area. At high electric voltages they exhibit the properties of solids; in particular, they are able to hold the shape of the final volume. The influence of the concentration of the dispersed phase of ERFs affects the character of the flow curves in the regime of steady shear. The effective viscosity in the absence of an electric field increases with increasing concentration of the solid phase. But the anomaly of the viscoplastic behavior under the electric action is more pronounced. ERFs in an electric field acquire the property of pseudoplasticity characterized by a yield strength whose value is a function of the dispersed-phase content [6, 11, 12].

In the present paper, the fluid investigated by the authors belongs to the second type according to the above classification.

Estimation of the concentration features of the hydromechanical behavior of the ERF has shown that with increasing concentration of the solid phase the dependence of the effective viscosity on the rate of shear increases, but to a lesser extent than on the field strength.

Figure 1 shows the measurement data for the viscoelastic characteristics of the ERF in the form of dependences of logarithms G' and G'' on the electric-field strength. At low values of C (10%), log $G'(E)$ and log $G''(E)$



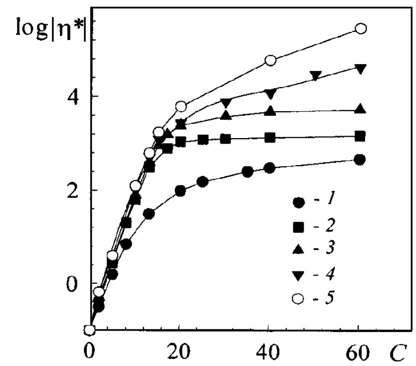


Fig. 2. Components of the complex shear modulus σ' (1, 3) and σ'' (2, 4) versus ERF filler content: 1, 2) E = 0.1; 3, 4) 2.6 kV/mm. γ = 0.0266. C, %.

Fig. 3. Dynamic viscosity of ERF (diatomite in transformer oil — DTM) versus filler concentration at electric field strength: 1) E = 0; 2) 0.33; 3) 0.5; 4) 0.6; 5) 0.8 kV/mm. C, %.

remain practically unchanged, and at C = 20% they smoothly increase. Note that the sharpest increase is observed for $G'(E)$, i.e., the considered regime is largely determined by the contact interaction between the structural elements.

Direct measurements of the viscoelastic characteristics have been made in the 0.01–100-Hz range on a mechanical spectrometer with a working unit in the form of coaxial cylinders operating in the regime of induced sinusoidal small-amplitude vibrations. The measurement data permitted analytical determination of G' and G'', as well as of the absolute value of the complex dynamic viscosity.

The influence of the filler concentration on the viscoelastic behavior of the ERF is illustrated in Fig. 2 as the dependence of σ', σ'' on C.

Comparison of curves 1–5 in Fig. 3 shows that the optimum electro-rheological effect can be achieved only at the optimum combination of both factors — the dispersed-phase concentration and the applied electric-field strength.

The dynamic viscosity measured under periodic deformation turns out to be much higher than the effective shear viscosity determined in rotational or capillary viscosimeters. The dependence of the strength characteristics on the frequency of small-amplitude dynamic loading points to the fact that up to frequencies of 10^2 Hz in high-concentration ERFs no breakage of the structural formations is observed, i.e., $G''(\omega)$ = const. The boundary of transition to the fluid-state zone corresponding to a sharp increase in the dissipative loss is displaced into the region of larger frequencies with increasing electric-field strength and dispersed-phase concentration at a constant value of the deformation amplitude.

The measured values of the elastic modulus and the dynamic viscosity make it possible, based on the Maxwell model, to carry out approximate estimation of the relaxation times $t_r = |\eta^*|/G''$ for the required conditions and, comparing them with the mechanical momentum duration $t_{m.m}$ and the Deborah number $\mathrm{De} = t_m/t_{m.m} \geq 1$, estimate the value of the relaxation term. For a 50% suspension of diatomite in the transformer oil $t_r \approx 10^2$ sec, i.e., under the action of small-amplitude dynamic loadings with a frequency less than 100 Hz, the relaxation properties of ERFs are insignificant [11].

In the present paper, we explore the possibility of using a 50% suspension of diatomite in the transformer oil in an electro-rheological shock absorber which can be used to damp the driver's cab (of a wheeled tractor), but not the whole body.

Such works are being carried out jointly with the Minsk Wheeled Tractor Plant (MWTP). Currently the MWTP manufactures mainly heavy-duty trucks, i.e., truck tractors.

Experimental. At the MWTP, a test of the model prototype of the shock absorber with a regulated characteristic developed in cooperation with the A. V. Luikov Heat and Mass Transfer Institute of the NAS of Belarus has been carried out. The shock-absorber characteristics are regulated by changing the electro-rheological working-fluid viscosity under the action of an electric field created by an external source in the throttle circular channel of the shock absorber.

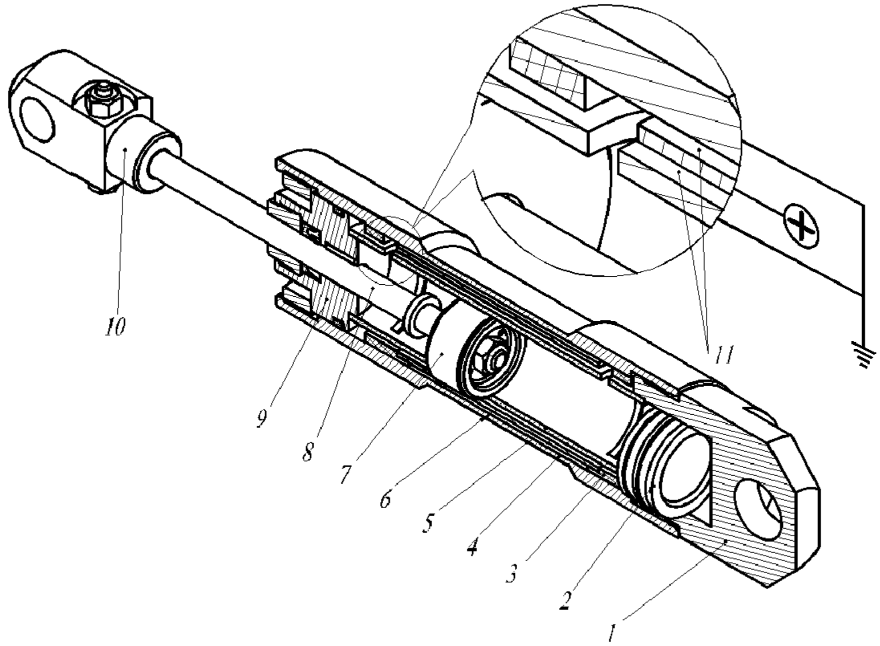


Fig. 4. Scheme of the ERF shock absorber: 1) upper head; 2) piston-separator; 3) insulator; 4) outer cylinder; 5) inner cylinder; 6) high-voltage electrode; 7) piston; 8) rod; 9) cover; 10) lower head; 11) ERF.

Between the outer 4 and inner 5 cylinders (Fig. 4) in the hydraulic chamber of the shock absorber two coaxial annular throttle gaps separated by a cylindrical electrode 6 are situated. On one side the hydraulic chamber of the outer cylinder is closed by the upper head 1 containing a pneumatic chamber separated from the hydraulic one by a piston-separator 2. On the opposite side, the hydraulic chamber of the shock absorber is closed by a cover 9 with a seal and a rod 8 guide. The piston 7 attached to the rod partitions the hydraulic chamber of the shock absorber into superpiston (on the side of the upper head) and subpiston or rod (on the side of the cover) chambers. The insulator 3 is located between the electrode 6 and the other parts of the ER shock absorber to avoid direct electrical contact.

The superpiston and rod chambers communite through the slots in the inner cylinder and the electrode going into the annular throttle gaps. The piston area is $1.257 \cdot 10^{-3}$ m^2, the side surface of the throttle channels is $1.131 \cdot 10^{-1}$ m^2, and the open area of the throttle channels is $3.77 \cdot 10^{-4}$ m^2.

The electrode-rheological shock absorber operates as follows. The piston, moving in the cylinder, displaces the working fluid from the super- and subpiston chambers into the sub- and superpiston chambers, respectively. In so doing, the volume of the fluid displaced by the rod is compensated by the corresponding change in gas volume in the pneumatic chamber. The pressure drop that is due to the fluid flow through the throttle channels determines the value of the resistance force of the shock absorber and depends on the fluid flow rate through the throttle channels and on the working fluid viscosity.

The experimental facility (Fig. 5) was made on the basis of the "longitudinal cylinder" stand of the company "Schenk" (Germany) with a PL-63N cylinder having the following characteristics: a rated force of 0–63 kN and a displacement range of ± 125 mm.

The control electric signal is formed in the functional generator FG (1), arrives at the FP312 control monitor (2), through the RV311 regulator (3), is sent to the force amplifier (4) and then to the hydrocylinder valve (5). The latter controls the working pressure fluid flow so that the hydrocylinder (8) completes the given force or displacement. The signal from the displacement transducers or force cells arrives through the MV318 amplifier (7) as a feedback to the RV311 regulator. After the amplifier the actual value of the signal gets onto the MA316 digital monitor (6) and the oscilloscope, and the value given after the control monitor gets onto the digital monitor and the oscilloscope, which permits routine monitoring of the given and actual values of the signal. Operational readings of the ER shock

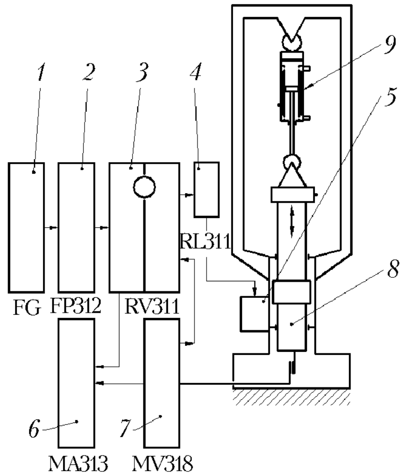


Fig. 5. Scheme of the experimental facility: 1) functional generator FG; 2) FP312 control monitor; 3) RV311 regulator; 4) RL311 power amplifier of the servovalve; 5) servovalve of the hydrocylinder; 6) MA313 digital display; 7) MV318 amplifier; 8) power cylinder; 9) ER shock absorber.

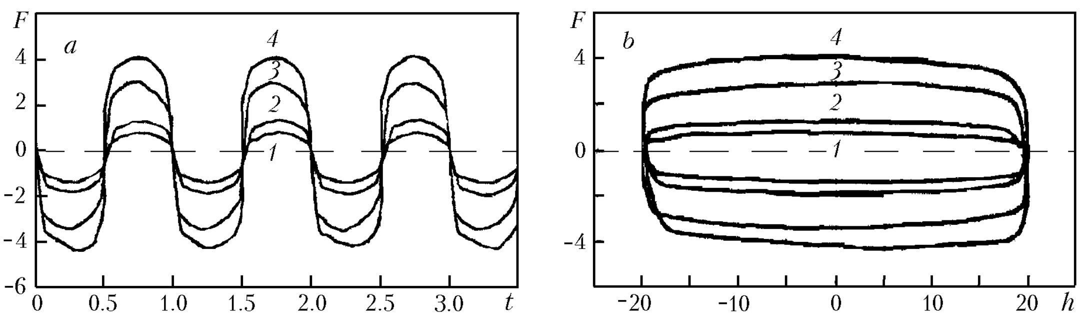


Fig. 6. ER shock-absorber forces versus time (a) and displacements (b): 1) E = 0; 2) 1; 3) 2; 4) 3 kV/mm. F, kN; h, mm; t, sec.

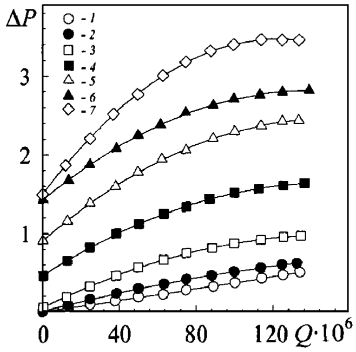
absorber (2) are recorded on the stand on the magnetic tape of an SR-30C "TEAC" tape recorder and simultaneously on an Endim 620.02 plotter.

As a working electrosensitive fluid, an ERF consisting of 50% modified silicon dioxide and transformer oil is used. The working fluid viscosity is varied due to the change in the electric-field strength in the throttle gaps achieved by varying the voltage applied to the electrode. The operation of the damping device was investigated in fields of various strength: 0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 kV/mm — under different amplitude-frequency operational conditions of the measuring stand: the range of amplitudes of ±5, 10, 20, 40-mm; the frequency range 0.05–3 Hz. In so doing, the force on the cylinder rod and the pressure drop in the throttle gap are measured. Temperature measurements on the outer wall of the shock-absorber cylinder are also taken at various values of the electric-field strength and the amplitude-frequency characteristics of the damping device. The voltage and the rate of shear of the ERF in the throttle channel and the energy dissipation in the damping device were calculated by the measured values.

Since, before testing the shock absorber with an electro-rheological fluid its functioning on PMS-200 fluid with Newtonian properties was checked, we can compare the parameters recorded for the operation of the shock absorber with different fluids.

The curve of changes in the forces developed by the shock absorber as its rod was moving by the harmonic law with an amplitude of 20 mm and a frequency of 1 Hz at various values of the voltage applied to the electrode is given in Fig. 6a.

At the start of the mechanical trajectory of the piston from the extreme point there is a sharp increase in the force on the rod, which then remains practically unchanged up to the middle point. In so doing, the $F(h)$ curve retains



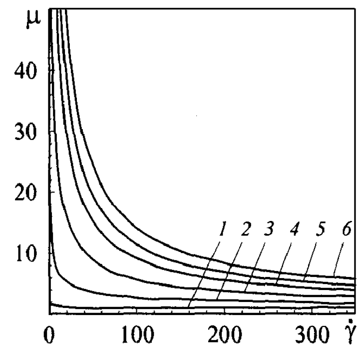


Fig. 7. Discharge-pressure characteristics of the throttle slot of the ER shock absorber: 1) E = 0; 2) 0.5; 3) 1; 4) 1.5; 5) 2; 6) 2.5; 7) 3 kV/mm. ΔP, MPa; Q, m^3/sec.

Fig. 8. Viscosity versus the rate of shear: 1) E = 0.5; 2) 1; 3) 1.5; 4) 2; 5) 2.5; 6) 3 kV/mm. μ, Pa·sec; $\dot{\gamma}$, sec^{-1}.

its shape in both direct and return motion. From Fig. 6b it is seen that as the electric-field strength is increased to 3 kV/mm, the force on the shock-absorber rod increases four times. The area of the geometric figures bounded by the curves of equal electric-field strength corresponds to the work of the external forces expended in overcoming the friction forces in the working gaps of the ER shock absorber at the given strength (Fig. 6b).

Results and Discussion. The test of the shock-absorber model has shown that in principle it is possible to control the discharge-pressure characteristics of such constructions.

Figure 7 shows the discharge-pressure characteristics of the ER shock-absorber throttle slot. Attention is drawn to the fact that as the electric-field strength increases, there is a change in the initial pressure drop ΔP_0, which in the absence of the field is practically not registered and the nonlinearity of the curves increases.

Figure 8 presents the dependences of viscosity on the rate of shear of the above ERF in the cylindrical gaps of the ER shock absorber.

In the general case, the ER shock-absorber heating depends on the energy dissipation in the cylindrical throttle gaps [13]. The quantity of heat generated by the shock absorber is

$$Q_{\rm d} = \tau\dot{\gamma}V = \frac{\Delta P \,\Sigma\, S_{\rm a.g}}{\Sigma\, S_{\rm s.s}} \frac{KAf\,(S_{\rm a.s} - S_{\rm rod})}{\Sigma\, S_{\rm a.g}\Delta d_i} V = \frac{\Delta PKAf\,(S_{\rm a.s} - S_{\rm rod})}{\Sigma\, S_{\rm s.s}\Delta d_i} V \,, \tag{1}$$

where K = 2 and $2\sqrt{2}$ for piston movement at a constant speed and by the harmonic law, respectively.

The power of the heat flow withdrawn into the atmosphere due to the induced convection is

$$Q_{\rm i.c} = \alpha S_{\rm o.s}\,(T_{\rm s} - T_{\rm env}) \,. \tag{2}$$

Our estimates show that at an effectively heat-transferring area of the outer surface of the damper $S_{\rm o.s}$ = $5.65\cdot10^{-2}$ m^2 and α = 23 W/(m^2·K) [14] for a temperature drop of 1 K, $Q_{\rm i.c}$ = 1.3 W will be transferred to the atmosphere.

The estimate of the dissipative process at various vibration frequencies depending on the electric-field strength at a vibration amplitude of 1 cm is shown in Fig. 9.

In the experiments, by means of a temperature-sensitive element the temperature on the outer side of the cylinder was registered during operation of the damper with a frequency of 1 Hz and an electric-field strength of 2 kV/mm. After 60 sec of continuous operation, the temperature on the outer side of the cylinder increased by 11$^{\rm o}$, which is somewhat less than the value determined analytically. This is likely to be due to the fact that in the approximate calculation the heat outflow along the damper rod, as well as the radiation component of the heat loss, were ignored.

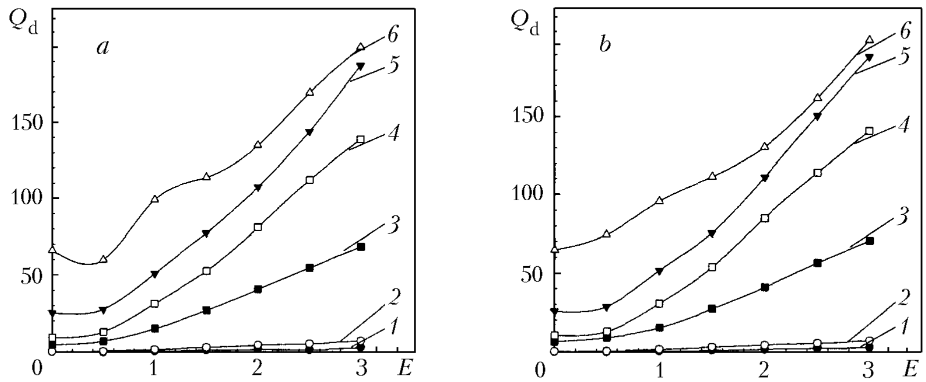


Fig. 9. Dissipative factor at forward (a) and backward (b) motion of the ER shock-absorber rod: 1) f = 0.05; 2) 0.1; 3) 1; 4) 1.5; 5) 2; 6) 3 Hz. Q_d, W; E, kV/mm.

At the present time, a complex of works to choose criteria and algorithms for controlling the shock-absorber resistance in order to provide maximum efficiency of the vibration insulation of the driver's seat under various external actions is being carried out and a control unit is being developed on the basis of optimal laws of kinematic load monitoring.

Thus, the preliminary model experiments have shown that the ability to control "intelligent" ERF materials can be used as applied to problems of automobile transport for damping vibrations, e.g., of the driver's cabs of heavy trucks, as well as of engine suspensions and driver's seats. In automobiles, small engine starters, positioning devices for doors, optical switches, and displacement transducers containing "clever" components can also be used. The use of shock-absorbers with an electro-rheological fluid makes it possible to change their resistance depending not only on the rate of deformation, but also on its value and the vibration level, as well as on different combinations of these factors. And the resistance thereby can be regulated with a high frequency (up to 100 Hz), which permits changing the resistance several times during one cycle of vibrations.

CONCLUSIONS

1. The preliminary model experiments have shown that the controllability of "intelligent" ERF materials can be used as applied to problems of automobile transport for damping vibrations of, e.g., the driver cabs of heavy trucks, as well as of engine suspensions and driver's seats.

2. The use of ERF shock absorbers makes it possible to vary their resistance, depending not only on the deformation rate but also on the deformation value and the vibration level, as well as on different combinations of the above factors.

NOTATION

A, piston movement amplitude, m; C, concentration, %; De, Deborah number; E, electric-field strength, kV/mm; F, force on the ER shock-absorber rod, N; f, number of vibrations, Hz; G', elastic modulus; G'', loss modulus; h, displacement of the ER shock-absorber rod, m; K, coefficient taking into account the law of piston moment; Q, volumetric rate of flow, m^3/sec; Q_d, energy dissipation in cylindrical gaps, W; $Q_{i.c}$, power of thermal flow withdrawn into the atmosphere due to induced convection, W; $S_{s.a}$, surface area of the shock absorber, m^2; $S_{o.s}$, effectively heat-transferring outer surface area; S_r, cross-section area of the rod, m^2; T_s, surface temperature, ^oC; T_{env}, ambient temperature, ^oC; t, time, sec; t_r, relaxation time, sec; $t_{m.m}$, duration of mechanical momentum, sec; V, volume of working ER fluid in circular channels, m^3; $\Sigma S_{s.s}$, total area of side surfaces of circular channels, m^2; $\Sigma S_{a.g}$, total area of annular gaps, m^2; α, heat-transfer coefficient, W/(m^2·K); γ, relative shear; $\dot{\gamma}$, rate of shear, sec^{-1}; Δd_i, thickness of annular gaps of the shock absorber, m; ΔP, pressure difference at the entrance and exit of circular channels, Pa; ΔP_0, initial pressure drop, Pa; η^*, dynamic viscosity, Pa·sec; σ', σ'', complex shear moduli; μ, viscosity, Pa·sec; τ, stress, Pa; ω, dynamic loading frequency, Hz. Subscripts: 0, onset of the process; i, number of annular gaps; r, relaxation; s.s, side surface; i.c, induced convection; d, dissipation; a.g, annular gap; m.m, mechanical momentum; o.s, outer surface; env, environment; s, surface; a.s, shock absorber surface; rod, rod.

REFERENCES

1. S. Morishita and T. Ura, ER fluid applications to vibration control devices and their adaptive neural-net controller, in: *Proc. of the Recent Advances in Adaptive and Sensory Materials and Their Applications*, Virginia Polytechnic Institute and State University Blacksburg, Virginia (1992), pp. 537–547.
2. S. Morishita and J. Mitsui, *Controllable Shock Absorber System* (*An Application of Electro-Rheological Fluid*), SAE Technical Paper 910744 (1991).
3. Z. P. Shul'man, E. V. Korobko, R. G. Gorodkin, et al., *Electro-Rheological Fastening Devices* [in Russian], Preprint No. 8 of A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, Minsk (1991).
4. S. B. Choi, J. H. Choi, M. N. Nam, C. C. Cheong, and H. G. Lee, A semi-active suspension using ER fluids for a commercial vehicle seat. Smart materials and structures, in: W. A. Bullough (Ed.), *Proc. 4th Eur. and 2nd MIMR Conf.*, Harrogate, UK (1998), pp. 217–224.
5. Z. P. Shul'man, Yu. F. Deinega, R. G. Gorodkin, et al., *Electro-Rheological Effect* [in Russian], Nauka i Tekhnika, Minsk (1972).
6. E. V. Korobko, *Electrically Structurized* (*Electro-Rheological*) *Fluids: Special Features of Hydromechanics and Possible Applications* [in Russian], ITMO AN Belarusi, Minsk (1996).
7. Z. P. Shul'man, E. V. Korobko, and M. L. Levin, *Electro-Rheological Fluids*, *Composition and Basic Properties* [in Russian], Preprint No. 4 of A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, Minsk (2001).
8. Z. P. Shul'man, B. M. Khusid, B. P. Khizhinskii, et al., *Electro-Rheological Vibration Isolation of Vibrating Systems* [in Russian], Preprint No. 22 of A. V. Luikov Heat and Mass Transfer Institute, BSSR Academy of Sciences, Minsk (1986).
9. M. Suh and M. Yeo, Development of semi-active suspension systems using ER fluids for wheeled vehicles, in: R. Tao (Ed.) *Proc. 7th Int. Conf. Electro-Rheological Fluids and Magneto-Rheological Suspensions*, Honolulu, Hawaii (1999), pp. 775–782.
10. E. P. Sapelkin and V. G. Bashtovoi (Eds.), *Proc. Int. Conf. and School-Seminar "New "Intelligent" Materials: Electro- and Magneto-Sensitive Fluids and Their Application to Energy-Saving Technologies"* [in Russian], Tekhnoprint, Minsk (2001).
11. Z. P. Shul'man, E. V. Korobko, and M. L. Levin, *Electro-Rheological Dampers of Transportation Facilities* [in Russian], Preprint No. 1 of A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, Minsk (2000).
12. W. L. Wilkinson, *Non-Newtonian Fluids. Fluid Mechanics*, *Mixing and Heat Transfer* [Russian translation], Mir, Moscow (1964).
13. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, *Transport Phenomena* [Russian translation], Khimiya, Moscow (1974).
14. V. N. Bogoslovskii, *Structural Thermal Physics* [in Russian], Vysshaya Shkola, Moscow (1970).