867. Simulation of oscillation dynamics of vibroprotective system with the electrorheological shock-absorber

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Abstract. The paper presents development of a mathematical model of a three-mass oscillating vibroprotective system with electrorheological (ER) shock-absorber by taking into account influences of temperature and electric field. Performance characteristics of the ER shock-absorber are established including dependences of force on rod displacement for different absorber geometry, rheological properties of ER fluid and magnitudes of temperature and electric field. This research work also provides comparison of simulation results of ER vibroprotective system during its linear movement through road profile “the sleeping policeman” in time domain. Amplitude-frequency characteristics of the vibroprotective system with ER shock-absorber are determined as function of electric field strength and temperature.

Keywords: oscillating system, electrorheological shock-absorber, simulation, electrorheological fluid, yield stress, viscosity, shear stress, temperature, electric field strength.

Introduction

Technical requirements on vehicle vibroprotection become more stringent every year. At present active and semi-active cushioning systems are increasingly applied to the decision of this problem. Such controlled systems are required in the construction of modern motor cars and tractors. One of the central questions of creation of adaptive cushioning systems is engineering design of devices with controlled damping characteristics. The most simple and technological of such devices are shock-absorbers based on application of active materials, namely electro- and magnetorheological fluids with properties that change under the external influence of electric and magnetic fields respectively.

The mathematical models of controlled shock-absorbers, considering features of rheological properties of working electroactive damping fluid, are described in works [1-4]. Most often rheological properties of non-Newtonian electrorheological fluid (ERF) are described by visco-plastic model Shvedov-Bingham [3-7]. As practice shows, such simplified model is convenient for technical calculations of shock-absorber performance characteristic. The most important task in the engineering process of adaptive systems is prediction of an overall performance of shock-absorber within an oscillatory system.

The experimental or theoretical research techniques are used for this purpose [2-9]. Modeling of shock-absorber performance characteristics in oscillatory system is the fastest and cheapest way of estimation of its operating modes, therefore construction of mathematical model of oscillatory system with the design shock-absorber is the most effective way to adjust its characteristics to the technical requirements [4, 10, 12]. Temperature influence on magnitude of fluid viscosity (i.e. operating mode of shock-absorber), is also important [4, 11-14].

The purpose of the presented research work is numerical modeling and analysis of oscillation dynamics of mechanical system of a quarter of vehicle suspension with the designed ER shock-absorber at the forced oscillations and during its movement through road obstacle of type “sleeping policeman” by taking into account influence of temperature and electric field.

Characteristics of the ER shock-absorber with non-Newtonian ER fluid have been experimentally investigated [12] and theoretically compared [15] by the authors previously.

1. Formulation of a mathematical problem

Let us consider a semi-active three-mass oscillating vibroprotective system (Fig. 1), which represents the mechanics of a quarter of a vehicle suspension accordingly [15, 16]. A working fluid with non-Newtonian properties is used in the ER shock-absorber. Effective viscosity of the fluid and damping force of the shock-absorber are varied at influence of controlled electric signal, therefore the system of equations for active oscillating system is:

$$M_s \ddot{z}_s + K_s(\dot{z}_s - \dot{z}_b) + C_s(z_s - z_b) = 0, \tag{1}$$

$$M_b \ddot{z}_b - K_s(\dot{z}_s - \dot{z}_b) - C_s(z_s - z_b) + F_{ERSA} + C_s(z_b - z_w) = 0, \tag{2}$$

$$M_w \ddot{z}_w - F_{ERSA} - C_b(z_b - z_w) + K_w(\dot{z}_w - \dot{z}_r) + C_w(z_w - z_r) = 0, \tag{3}$$

where M, K and C are the mass, coefficients of damping and stiffness; z, $\dot{z}_s = \partial z_s / \partial t$ and $\ddot{z}_s = \partial^2 z_s / \partial t^2$ is the displacement, velocity and acceleration respectively; t is the time variable; indexes r, s, b, w, r are the road, seat, body and wheel respectively; F_{ERSA} is the force of ER shock-absorber.

The mathematical model of the ER shock-absorber which allows to calculate its damping force F_{ERSA}, should consider shock-absorber geometry, rheological properties of a working ER fluid (its visco-plastic parameters), rod displacement and magnitudes of controlled electric signal and temperature.

1.1 Mathematical model of the ER shock-absorber

We use the cylindrical coordinate system for the ER shock-absorber geometry (Fig. 2) with the following assumptions: 1) flow regime in annular channel of the ER shock-absorber is completely developed; 2) laminar flow; 3) the electrorheological fluid is incompressible; 4) the annular channel has sufficient length, therefore the end effects are neglected; 5) at the channel walls the ERF velocity is equal to zero (sticking condition).

The generated damping force of telescopic one-ring pneumatic hydraulic shock-absorber F_{ERSA} can be defined as:

$$F_{ERSA} = F_f + F_g + F_{ERF}, \tag{4}$$

where F_f, F_g, F_{ERF} – forces of dry friction, gas resistance and hydraulic resistance of ERF. Force of inertia of the shock-absorber piston is very small in comparison to damping force of the shock-absorber, therefore we neglect it. Each force is described by the following expression:

$$F_f = (F_0 + c_1 \Delta P)\,\mathrm{sgn}(v_p); \tag{5}$$

$$F_g = P_0 \left[\frac{V_0}{V_0 - A_r(l_r - z)} \right]^n A_r; \tag{6}$$

$$F_{ERF} = (A_p - A_r)\Delta P, \tag{7}$$

where A_p, A_r – cross-section area of piston and rod respectively; F_0, c_1 – parameters defining dry friction force from experiment; n – exponent of power; ΔP – pressure drop in annular gap, Pa; v_p – velocity, m/s; P_0 – initial pressure, Pa; V_0 – initial volume, m^3; l_r – depth of rod immersing in shock-absorber chamber, m.

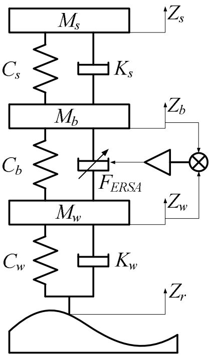

Fig. 1. The scheme of 3-mass oscillation vibroprotective system with controlled ER shock-absorber

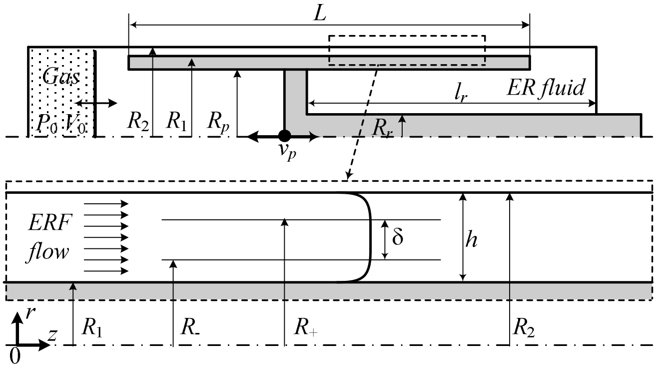

Fig. 2. The scheme of ERF flow in the ER shock-absorber annular gap (cylindrical coordinate system): R_1, R_2, R_p, R_r – radii of the internal and external wall of annular channel, piston and rod respectively; δ – dimensionless width of quasi-solid kernel of ERF flow in the annular channel; r, z – axes and variables in cylindrical system of coordinates; "–", "+" – indexes of the bottom and top borders of quasi-solid kernel; V_0 and P_0 – volume and pressure in the pneumatic chamber at completely extended rod from the shock-absorber; h and L – thickness and length of the annular channel

Pressure drop and velocity profile are defined on numerical solution of equation system (motion equation, rheological equation of state and continuity equation) for the non-stationary flow of visco-plastic ER fluid in annular channel of the shock-absorber:

$$\rho\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial u}{\partial r}\right), \tag{8}$$

$$\eta\left(E,T,\frac{\partial u}{\partial r}\right) = \frac{\tau_0(E,T)}{\left|\partial u/\partial r\right|} + \mu(E,T)\left(\frac{\partial u}{\partial r}\right), \tag{9}$$

$$2\pi\int_{R_1}^{R_2} u(r,t)\, r\, dr = \dot{V}(t), \tag{10}$$

where τ_0 – yield stress, Pa; η and μ – apparent and plastic viscosity respectively, Pa·s; $du/dr = \dot{\gamma}$ – shear rate, s^{-1}; ρ – density, kg/m^3; t – time, s; r – radius, m; E – electric field strength, kV/mm; T – temperature, °C; $\dot{V}$ – volume flow, m^3/s; u – velocity, m/s.

Volume flow of ER fluid in channel is defined on set-up sinusoidal law of motion piston $x(t) = A_m \cdot \sin(2\pi f t)$:

$$\dot{V}(t) = \left(A_p - A_r\right)\dot{z}(t) = 2\pi^2\left(R_p^2 - R_r^2\right) f A_m \cos(2\pi f t), \tag{11}$$

where z – displacement, m; A_m – amplitude, m; f – frequency, m.

At the moment of time $t = 0$ the fluid is considered motionless:

$$u(r,\ t=0)=0. \tag{12}$$

No-slipping conditions on walls of ring channels are set:

$$u(r=R_1,\ t)=0,\ u(r=R_2,\ t)=0. \tag{13}$$

We use net method [17] for calculation of equation system (8)–(13):

$$\rho\frac{1}{\Delta t}\left(u_{i;j}^{k}-u_{i;j}^{k-1}\right)=-\left(\frac{\partial p}{\partial z}\right)_i^k+\frac{1}{r_j}\frac{1}{\Delta r^2}\left[r_{j+0.5}\eta_{j+0.5}\left(u_{i;j+1}^{k}-u_{i;j}^{k}\right)+r_{j-0.5}\eta_{j-0.5}\left(u_{i;j-1}^{k}-u_{i;j}^{k}\right)\right], \tag{14}$$

$$\eta_j=\frac{\tau_0(E,T)}{\left(u_{i,j+1}^{k}-u_{i,j-1}^{k}\right)}+\mu(E,T)\left(u_{i,j+1}^{k}-u_{i,j-1}^{k}\right), \tag{15}$$

$$\frac{1}{2}u_0r_0+u_1r_1+\ldots+u_{N-1}r_{N-1}+\frac{1}{2}u_Nr_N=\frac{-\dot{V}(t_i)}{2\pi\Delta r}, \tag{16}$$

where $\eta_{j\pm0.5}=2\,\eta_{j\pm1}\,\eta_j/\left(\eta_{j\pm1}+\eta_j\right)$; $r_{j\pm0.5}/r_j=\left(R_1+(j\pm0.5)\Delta r\right)/\left(R_1+j\Delta r\right)$; Δr – step of variable r in annular channel; i, j, k – indexes of coordinates z, r and t respectively.

On the calculated gradient of pressure from (14)–(16) it is possible to calculate velocity u. We calculate pressure drop $\Delta p(t_k)$ at the moment of time t_k on all annular channel as the sum of pressure drop $(\partial p/\partial z)_i^k$ on all i to layers of a numerical grid along the channel. Now it is possible to calculate shock-absorber performance characteristics, for example, shock-absorber depending on displacement or velocity of rod displacement.

It is necessary to know rheological properties of ER fluid (parameters of dynamic viscosity and yield stress) for calculation of pressure drop in the annular channel and shock-absorber force according to (14)–(16).

1.2 Rheological properties of ER fluid

Two-component ER fluid has been developed in laboratory conditions [14]. Measurements of rheological properties of ERF are executed in a range of shear rates 1–3500 s^{-1} on rheometer "Physica MCR 301" manufactured by "Anton Paar" with high-voltage measuring cell, which represents system of coaxial cylinders. Rheological curves are constructed by results of experimental investigation for given formulation of ERF, at investigated shear rate they depend on electric field strength in a range of 0–2.5 kV/mm and temperatures 10–80 °C. All of them can be described by visco-plastic Shvedov-Bingham model with processing error less than 15.9 %:

$$\tau(\dot{\gamma},\ E,\ T)=\tau_0(E,\ T)+\mu(E,\ T)\,\dot{\gamma}. \tag{17}$$

Rheological model (17) is used in mathematical model of the ER shock-absorber (4)–(13). Dependence of plastic viscosity on various values of temperature and electric field strength is defined as:

$$\mu(T,E)=\frac{A_3(E)}{A_4(E)+T}, \tag{18}$$

where $A_3(E) = 8.221+5.253\cdot E$ [Pa·s·°C] and $A_4(E) = 3.2+8.342\cdot E$ [°C] – coefficients, which depend on electric field strength E.

According to experimental investigations dependence of yield stress τ_0 from electric field strength and temperature is defined as:

$$\tau_0(E,T) = A_1(E)\exp[A_2(E)T], \tag{19}$$

where $A_1(E) = 70.347\cdot E^2+18.389\cdot E+1.423$ [Pa] and $A_2(E) = 0.0355\cdot\exp(-0.362\cdot E)$ [1/°C] – coefficients, which depend on electric field strength E.

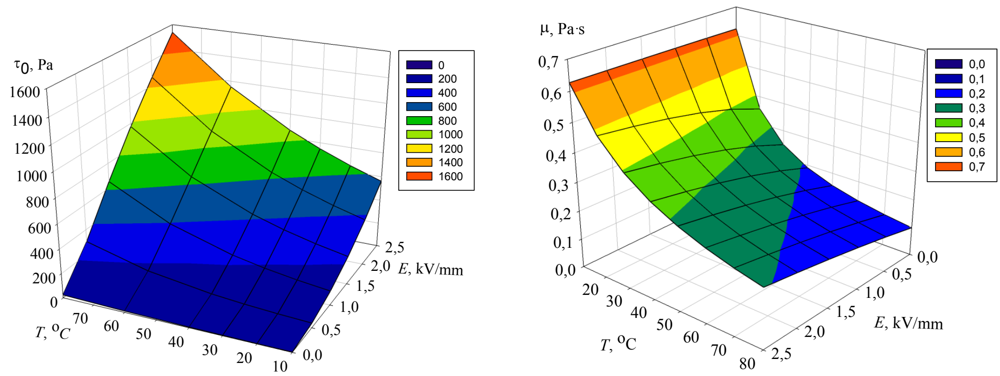

Fig. 3. Dependence of field stress τ_0 and plastic viscosity μ on temperature and electric field strength according to eq. (18) and (19)

Feature of rheological behavior of ERF unlike other fluids is the increase of yield stress with temperature growth at influence of external electric field. At the same time for the majority of known fluids the yield stress decreases at temperature growth. The closest example is magnetorheological fluid at influence of an external electromagnetic field [18].

Approximation by rheological Shvedov-Bingam model at dependence of its parameters on electric field strength in a range of 0–2.5 kV/mm and temperature in range of 10–80 °C can be used at calculation of performance characteristics of hydraulic devices taking into account flow and heat transfer of ER fluid in channels of various geometry.

2. Numerical modeling of oscillation dynamics of mechanical system, performance characteristics of the ER shock-absorber

For calculation of characteristics of the ER shock-absorber we use the following data: $R_r = 0.008$ m; $R_p = 0.02$ m; $R_1 = 0.023$ m; $R_2 = 0.024$ m; $h = (R_2–R_1)/2 = 0.001$ m; $L = 0.1$ m; $P_0 = 10.5$ MPa; $V_0 = 0.000049$ m^3; $l_r = 0.04$ m; and auxiliary formulas $A_p = \pi R_p^2$; $A_r = \pi R_r^2$.

For the analysis of the oscillation system we use the following parameters: $K_w = 400$ N·s/m; $C_w = 225000$ N/m; $M_w = 31$ kg; $K_b = 1500$ N·s/m; $C_b = 29000$ N/m; $M_b = 290$ kg; $K_s = 3000$ N·s/m; $C_s = 8000$ N/m; $M_s = 90$ kg.

Comparison of results of experiment and simulation of operating regime of the ER shock-absorber has been performed for amplitudes of rod displacement in a range of 5–25 mm and frequencies in a range of 0.5–5 Hz, and that also has demonstrated good agreement [15]. The correctness of numerical analysis of mathematical model of oscillation system (1)–(3) is confirmed by close fit of task solving results (displacements of sprung weights) test model of passive oscillatory system with its parameters (weight, coefficient of damping and rigidity) [15, 16]. Results of numerical study of the velocity profile in annular gap of the ER shock-absorber at rod motion under characteristic average velocities 0.09 and 0.9 m/s are provided in Fig. 4.

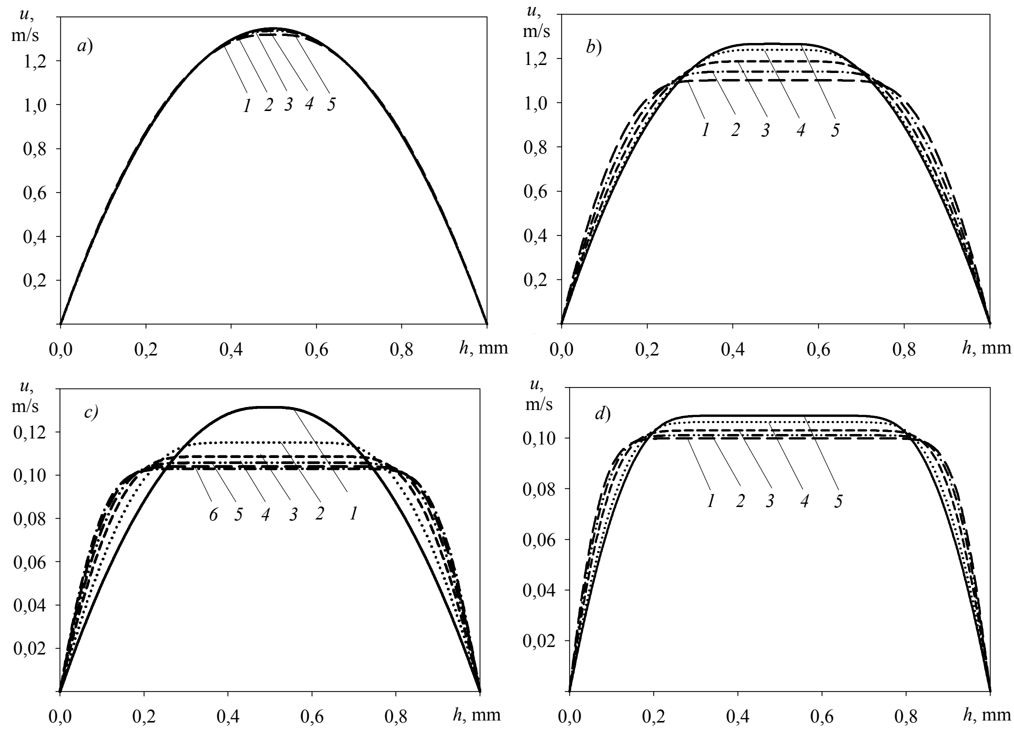

Fig. 4. Velocity profile in annular channel of the ER shock-absorber at various values of electrical field strength E, temperature T and flow average velocity u:
a) u = 0.9 m/s, E = 0 kV/mm, 1 – T = 10 °C, 2 – 20, 3 – 40, 4 – 60, 5 – 80;
b) u = 0.9 m/s, E = 2.5 kV/mm, 1 – T = 10 °C, 2 – 20, 3 – 40, 4 – 60, 5 – 80;
c) u = 0.09 m/s, T = 40 °C, 1 – E = 0 kV/mm, 2 – 0.5, 3 – 1, 4 – 1.5, 5 – 2, 6 – 2.5;
d) u = 0.09 m/s, E = 2.5 kV/mm, 1 – T = 10 °C, 2 – 20, 3 – 40, 4 – 60, 5 – 80

Simulation results indicate that temperature exerts small influence on velocity profile shape at the absence of electric field E = 0 kV/mm (Fig. 5*a*). On the other hand, temperature strongly influences velocity profile at the presence of electric field E = 0.5–2.5 kV/mm (Fig. 5*b*, *c*, *d*), hereupon width of quasi-solid kernel of flow of ER fluid and hydraulic resistance accordingly increase.

According to the statement of problem (eqs. (4)-(13)), performance characteristic of the ER shock-absorber has been established for amplitudes of rod displacement in a range of 5–25 mm and frequencies in a range of 0.5–5 Hz by taking into account influence of electric field and temperatures on the rheological properties of ERF. In particular, dependences of resistance force on rod moving (without force in the gas chamber) under the sinusoidal law with amplitude A_m and frequency f were obtained:

– A_m = 30 mm and f = 3 Hz at temperature in range 20–80 °C over E = 0 kV/mm (Fig. 5*a*) and 2.5 kV/mm (Fig. 5*b*);

– A_m = 10 mm and f = 0.5 Hz at temperature 20 °C and 60 °C, electric field strength 0 and 2.5 kV/mm (Fig. 5*c*);

– A_m = 20 mm and f = 1 Hz at temperature 20 °C and 60 °C, electric field strength 0 and 2.5 kV/mm (Fig. 5*d*).

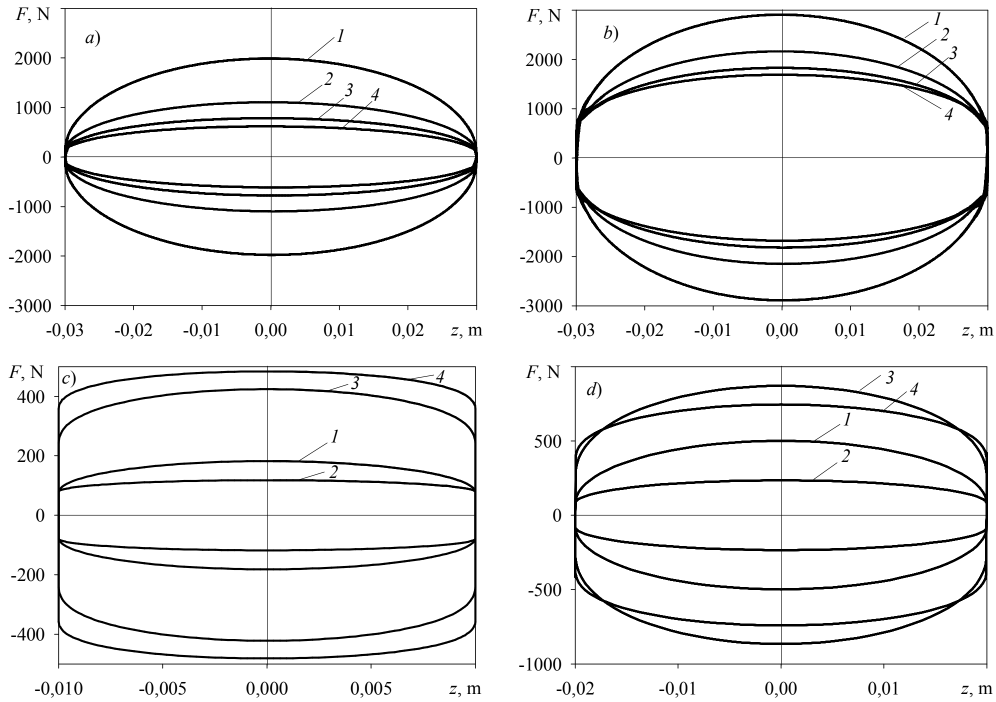

Fig. 5. Dependence of force of the ER shock-absorber F on rod displacement z at various values of electrical field strength E and temperature T:
a) E = 0 kV/mm and *b*) E = 2.5 kV/mm: A_m = 30 mm and f = 3 Hz, 1 – T = 20 °C; 2 – 40; 3 – 60; 4 – 80; *c*) A_m = 10 mm, f = 0.5 Hz and *d*) A_m = 20 mm, f = 1 Hz: 1 – T = 20 °C, E = 0 kV/mm; 2 – 60 °C, 0 kV/mm; 3 – 20 °C, 2.5 kV/mm; 4 – 60 °C, 2.5 kV/mm

Calculation results indicate that ER shock-absorber resistance force F decreases with temperature growth: at the absence of electric field (Fig. 5*a*; Fig. 5*c*, *d*, lines 1 and 2) and more strongly at electric field strength E = 2.5 kV/mm (Fig. 5*b*; Fig. 5*c*, *d*, lines 3 and 4). Such regularity of resistance force is provided by yield stress growth at increase of temperature and electric field strength. Thus, at a warming up of the shock-absorber with ERF it is possible to provide the minimum reduction of resistance force.

Calculation of amplitude-frequency characteristics is performed for semi-active oscillating vibroprotective system (Fig. 1) with the ER shock-absorber (Fig. 2) in the presence and absence of electric field for three values of temperatures (Fig. 6).

Temperature growth essentially influences the oscillating mode of the vibroprotective system, where oscillation amplitude A_m increases more than 2 times (Fig. 6, maximum of lines 1 and 5). Switching on electric field of 2.5 kV provides effective damping of the oscillations in the area of resonant frequency of 1.4 Hz, therefore under such conditions oscillation amplitude remains essentially identical for frequency range of 0.5–2 Hz within temperature range of 20–80 °C, that is provided with feature rheological behavior of ERF at simultaneous influence temperature and electric field strength (Fig. 6, lines 2, 4 and 5).

We can observe similar behavior during analysis of oscillation modes of the vibroprotective system at the presence of obstacle “the sleeping policeman” (Fig. 7).

We investigate vibroprotective system operation at its linear movement with velocity of 30 km/h through “the sleeping policeman” of trapezium shape according to the standard [19] in the absence of electric control signal and using control algorithm [20] that functions by a principle of make-and-break of control signal depending on a combination of modes of shock-absorber rod stripping (compression and stretching) and movement velocity of cushion weights.

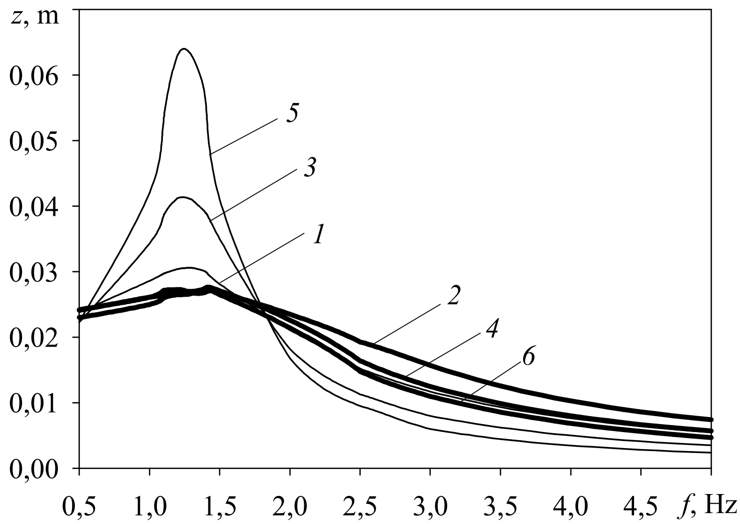

Fig. 6. Amplitude-frequency-characteristics of oscillation system with the ER shock-absorber: 1, 2 – T = 20 °C; 3, 4 – 40 °C; 5, 6 – 80 °C; (thin lines – E = 0 kV/mm, bold lines – 2.5 kV/mm)

Simulation results reveal (Fig. 7) that the temperature considerably influences the time of oscillation damping (from time moment maximum deviations of driver seat till the moment of time of absence of periodic oscillations) at motion of system (Fig. 1) through an obstacle "the sleeping policeman" when using the aforementioned control algorithm [20].

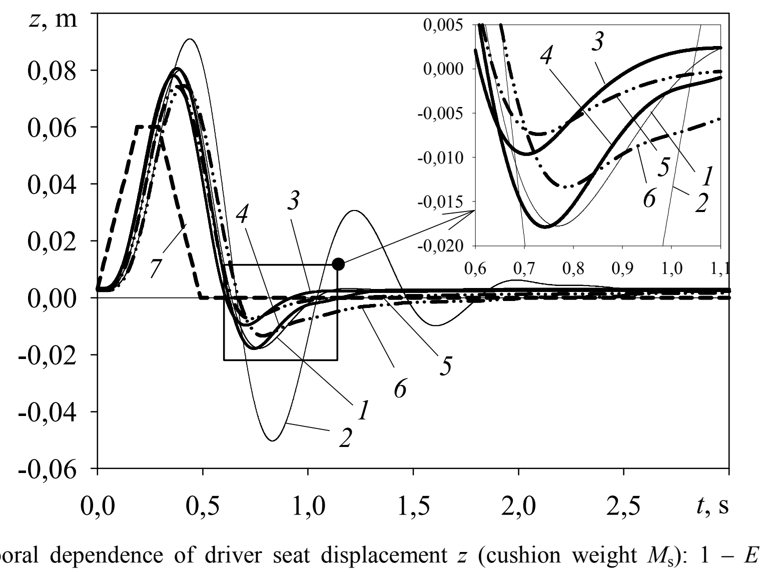

Fig. 7. Temporal dependence of driver seat displacement z (cushion weight M_s): 1 – E = 0 kV/mm, T = 20 °C; 2 – 0 kV/mm, 80 °C; 3 – 2.5 kV/mm, 20 °C; 4 – 2.5 kV/mm, 80 °C; 5 – control algorithm [20] at T = 20 °C; 6 – control algorithm [20] at T = 80 °C; 7 – road profile "the sleeping policeman" in time domain

Time of oscillation damping of system (1)–(3) is equal to 2.5 s at $T = 80$ °C and is less than 1.2 s at $T = 20$ °C when electric field is deactivated; 1.5 s at $T = 80$ °C s and 1 s at $T = 20$ °C when electric field is activated ($E = 2.5$ kV/mm). When we use the control algorithm [20], time is equal to 1.4 s at $T = 80$ °C s and 0.9 s at $T = 20$ °C. Thus, efficiency of oscillation damping in time domain varies more than 1.5 times at comparison of oscillations of vibroprotective system with the control algorithm at temperature $T = 20$ °C and 80 °C, that it is necessary to jointly consider influence of electric field and temperature by development of control algorithm.

Conclusions

The paper reported on development of a mathematical model of a vibroprotective system by taking into account ER shock-absorber characteristics and rheological properties of working ER fluid. Efficiency of oscillation damping in time domain constitutes more than 2 times when comparing passive and active oscillation systems. Velocity profile in annular channel and performance characteristics of the ER shock-absorber were established including dependences of force on rod displacement for varying shock-absorber geometry, rheological properties of ER fluid, temperature and electric field magnitudes. The analysis of operating efficiency of the oscillation system was accomplished by determining the amplitude-frequency characteristic and using them to estimate oscillating damping time. The results of the research demonstrate that it is necessary to consider influence of both the electric field and temperature by developing a corresponding control algorithm of shock-absorber performance characteristics.

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