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SEMIACTIVE VIBRATION REDUCTION OF OPERATOR'S SEAT WITH THE USE OF CONTROLLED MAGNETORHEOLOGICAL DAMPER

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Abstract

Low speeds of mobile heavy machines makes that the force derived from rough roads cause intense excitation of low frequency vibration, the reduction of which is possible only by active or semi active methods. In conditions of low frequency, the energy dissipation in the tire reduces the vibration intensity in a minor degree only magnetorheological dampers are free from this defect, which they properties changing under influence an electric field functioning on ferromagnetic particles of oil suspension. A controlling coil current, which is mounted in the damper piston, could control density of magnetic field lines (magnetic field intensity) directly in viscous hole of piston, and hence viscous drag force. Electric energy needed to control magnetorheological damper is generally available in each of mobile heavy machines. Simulation tests were performed to investigate effectiveness and stability of the proposed solution and the results were deemed satisfactory. The system was found to be feasible and implementable with respect to every parameter. The purpose of this study was to develop a simulation model of the semi active suspensions of operator's seat based on magnetorheological damper, and to examine the effectiveness of using different control strategies.

Keywords: *seats suspensions, mobile machines, magnetorheological damper, semi active methods, controlled suspension, reduction of vibration*

1. Introduction

The majority of heavy machines are undamped machines, which in combination with high values of curb weight and mass moment of inertia causes excitation of low frequency vibrations [7]. These vibrations, only in a minor degree could be reduced by tires. In purpose of reduction of vibrations acting on operator of heavy machine, semi active and active systems are used.

Semiactive systems do not produce additional energy to the dynamical system and these systems are most often various types of controlled vibration absorber. Magnetorheological dampers, which control damping force, allow for much better elimination of vibrations than the passive systems especially in lowest range of vibration frequency. These systems require external electrical energy only to produce electromagnetic field, which control field strength, which causes the possibility to change damping force in a wide range. Properties mentioned above make magnetorheological dampers an appropriate component of operator's seat suspension of undamped heavy machines.

There are various literature descriptions of magnetorheological damper models for different applications, and which different level of complexity of mathematical description. On low velocities, there is a noticeable greater impact of hysteresis [9], which shortens the choice to two models: Specner, and Bouc-Wen. This article is based on Bouc-Wen model.

2. Physical model of operator's seat of undamped self-propelled machinery

In Fig. 1 there is a model of semi active dynamical system of operator's seat suspension, in which a controlled magnetorheological damper shapes force $F(s)$, which is the main bearing reaction of operator's seat platform, which is located object of load G ($G = 981$ N).

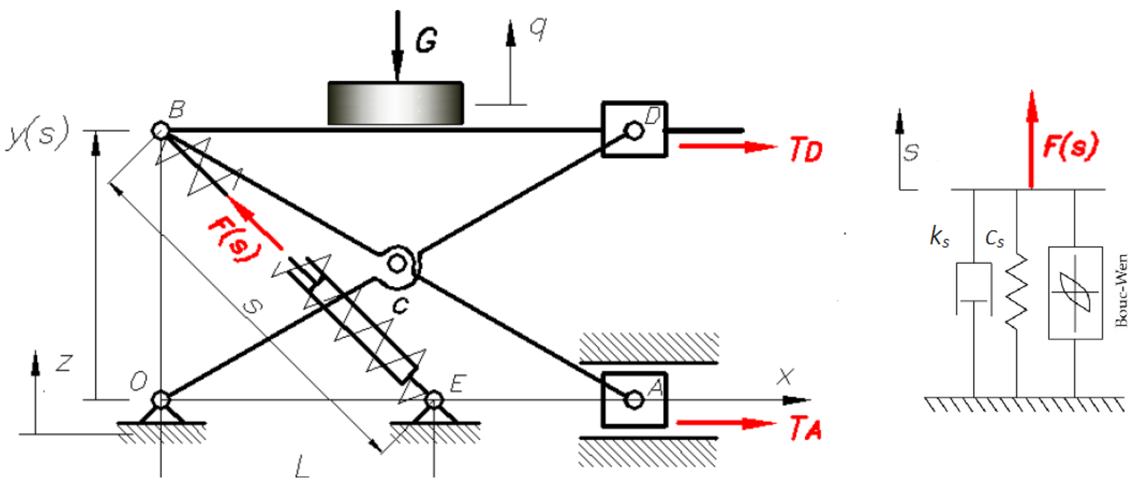

Fig. 1. Schema of heavy machine operator's seat

The entire force $F(s)$ shaping of the movement of operator's seat suspension include spring reaction, viscous resistance of damper, and additional reaction force of magnetorheological fluid elasticity, resistances witch attend energy dissipation in fluid which comes from magnetization reversal, and losses from hysteresis model of Bouc-Wen [3].

$F(s)$ force is described by equation of motion (1) with differential equation which is modeling the formation of the hysteresis loop (2):

$$F(s) = -c(s - s_{\max}) - c_s(s - s_{\max}) - k_s \frac{\mathrm{d}s}{\mathrm{d}t} - \alpha_0 z_0, \tag{1}$$

$$\dot{z}_0 = -\gamma |s| z_0 | z_0 |^{n-1} - \beta \frac{\mathrm{d}s}{\mathrm{d}t} | z_0 |^n + A \frac{\mathrm{d}s}{\mathrm{d}t}, \tag{2}$$

where:
$s_{\max}$ – initial length of spring ($s_{\max} = 0.2$ m),
c – coefficient of stiffness of relief spring ($c_s = 9284$ N/m),
c_s – coefficient of stiffness of magnetorheological fluid ($c = 2200$ N/m) [5],
k_s – coefficient of viscous damping of damper ($k_s = 550$-3900 Ns/m) [5],
z_0 – variable responsible for formation of hysteresis loop (m),
α_0 – coefficient of hysteresis losses ($\alpha_0 = 0.7$-13.5 N/m) [5],
A – coefficient of hysteresis ($A = 3000000$) [5],
γ – coefficient of hysteresis ($\gamma = 300$-20 m^{-2}) [5],
β – coefficient of hysteresis ($\beta = 330$ m^{-2}) [5],
n – exponent of the hysteresis loop in Bouc-Wen model ($n = 2$) [5].

Absolute motion of operator's seat with operator describes equation:

$$q(t) = y[s(t)] + z(t). \tag{3}$$

Relative motion of operator's seat – $y(s)$ is formed by controlled length of magnetorheological dampers. For model shown in Fig. 2, relative motion describes equation:

$$y(s) = \sqrt{s^2 - L^2}. \tag{4}$$

Vertical vibrations of vehicle operator's resting on seat suspended as illustrated in Fig. 2 with friction describe equation:

$$m\frac{\mathrm{d}^2q(t)}{\mathrm{d}t^2}=\frac{\sqrt{s^2-L^2}\left[s\,L\,\mu\,\mathrm{sign}\left(\frac{\mathrm{d}s}{\mathrm{d}t}\right)-5L^2+s^2\right]}{s\left[2\sqrt{s^2-L^2}\;L\,\mu\,\mathrm{sign}\left(\frac{\mathrm{d}s}{\mathrm{d}t}\right)-5L^2+s^2\right]}F(s)-G\,. \tag{5}$$

For the calculation assumes that $L_{AB} = L_{OD} = 2L = 0.6$ m and coefficient of friction in prismatic of scissor mechanism – $\mu = 0.1$.

3. Sky-Hook control

The simplest and most common for semi active systems is controlling by Sky-Hook method. That method relies on turning on and off power supply of the system, which causes maximization and minimization of system damping value [4, 8].

Voltage change, thereby damping causes the changes of velocities. If value of the product is positive, then damping force is maximal, if value of product is negative, then damping force is minimal. For discussed system, dependencies are following:

$$\begin{cases}\frac{\mathrm{d}y}{\mathrm{d}t}\frac{\mathrm{d}z}{\mathrm{d}t}<0 & \Rightarrow \text{ minimum voltage,}\\[2ex] \frac{\mathrm{d}y}{\mathrm{d}t}\frac{\mathrm{d}z}{\mathrm{d}t}\geq 0 & \Rightarrow \text{ maximum voltage.}\end{cases} \tag{6}$$

However, parameters like k_s, α_0, γ show strong relation from control voltage u_s, for RD-1003-5 model of magnetorheological damper, these values are changing nonlinearly [5], but with Sky-Hook algorithm, intermediate values can be ignored, because these changes occur suddenly.

It is assumed that: a_1 = 2.56 N/mV, b_1 = 0.7 N/m, a_2 = 670 Ns/mV, b_2 = 550 Ns/m, a_3 = = –56 1/m^{2}V, b_3 = 300 1/m^2, u_s = 0-5 V.

Coefficients k_s, α_0, γ could be calculated from linear equations below:

$$\alpha_0 = a_1\,u_s + b_1\,, \tag{7}$$

$$k_s = a_2\,u_s + b_2\,, \tag{8}$$

$$\gamma = a_3\,u_s + b_3\,. \tag{9}$$

4. Fuzzy Sky-Hook control

Fuzzy logic was proposed by Lotfi Zadeh, Boolean logic has been dropped for many-values approach [6]. The logic is widely used wherever there is a problem with description of mathematical model of object. In control system, engineering, fuzzy logic is generally used in fuzzy regulators, which allows to the creation of self-adaptive system of control.

Due to its increasing popularity in industry, simulation programs such as MATLAB-Simulink were expanded for library Fuzzy Logic Toolbox, which allows to create models of own control system. Fuzzy regulators include three fundamental processes: fuzzyfication, fuzzy rule-based system, and defuzzification. In fuzzyfication process, input data are "Fuzzificating".

In this process, input functions are determined in degree to which they belong to each of the appropriate set. In fuzzy rule, based system is defined function of membership from rules and "fuzzificated" input data. In defuzzification process, input is matched to membership function, and is defined value of the output.

In fuzzy rule-based system are generated set of conditions which determinate operation algorithm.

These conditions could be recorded by using tables. This condition is based on our own experience and knowledge about model. In Tab. 1 shown relation of this simulated object [6].

Table 1. Table of conditions

		y		
		P	**Z**	**N**
z	**P**	S	M	L
	Z	M	S	M
	N	L	M	S

Note to table 1:

When z and y are positive then u_s is small.

When z and y are opposite signs then u_s is large.

When z and y are simultaneously zeros then u_s is medium.

In figure above shown effect of fuzzification of output signal. By the letters defined levels of signal where: S – small, M – medium, L – large.

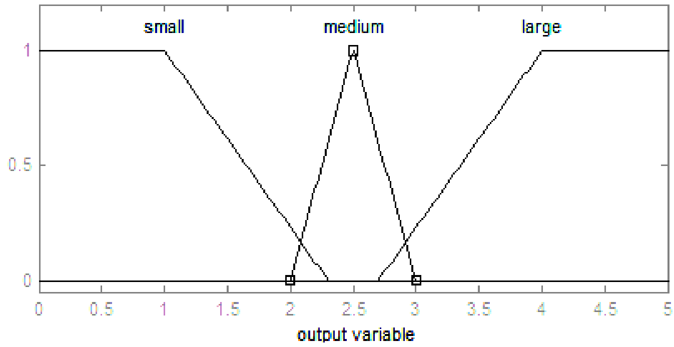

Fig. 2. Output signal of fuzzy regulator

5. Model of extortion

From ISO 8606 standard, where were described profiles of rough roads by PSD, and for different class of roads [2]. Kinematic extortion from rough roads is stochastic processes.

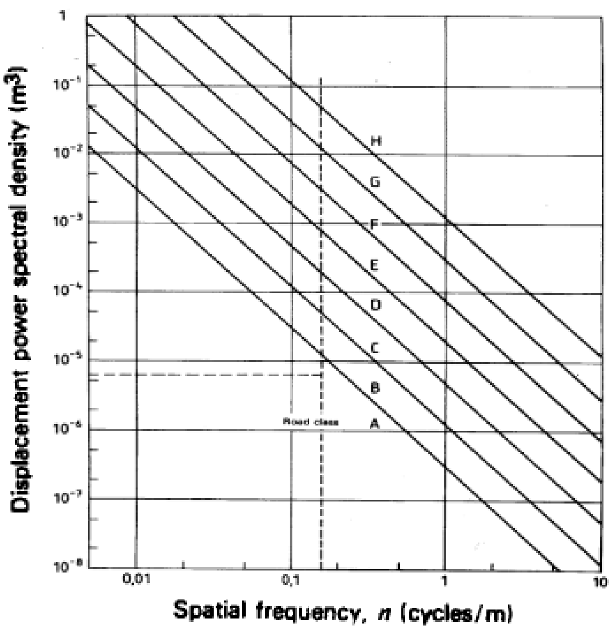

Fig. 3. Road classification due to the quality [2]

In Fig. 3 shown PSD characteristics of rough roads ranked by roads quality. Line A is the best quality of the road, and line H is the worst quality of the road. Decreasing value of amplitude of roads inequality with frequency is a natural state.

Considering the low velocities of ride and extortion of frequency in range of 1-4 Hz, based on PSD of extortion corresponding with line D in Fig. 3, model of kinematic extortion was recorded in the field of time, as a poliharmonical signal in the form of [1]:

$$z(t) = \sum_{n=1}^{N} A_n \sin(n\,\omega_0 t - \theta_n)\,. \tag{10}$$

Angular frequency is determined on the base of spatial frequency of extortion:

$$\omega_0 = v\,\Omega\,. \tag{11}$$

N-th harmonic amplitude would be calculated by:

$$A_n \sqrt{\Phi(\Omega_n)\frac{\Omega}{\pi}}, \quad n = 1 \ldots N\,, \tag{12}$$

where:
Ω – angular frequency of road roughness (rad/s),
Φ – road profile PSD,
v – vehicle velocity (m/s),
θ – random phase angles.

Amplitude of extortion and phase shifts is selected in MATLAB-Simulink program in a case of random number generator. An example of extortion is shown in Fig. 4.

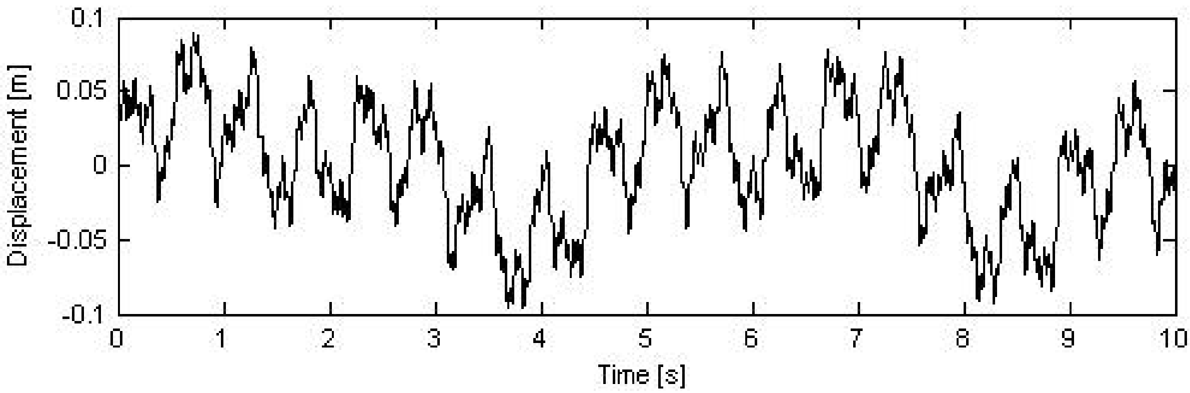

Fig. 4. Extortion vs. time, at frequency range 1-10 Hz

6. Simulation studies of semi active suspension of seat

Effectiveness of different algorithms of regulations was studied by computer simulation method in MATLAB-Simulink program.

In this case, it was to determine transfer function for displacement defined as quotient of displacement of operator's to instantaneous value of height of micro-profile road.

For extortion shown in Fig. 8 it was studied the reduction rate of vibration for different methods of regulations like *Sky-Hook* – Fig. 5, *Fuzzy Sky-Hook* – Fig. 6.

In comparison to the system with disabled controller – Fig. 7 it achieved 2.5 time reduction of vibration amplitude.

Driving comfort depends on RMS values of vibration acceleration of the vehicle operator. Effectiveness of regulations algorithms by methods: *Sky-Hook* and *Fuzzy Sky-Hook* in shaping indicators of driving comfort are shown in Fig. 9 and 10.

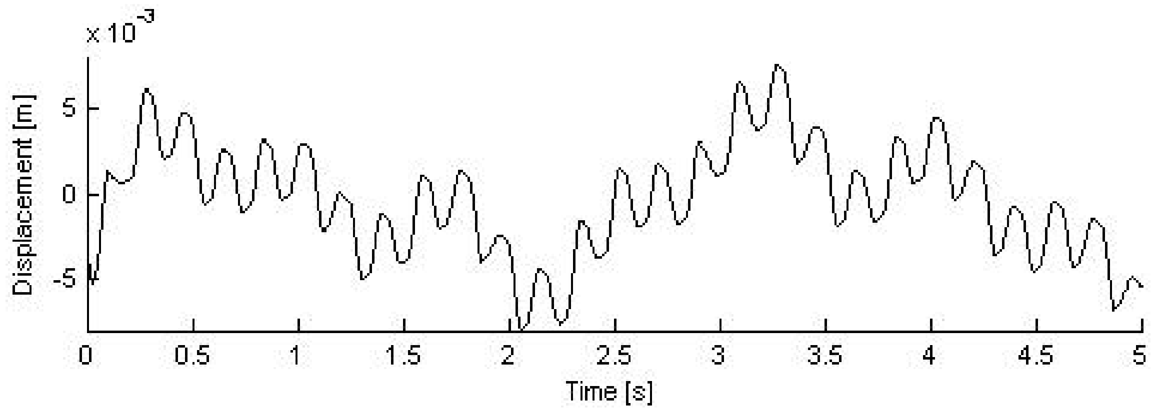

Fig. 5. System response for Sky-Hook algorithm

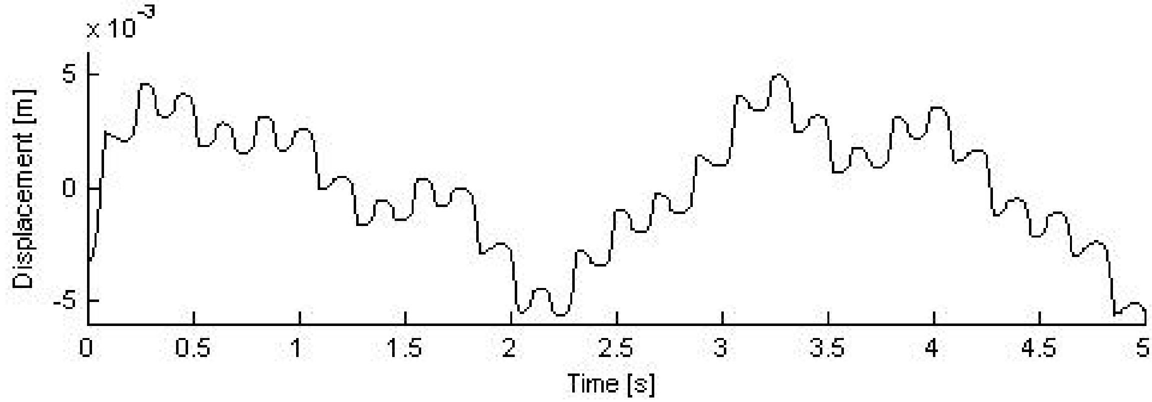

Fig. 6. System response for Fuzzy Sky-Hook algorithm

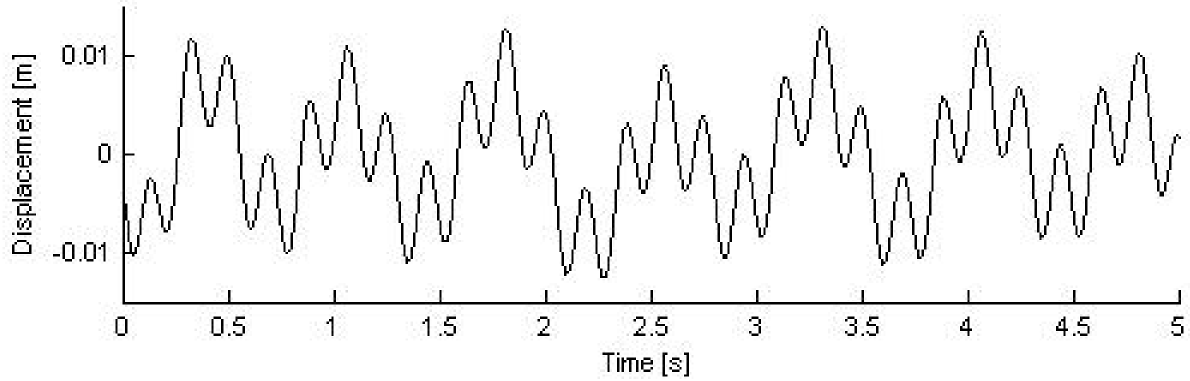

Fig. 7. System response for system without algorithm

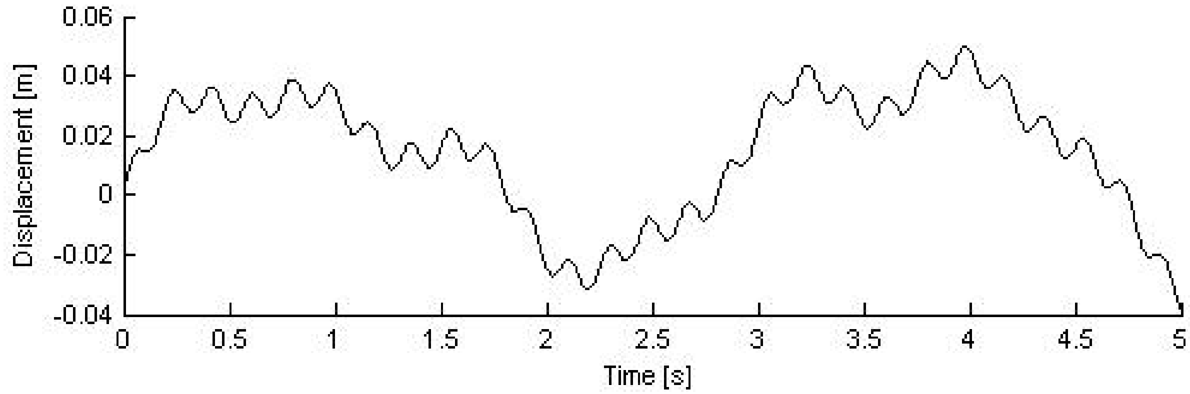

Fig. 8. Extortion at frequency range 1-4 Hz, D quality of road, and velocity of ride 3 m/s

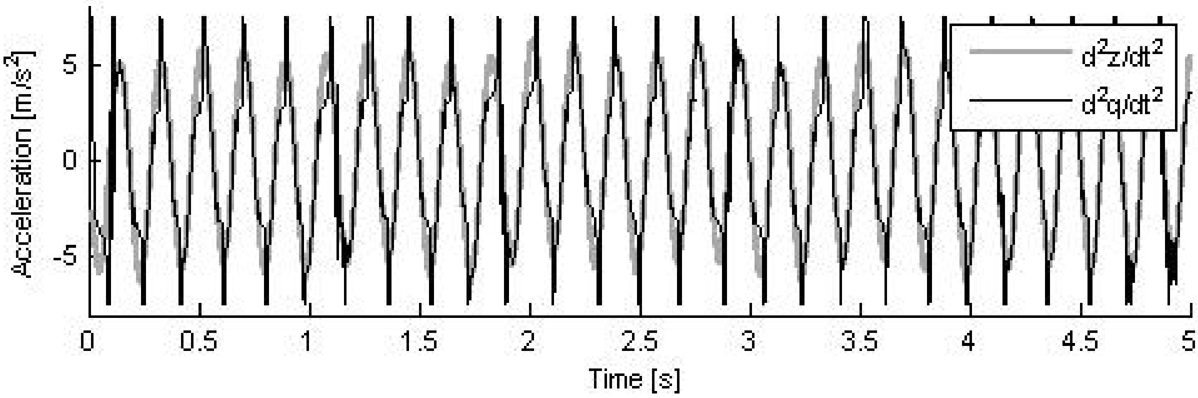

Fig. 9. Acceleration of extortion vibration and operator's vibration with Fuzzy Sky-Hook algorithm. On black, function d^2q/dt^2, on grey d^2z/dt^2

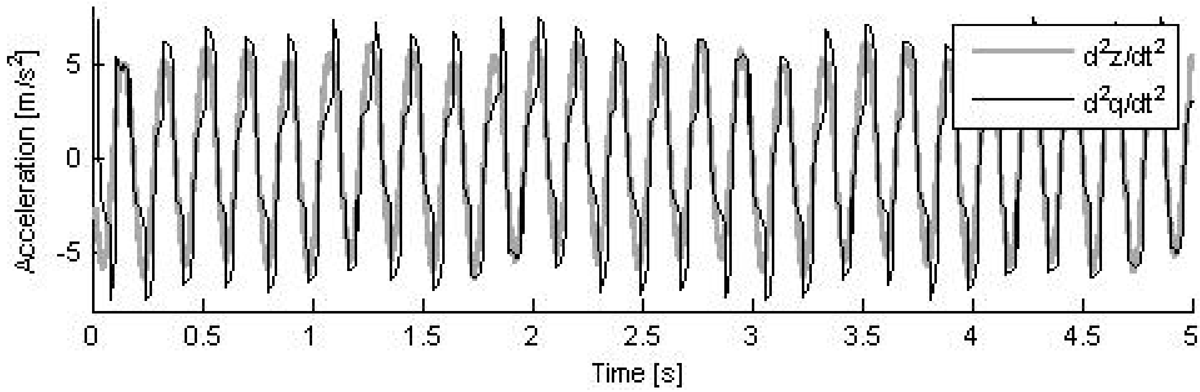

Fig. 10. Acceleration of extortion vibration and operator's vibration with Sky-Hook algorithm. On black, function d^2q/dt^2, on grey d^2z/dt^2

Both characteristics shown comparison of acceleration waveform of extortion signal of vibration (grey line) in response to object signal (line black).

Regulation of damping based on the method of *Sky-Hook* leads to stepping changes of voltage control (without passing through intermediate stages of signal) thereby causing fast changes of damping from minimum to maximum.

Voltage waveform signal for control voltage as result of *Sky-Hook* acting regulator shown in Fig. 11.

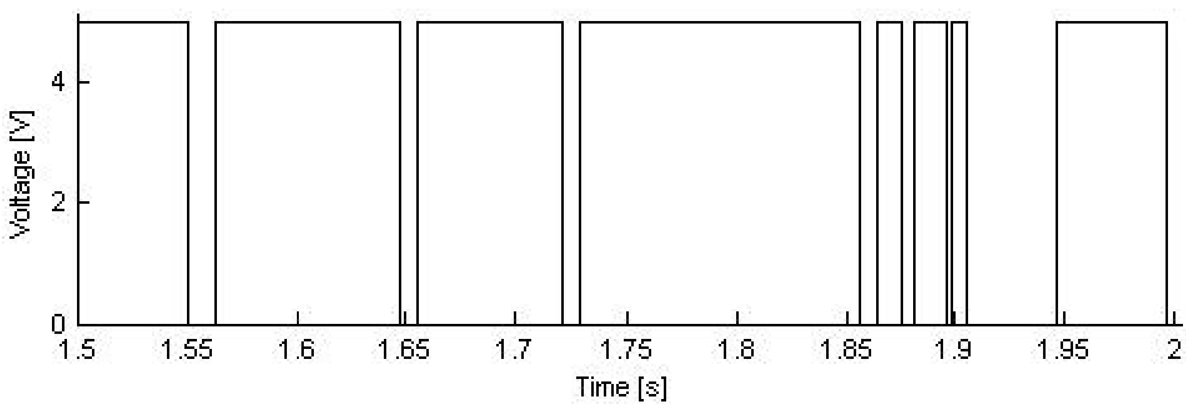

Fig. 11. Part of voltage control signal of Sky-Hook regulator

Fuzzy Sky-Hook allows passing through intermediate stages of signal. However, it requires more work to describe tables more complex of switching states.

7. Conclusions

In this paper there was presented a model of semi active system of operator's seat suspension working in conditions of low frequency extortion. In the modelling of kinematic extortions derived from rough roads, it also included their randomness.

Magnetorheological damper was developed based on literature model, and the model was included in model of operator's seat suspension.

The complexity of damper caused that initially only *Sky-Hook* method of controlling was performed, for which it was developed an appropriate algorithm of regulation in simulation program.

Then the algorithm based on *Fuzzy Sky-hook* method was performed.

In simulation studies, the effectiveness and stability of the shown solution were studied.

The results of studies were satisfactory for both regulation methods.

Effectiveness of semi active systems with magnetorheological dampers is significantly better than passive systems.

Effectiveness of semi active systems depends strongly on strategy of control. In future, there are predictions about studies over other, more complex strategies of control, providing even more improved reduction of vibrations.

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