Simulation model for the determination of energy losses during vibrations of the working equipment of a earth-moving machine in the transport mode

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Abstract. A simulation model for a earth-moving machine is developed using a motor grader as an example. The model comprises a chassis base frame, a front balancing bridge, rear balancing carts and working equipment – a traction frame with a moldboard. These elements are included in the form of separate moving elements. The simulation model allows the vibrations of the machine units to be explored while it moves along the microrelief of a reference surface, as well as the energy loss due to friction in the suspension elements of the working equipment to be determined. Using this simulation model, the amount of energy accumulated with the help of improved suspension devices for the working equipment of the motor grader can be assessed. This allows for the combination of the vibration damping of the working equipment in the transport mode and the oscillation energy accumulation. The effect of the stiffness and viscous friction coefficients of the hydraulic cylinders for raising and lowering the moldboard with a device for dynamic vibration damping and the accumulation of their energy on the total amount of energy spent on dissipation in the hydraulic components of the working equipment suspension elements is established. The resulting graphical functional dependence allows the optimization of the parameters of the hydraulic, mechanical and electrical parts of the system of the vibration damping and energy storing device to be implemented.

Keywords: earth-moving machine, moldboard, motor grader, vibrations, energy, dissipation.

1. Introduction

Earth-moving machines (EM), including motor graders widely used in road construction, remain a significant part of time in the transport mode. During EM movement over the microrelief irregularities of the reference surface, the kinematic excitation from the irregularities causes the fluctuations of both the chassis base frame and other moving elements of the EM, and the moldboard, which is the main EM working equipment [1, 2, 3, 4].

Oscillations and vibrations act as an unfavorable production factor for EM. Their impact adversely affects EM elements, causing their wear, increasing the probability of destruction, and reducing the time of their operation. Vibration affects the EM operator as well. There are quite a large number of methods and constructions to reduce vibration. Vibration protection solutions are widely used in construction and road machines, in particular, for motor graders [5, 6, 7], bridge and gantry cranes [8, 9, 10], sweepers [11, 12], etc.

Similar vibration protection systems are used in many other sectors of the economy, in particular, in agriculture [13], woodworking [14], transport and technological machines [15], metal working [16], railway transport [17], etc.
As a result of the application of known solutions, the energy of vibrations, as a rule, is converted into thermal energy. The latter is dispersed into the environment. A disadvantage of the known vibration damping systems is the lack of beneficial use of the released thermal energy. In order to eliminate this drawback, the authors have developed several constructions of hydro-electro-mechanical devices, accumulating the vibration energy simultaneously with the dynamic vibration damping [18, 19, 20]. It is advisable to assess the amount of energy that passes into thermal form when damping vibrations of the working equipment of the motor grader in the transport mode. This will allow the prospects for further use of the proposed structural solutions to be evaluated, such as simultaneous energy accumulation and dynamic vibration damping.

2. The description of the simulation model for determining energy losses in the working equipment suspension

In order to determine the amount of energy that dissipates when damping oscillations of the working equipment, a simulation mathematical model of a motor grader was developed using MATLAB Simscape Multibody system [21, 22, 23]. The calculated scheme of the mechanical part of the mathematical model is presented in figure 1.

![Figure 1. Calculated motor grader scheme](image)

The mechanical subsystem of the motor grader includes 5 elements. These are chassis base frame (ridge beam with cab and sub-frame) with \( m_1 \) mass, front balancing bridge with \( m_2 \) mass, the left balance beam of rear balancing cart with \( m_3 \) mass, the right balance beam of rear balancing cart with \( m_4 \) mass, and the working equipment (traction frame with moldboard) with \( m_5 \) mass. During the development of a mathematical model of the motor grader, the following assumptions were taken into account [3, 25]:
- the motor grader is a hinged articulated multi-unit;
- the links imposed on the dynamic system of the motor grader are holonomic and stationary;
- elements of metal structures are described as absolutely rigid rods;
- the mass-inertial properties of the elements of metal structures of the motor grader are characterized by masses, coordinates of the mass centers, moments of inertia and centrifugal moments of inertia;
- there are no backlashes in the articulations;
- there are no dry friction forces in the hydraulic cylinders and pneumatic tires of the motor grader.

![Connection diagram of the modeling elements within a simulation model of the motor grader]

The motor grader mechanism has 9 degrees of freedom. The corresponding generalized $q_1, \ldots, q_9$ coordinates of the mechanical system of the grader are given in table 1.

**Figure 2.** The connection diagram of the modeling elements within a simulation model of the motor grader
The mechanical system of the motor grader is considered in the fixed $O_0X_0Y_0Z_0$ coordinate system. The units of the left and right balance beam, as well as the unit of the front balance bridge, are connected by Voigt elements [24] with a fixed frame (figure 2). Each Voigt element № 1 ... 6, in this case, models the elastic and damping properties of a separate pneumatic wheel of a motor grader. In addition, the unit of the main frame is connected by the three Voigt elements № 7 ... 9 with the unit of the working equipment. In the latter case, two Voigt elements № 8 and № 9 model the elastic-viscous properties of two hydraulic cylinders for raising and lowering the moldboard in conjunction with the elastic-viscous properties of the vibration damping and energy storage device, brought to the hydraulic cylinder rods. The Voigt elements № 7, 8, for which the developed model allows the energy loss to be estimated, are highlighted in figure 2 by thick lines. The elastic and viscous properties in all Voigt elements are specified using two linearized coefficients. These are the $c_i$ stiffness and $b_i$ viscous friction coefficients, respectively.

From the side of the supporting elements (pneumatic wheels), the forces of the normal reactions $R_1...R_6$ act on the units of the two balance beams and the front balancing bridge. They are directed vertically along the $O_0Z_0$ axis. Their magnitude is determined by the vertical coordinates of the microrelief along the $z_l(t)$ left and $z_r(t)$ right tracks, respectively. The values of the vertical coordinates of the microrelief are fed to the № 3 and № 4 supporting elements with the $\tau_1$ and $\tau_2$ time delay, respectively, relative to the supporting element № 1, as well as for № 3 and № 4 supports with respect to № 2 support.

The simulation model designed according to the calculated scheme (see figure 2), in the MATLAB / Simulink / Simscape Multibody notations, is shown in figure 3. It allows the fluctuations of the motor grader units to be explored during the simulation of the machine movement at a constant speed.

When creating the model, the following main blocks of the Simscape Multibody library were used (see figure 3):

- **Solver Configuration** is a block, in which the numerical parameters of the solver of the physical model of Simscape are set. In particular, the parameters for the initialization of the model at the initial moment of time, and during an abrupt change in the values of physical parameters.

- **Mechanism Configuration** is a block of setting parameters that apply to the motor grader mechanism. These are the components of the gravitational vector and the values of the perturbation for calculating the partial derivatives when the model is linearized.

- **World Frame** – fixed ($O_0X_0Y_0Z_0$) coordinate system

- **Solid** – a block describing the properties of an individual mobile unit of the motor grader. In the parameter settings window of this block, the following are specified: body mass, moments of inertia, graphic information for the animation of movements. The moments of inertia can be set manually or calculated automatically, according to the geometry of the body, specified by the file of the three-dimensional model.
Rigid Transform – a block of shifts and turns. It sets constant linear displacements and angular turns of the subsequent local coordinate system relative to the previous local coordinate system.

Figure 3. The simulation model of a motor grader within the MATLAB / Simulink / Simscape Multibody system, simulating the unit oscillations when moving over the irregularities of the microrelief (a) with a window for visualizing the machine movements (b)

Revolute Joint – rotary joint unit with one degree of freedom. The internal mechanism is built within each similar hinge. It models the moment of viscous friction and the moment of elasticity with regard to a given angle of equilibrium. Revolute Joint, like any other Simscape Multibody hinge, provides the ability to apply additional torque as well. The latter can be set arbitrarily using an external input. Universal Joint is a hinge block with two rotational degrees of freedom. For each degree of freedom an internal mechanism can be used. An external moment of force is also can be connected. Elastic-viscous power elements (Voigt elements) in the simulation model of a motor grader are described using separate subsystems (figure 4).
In the Voigt element subsystem of the pneumatic wheel (see figure 4, a), the External Force and Torque block was used. Using this block, an external force (normal reaction $R_i$, $i \in [1; 6]$) is applied to the corresponding point of each unit of the two balance beams and the front balancing bridge. The values of normal reactions were calculated by the formula $R_i = -c_i l_i - b_i l_i$, where $l_i = z_{vi} - z_{li}$ are small deviations of Voigt element lengths relative to their own equilibrium positions; $z_{vi}$ – the value of the vertical coordinate of the attachment point of the Voigt element in the unit of one of the two balance beams or the front balancing bridge; $z_{li}$ is the value of the vertical coordinate of the microrelief under the corresponding supporting element (for example, on the left track). Dots hereinafter denote the derivatives of parameters with respect to time.

In the subsystem of the Voigt element of the hydraulic cylinder, lifting the moldboard (see figure 4, b), the Internal Force block was used. Unlike the External Force and Torque block, the Internal Force block acts simultaneously on two points, belonging to the unit of the subsequent local coordinate system and the unit of the previous local coordinate system. The force was calculated similarly to the External Force and Torque block. The Voigt element № 9 was immovable. The $q_9$ generalized coordinate was immovable as well.

The calculation of the microrelief profile height was carried out in a separate program. The latter was represented in the form of a MATLAB program code, launched prior to the launch of the simulation model. In this program code, the values of all constant parameters of the simulation model were set as well.

The calculation of the $(z_1, z_2)$ microrelief profile height along the left and right tracks was carried out using the following sequence of formulas [1, 2, 3, 4]:

$$ h = v \cdot dt \cdot \gamma \cdot h; \quad \gamma_0 = \beta \cdot h; \quad \gamma = e^{-h}; \quad c_0 = \rho (\rho^2 - 1) \cos \gamma_0; \quad c_1 = 1 - \rho^4; \quad q_1 = 2 \cdot \rho \cdot \cos (\gamma_0); \quad q_2 = -\rho^2; \quad c = \sqrt{c_1^2 + 4 - c_0^2}; \quad a = \sigma_x \cdot c_0; \quad Q = \sigma_y \cdot c; \quad z_{1,2} (n) = Q \cdot x(n) + a \cdot x(n-1) + q_1 \cdot z(n-1) + q_2 \cdot z(n-2), $$

Figure 4. The subsystems of Voigt elements for pneumatic wheels (a) and for hydraulic cylinders lifting the moldboard (b)
where \( v \) is the speed of the motor grader, \( m/s \); \( dt_{op} \) — time step between two adjacent profile reference points, \( s \); \( h \) — profile step, \( m \); \( \alpha_x, \beta_i \) — constant coefficients depending on the type of profile; \( x(n) \) is a sequence of normally distributed random numbers with the following parameters: expected value \( m=0 \), standard deviation \( \sigma=1 \); \( n \) is the sequence number of the current profile point; \( \sigma_k \) is the standard deviation of the points of the formed profile, \( m \).

To transfer the vertical coordinates of the microrelief profile to the model, \textit{From Workspace} blocks were used. They are designed to transfer data from the MATLAB workspace to the Simulink model. In the parameters of this block, the step of sampling the downloaded data over the time was used. It was denoted as \( dt \) and took values significantly smaller than \( dt_{op} \). In the MATLAB program code, the values of the microrelief profile heights at intermediate points (with a small time step \( dt \)) were also calculated. For this, a cubic spline interpolation method was used [26]. It was implemented using the built-in \textit{spline} function of the MATLAB programming language.

The time sequence of the values of the energy loss due to friction in the suspension elements of the working equipment was saved from the model to the working area of the MATLAB memory, using \textit{To Workspace} block. The amount of energy loss \( E \) consumed to overcome friction was determined in the model using the \textit{Integrator} numerical integration block. A temporary sequence of the rate of energy loss \( E(t) \) was fed at its input. The latter was determined using the dependence of the doubled dissipative Rayleigh function \( F \) [27]. Under the equality condition of the above coefficients of dissipation of moldboard hydraulic cylinders with a device for oscillation damping and energy storage \( b_7=b_8 \), the expression for the rate of energy loss is:

\[
E(t) = 2 \cdot F_1 + 2 \cdot F_2 = 2 \cdot \left( \frac{1}{2} \cdot \dot{i}_1 \cdot b_1 + \frac{1}{2} \cdot \dot{i}_2 \cdot b_2 \right) = (\dot{i}_1 + \dot{i}_2) \cdot b_3,
\]

where \( \dot{i}_i \) (\( i=7;8 \)) are the small deviations of the lengths of Voigt elements of hydraulic cylinders relative to their own equilibrium positions, \( m \).

### 3. Experimental results

In figure 5, the graphical dependences obtained using the developed simulation model are given as an example. In figure 5, \( a \), the random dependences of the vertical coordinates of the microrelief along the left and right tracks \( z_l(t) \) and \( z_r(t) \) versus time are shown under the supports \( \#1 \) and \( \#2 \) of front balancing bridge of the motor grader, respectively. Figure 5, \( b \) shows the dependence of the deviations of the length of Voigt elements of two hydraulic cylinders of the moldboard versus time, regarding its own equilibrium positions. In figure 5, \( c \) and \( d \), the dependences of the rate of change of \( E(t) \) energy consumed to overcome the friction forces in the suspension elements of the working equipment, and the \( E(t) \) energy are given, respectively.

The dependencies, shown as an example in figure 5 \( a-d \), are obtained for the following values of the constant parameters of the dynamic system: \( v=5 \) \text{ m/s} \text{ (18 km/h);} \( \sigma_v = 0.054 \) \text{ m;} \( \alpha_s = 0.5; \beta_i = 0; dt = 0.1; \)

\( c_7 = c_8 = 10000 \) \text{ N/m; } \( b_7 = b_8 = 10000 \) \text{ N/(m/s).} \) Other constant parameters of the dynamic system corresponded to the design of the heavy motor grader of the DZ98 model.

Simulation time was 110 \text{ s.} The first 10 \text{ s} did not affect at the chassis components (pneumatic tires) from the change of microrelief. During this period, the damping of the initial oscillations of the system occurred. Accounting for the energy consumed to overcome the friction forces in the suspension elements of the working equipment, was carried out starting from 10 \text{ s} of the dynamic process. Thus, the time for accounting the energy spent on overcoming the friction forces, in the computational experiment under consideration was a constant value of 100 \text{ s.}

The functional dependences of the \( E \) amount of energy consumed to overcome the friction forces in the suspension elements of the working equipment, on the values of the reduced \( c_7 = c_8 \) stiffness and \( b_7 = b_8 \) viscous friction coefficients, are presented in figure 5, \( e \) and \( f \).

The latter dependences are obtained by varying the coefficients of stiffness and viscous friction within:

\[ c_7 \in [1000; 40000] \text{ N/m; } b_7 \in [1000; 20000] \text{ N/(m/s)} \text{ (see figure 5, } e \text{) and } c_7 \in [5000; 20000] \text{ N/m; } b_7 \in [500; 5000] \text{ N/(m/s)} \text{ (see figure 5, } f \text{).} \) All other parameters, except \( c_7 = c_8 \) and \( b_7 = b_8 \), while \( c_7 \) and \( b_7 \) varying, took the fixed values given above.
Figure 5. The results of computational experiment using a motor grader simulation model (the examples of dependencies): a) the microrelief height coordinates versus time; b) changes in the lengths of the hydraulic cylinders of the moldboard versus time; c) the change rate of energy spent on overcoming friction forces versus time; d) energy spent on overcoming friction forces versus time; e), f) energy versus the stiffness and viscous friction coefficients

4. Discussion
The resulting functional dependence of the energy consumed to overcome friction in the suspension elements of the working equipment, on the values of the reduced stiffness and viscous friction coefficients (see figure 5, e, f) has a global maximum. The value of the function at the maximum point is 1090 J. It is 92 times higher than the minimum value in the considered variation range of the arguments - 11.85 J. The values of the arguments at the maximum point of the function are $c_7=10200$ N/m, $b_7=5000$ N/(m/s). At the minimum point of the function, the arguments are $c_7=40000$ N/m, $b_7=5000$ N/(m/s).

5. Conclusions
1. A calculation scheme for a motor grader with supporting elements described in the form of Voigt elements has been developed. The scheme includes a moldboard – a unit of the main working equipment of the motor grader. The suspension of the working equipment is also described as Voigt elements.
2. A mathematical simulation model for the complex dynamic system of a motor grader moving over the irregularities of the reference surface microrelief has been developed taking into account the vibrations of the components of the earth-moving machine with the working equipment. The developed calculation scheme allows a simulation mathematical model of the motor grader to be created with the possibility of determination of energy losses on friction in the suspension elements of the working equipment — the Voigt elements, describing the hydraulic cylinders lifting the average moldboard of the motor grader, which are connected with the device of damping moldboard vibrations the and simultaneous accumulation of energy.

3. A computational mathematical study of the movement of a motor grader over the irregularities of the reference surface microrelief has been carried out. It is established that during the motor grader moving time of 100 s at a speed of 18 km/h, across the surface with the standard deviation of the profile microrelief $\sigma = 0.054$ m (average soil surface), the energy from 11.85 to 1090 J is spent on the friction in the suspension elements of the working equipment. Depending on the values of the reduced stiffness and viscous friction coefficients of Voigt elements of the working equipment suspension, global energy maximum (1090 J) is achieved with the minimum value of viscous friction (500 N/(m/s) in the experiment) and stiffness (10200 N/m) coefficients.

4. The created complex Simulink-model of a motor grader allows the transport modes to be studied at the stage of designing such machines. The model allows the amount of friction energy losses in the suspension elements of the working equipment to be evaluated and, thus, the upper estimation of the energy level to be defined, which can be accumulated by means of improved suspension devices of the working equipment of the motor grader. If the values of stiffness and viscous friction coefficients of the Voigt elements of the working equipment suspension are optimized, the amount of the specified energy can exceed 1000 J for 100 s. This results in a conclusion about the expediency and prospect use of the devices of dynamic vibration damping of the moldboard with simultaneous accumulation of energy.

References

[1] Malakhov I and Sukovin M 2016 Mathematical model of the system «microrelief – working equipment» *Online Journal of Science* vol 8 2 116
[2] Malakhov I 2008 The system of automated modeling of a complex dynamic system «microrelief – base machine – cabin – human operator» *Bulletin of the Siberian State Automobile and Highway Academy* 10 80–85
[3] Shabalin A 2013 Model of the interaction of a crawler engine with the ground for modeling road and construction machines in MATLAB SimMechanics *Mechanization of construction* 9 36–38
[4] Chakurin I and Korchagin P 2007 Mathematical representation of the microrelief of the soil surface *Proceedings of higher educational institutions. Building* 10 62–67
[5] Chakurin I and Korchagin P 2007 Vibration protection equipment *Construction and road machines* 5 51–53
[6] Aleshkov D, Stolyarov V and Sukovin M 2015 Reducing the equivalent level of vibration by improving the structures of the elements of vibration protection of road construction machines *Online Journal of Science* vol 7 5 114
[7] Aleshkov D, Stolyarov V and Sukovin M 2015 Methods to reduce the harmful effects of industrial vibration on the human body - the operator of road construction machines *Online Journal of Science* vol 7 5 115
[8] Akira I and Yoshiyuki N 2016 Fast trajectory planning by design of initial trajectory in overhead traveling crane with considering obstacle avoidance and load vibration suppression *Journal of Physics: Conference Series* vol 744 1 012070
[9] Bondarenko V and Chukarin A 2017 Reducing noise and vibration of high-capacity overhead crane gearboxes *Bulletin of the Rybinsk State Aviation Technological Academy* 2 308–314
[10] Kobzev K 2016 Substantiation of vibration reduction system parameters at workplaces of gantry crane operators *Online Journal of Science* vol 8 5 73
Korchagin P and Teterina I 2017 *Improving the efficiency of the vibroprotection system of the road sweeper: monograph* (Omsk: SibADI) p 137

Korchagin P, Teterina I and Rahuba L 2018 Improvement of human operator vibroprotection system in the utility machine *Journal of Physics: Conference Series* vol 944 1 012059

Kornev A and Orobinsky V 2016 Technical solutions for reducing vibrations arising during the operation of sieve cleaning machines *Bulletin of the Voronezh State Agrarian University* 4 100–105

Buglaev A, Bokacheva M and Sivakov V 2017 Study of the possibility of reducing the vibration of woodworking equipment *Proceedings of higher educational institutions. Forest Journal* 3 132–142

Ustinov Y, Muravev V, Kravchenko A, Koltakov A, Drozd A and Naumkin A 2017 Vibration isolators to reduce vibration in transport and technological machines *Scientific Bulletin of the Voronezh State University of Architecture and Civil Engineering. Series: High Technologies. Ecology* 1 32–37

Međunetsky V, Niteysky and Raschupkin A 2018 Introduction of a damping system to reduce the vibration of the milling setup *Omsk Scientific Bulletin* 1 5–9

Yaitskov I 2018 Reducing the impact of vibrations on employees of locomotive crews in the process of braking and controlling the speed of movement in the design and modernization of diesel locomotives and locomotives *Bulletin of the Rostov State University of Communications* 1 27–31

Scherbakov V, Korchagin P and Ots D 2014 Device for damping oscillations of the working equipment of a motor grader *Patent 145798 of the Russian Federation* buл 27 p 2

Scherbakov V, Korchagin P and Ots D 2014 Device for reducing oscillations of the working body of the grader *Patent 147965 of the Russian Federation* bul 32 p 2

Scherbakov V, Korchagin P and Ots D 2015 The device for damping oscillations of the working body of the motor grader in the transport mode *Patent 154404 of the Russian Federation* buл 23 p 2

Komarov E D and Ruppel A A 2013 Mathematical modeling of complex technical systems using Simulink *Automation and Software Engineering* 2(4) 71–81

Vedel P M 2018 Study of the hydraulic system model in Matlab Simscape *Automation and Software Engineering* 1(23) 61–70

Korytov M, Scherbakov V and Titenko V 2018 Comparative analysis of methods of cargo vibration damping moved by overhead crane *Journal of Physics: Conference Series* vol 1050 1 012038

Rossikhin Y and Shitikova M 2018 The fractional derivative Kelvin–Voigt model of viscoelasticity with and without volumetric relaxation *Journal of Physics: Conference Series* vol 991 1 012069

Monakhov V A and Gavrilov P K 2018 Analysis of methods for calculating rod systems represented by mechanical models of finite elements *Modeling and mechanics of structures* 7 7

Kalitkin N 2011 Numerical methods (Saint Petersburg : BHV-Petersburg) p 592

Minguzzi E 2014 Rayleigh's dissipation function at work *European Journal of Physics* vol 36 3 035014