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DEVELOPING A MATHEMATICAL SUBSTANTIATION FOR THE PHYSICAL MODELLING OF THE SOIL-RIPPING EQUIPMENT WORK PROCESS

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Визначені та описані реакції ґрунту при його руйнуванні призводять до некерованого переміщення робочого органа з низькочастотними та високочастотними коливаннями, що діють на навіску зменшуючи надійність робочого обладнання. Сформульовано умови мінімізації динамічних навантажень базової машини за рахунок створення керуючого сигналу на навіску розпушувача. Статистичний аналіз рельєфу місцевості дозволив зменшити динамічні навантаження

Ключові слова: розрахунок розпушувача, рельєф ґрунту, модель роботи розпушувача, робочий орган розпушувача

Определенные и описанные реакции грунта при его разрушении приводят к неуправляемому перемещению рабочего органа с низкочастотными и высокочастотными колебаниями, действующими на навески, уменьшая надежность рабочего оборудования. Сформулированы условия минимизации динамических нагрузок базовой машины за счет создания управляющего сигнала на навеску разрыхлителя. Статистический анализ рельефа местности позволил уменьшить динамические нагрузки

Ключевые слова: расчет рыхлителя, рельеф грунта, модель работы рыхлителя, рабочий орган рыхлителя

1. Introduction

Intensive exploration of mineral deposits, transportation and construction of oil and gas pipelines is impossible without modern earth moving machinery, capable of developing strong, frozen and rocky soils.

Taking into consideration that frozen and hard soils have elevated strength, exploration by the earth moving machines is impossible without a pre-treatment aimed at reducing soil resistance to its further development [1].

Different methods haven been employed for the excavation of frozen and rocky soils [2, 3], the main of which are the drilling and blasting operations and loosening the soil by tractor mounted rippers.

It is an important problem to improve control systems of ripping aggregates in order to partially or completely replace human-operator from the control circuits over internal combustion engines and the position of the working body.

2. Literature review and problem statement

The most effective way to destroy frozen and hard soils in terms of machine performance and the cost of soil development is the horizontal layer-wise loosening by the mounted rippers based on powerful tractors [1].

In paper [2], authors analyze existing designs of ripping units and principles of their implementation, but fail to outline development trends for rippers with respect to mathematical substantiation.

During horizontal loosening, a soil chip is torn off the massif is in the direction of the open surface, which is the least energy intensive. In this case, the efforts of stretching (tearing) dominate, which are several times smaller than the efforts of compression or shear [4].

Loosening the soil, in comparison with carrying out earthwork by a drilling and blasting method, ensures lower costs, improves the quality of work and are less hazardous to the environment [5].

The efficiency of the ripping unit largely depends on the rational modes of operation of a power unit. Control systems that are commercially available now, indicating instruments, as well as the slow reaction of the human operator to the conditions of work process that change fast, make it impossible to utilize the traction-coupling properties of the machine in full [6].

In the process of work of the ripping unit, its running hardware interacts with the soil, which causes uncontrolled displacement of the working body in space. This leads to a change in the depth of loosening and, consequently, to a change in the soil reaction on the working body. [7].

Papers [8, 9] analyzed factors and presented mathematical equations to determine a position of the working body of the ripper. Article [8] did not construct a mathematical model of interaction between the engine and the soil. In paper [9], authors did not examine the impact of soil reaction when it is destroyed on the uncontrolled displacement of the working body.

Thus, based on an analysis of the scientific literature, it was revealed that a scientific problem on stabilizing the motion of mounted equipment of the ripping unit has not been stated up to now. Given large dynamic loads on the base machine, it is necessary to improve the reliability of mounted equipment by controlling the uncontrolled displacement of the working body.

3. The aim and objectives of the study

The aim of present study is to improve efficiency of the ripping unit by reducing dynamic loads through the formation of a controlling signal to the mounted equipment of a ripping unit.

To accomplish the set aim, the following tasks must be solved:

– to develop physical models and formulate criteria of similarity for the mathematical and physical modelling of the controlling signal to the mounted equipment of a ripper taking into consideration actual relief of terrain;

– to construct a mathematical model of soil relief during interaction between a ripper engine and the surface of soil;

– to construct a mathematical model of the influence of soil reaction at its destruction on the uncontrolled displacement of the working body;

– to compare experimental and modelled micro reliefs and random processes and to prove adequacy of the proposed mathematical models.

4. Development of basic approaches and mathematical substantiation for physical modelling of the working process of ripping equipment

A mathematical model of the soil surface may be represented by deterministic or stochastic (random) functions [8, 9].

Soil surface irregularities are a mathematical notation in the form of deterministic functional dependences of the vertical coordinate of soil surface $z_p(t)$ on time [8]. These dependences are used mainly in research aimed at increasing the level of soil development and when determining boundary values for parameters. They can be represented in the form [9, 10]:

– harmonic signal

$$z_p(t) = A \cdot \sin(\omega \cdot t + \psi);$$

– pulse

$$z_p(t) = \frac{dl_0(t)}{dt};$$

– stepwise action

$$z_p(t) = \begin{cases} 0 & \text{at } t \le 0; \\ \pm h & \text{at } t = 0. \end{cases}$$

Application of the stochastic models of soil relief makes it possible to solve the tasks on the interaction between an engine and soil during motion of the base machine along a supporting surface taking into consideration actual soil relief [9–11].

Uneven terrain relief can be divided into macro relief, micro relief, and roughness. The macro relief includes irregularities of considerable length (over 100 m) and relative height, which practically do not cause oscillations of the machine and uncontrolled displacement of the working body [8]. Roughness is characterized by irregularities with length less than 0.5 m, which are compensated for by the levelling capability of the elements of running equipment [8, 9].

Micro relief irregularities are one of the main reasons that cause uncontrolled displacement of the frame of machine and the working body [9]. In line with the purpose of present work, of the greatest interest is the action of micro relief on the elements of running equipment of the ripping unit.

Mathematical notation of the micro relief has been addressed in many studies whose authors conducted statistical analyses of different soil surfaces [8].

In papers [8–10], the surface of soil is considered to be a stationary and ergodic random function of two variables:

$$y = y(x,z), \tag{1}$$

where x, z are, respectively, longitudinal and transverse coordinates of a certain average plane, relative to which the heights of irregularities change.

In this case, sufficient statistical characteristics of the soil micro relief is its correlation function $R(l)$, or a normalized correlation function $r(l)$ and spectral density $S(\omega)$.

Correlation function $R(l)$ gives an idea about a change in the micro relief along the length of section l, spectral density $S(\omega)$ about frequency of repeated lengths of irregularities. The argument of the spectral density is the road frequency:

$$\omega = \frac{\pi \cdot v_{tr}}{L_y}, \tag{2}$$

where v_{tr} is the motion speed of machine; L_y is the length of a micro relief irregularity.

Two-dimensional correlation function of the surface, which is described by equation (1), takes the form [8, 9]:

$$R(l_1,l_2) = = \lim_{\substack{x\to\infty \\ y\to\infty}} \frac{1}{4xz} \int_{-x}^{x}\int_{-z}^{z} y(x,z)\cdot y(x+l_1,z+l_2)\mathrm{d}x\mathrm{d}z. \tag{3}$$

Two-dimensional correlation function $R(l_1, l_2)$ is replaced with two non-correlated functions: a function of the middle cross-section of longitudinal profile $y(l)$, and a function of the inclination angle of cross-section $\gamma_p(l)$ of the surface [8, 9]:

$$y(l) = 0.5\cdot(y_p(l) + y_l(l)); \tag{4}$$

$$\gamma_p(l) = \frac{(y_p(l) - y_l(l))}{L_k}, \tag{5}$$

where $\gamma_p(l)$ and $y_l(l)$ are the functions of micro relief of cross-sections of soil surface according to the left and right track; L_k is the track width.

Statistical characteristics of the micro relief are described by two correlation functions:

$$R_y(l) = \lim_{x\to\infty} \frac{1}{2x}\int_{-x}^{x} y(x)\cdot y(x+l)\mathrm{d}x; \tag{6}$$

$$R_\gamma(l) = \lim_{x\to\infty} \frac{1}{2x}\int_{-x}^{x} \gamma(x)\cdot \gamma(x+l)\mathrm{d}x. \tag{7}$$

A normalized correlation function takes the form:

$$r(l) = R(l)/R(0); \tag{8}$$

$$R(0) = D = \sigma^2, \tag{9}$$

where D is the variance; σ is the root-mean-square deviation.

Spectral composition of the random function is characterized by spectral density $S(\omega)$, which can be determined from the correlation function by applying the Fourier transform [8, 9]:

$$S(\omega) = \int_{-\infty}^{\infty} R(l)\cdot e^{-j\omega l}\mathrm{d}l. \tag{10}$$

In a general case, existing models of the micro relief can be represented in the form:

$$r(l) = \sum_{i=1}^{n} A_i e^{-\alpha_i |l|}\cdot \cos\beta_i l, \tag{11}$$

where

$$\sum_{i=1}^{n} A_i = 1,$$

α_i are parameters that characterize correlation attenuation; β_i are parameters that characterize correlation periodicity.

To implement a random micro relief, a computer usually employs a special algorithm [8]. This algorithm is based on converting a stationary sequence of x_i independent normally distributed random numbers (discrete white noise) into sequence y_n. A recurrent equation of the following form is used for this purpose [12, 13]:

$$y_i = a_0x_i + a_1x_{i-1} + \ldots + a_lx_{i-l} - b_1y_{i-1} - b_2y_{i-2} - \ldots - b_my_{i-m} = = \sum_{K=0}^{l} a_K x_{i-K} - \sum_{K=1}^{m} b_K y_{i-K}, \tag{12}$$

where xi is the implementation of independent normally distributed numbers with parameters m_x=0 and σ_x=1.

In this case, the form of a recurrent equation is defined by the from of correlation function [14].

Equation (12) describes the behavior of some discrete filter that would convert white discrete noise that is sent to its input into a stochastic process with assigned correlation characteristic. Transfer function of this filter takes the form [12, 14]:

$$y(z) = \frac{a_0 + a_1z + \ldots + a_lz^l}{1 + b_1z + \ldots + b_mz^m} = \frac{\sum_{k=0}^{l} a_k z^k}{1 + \sum_{k=1}^{m} b_k z^k}. \tag{13}$$

Based on transfer function (13), it is possible to map a principal circuit of the discrete filter (Fig. 1), which is described by recurrent equation (12) [12, 14].

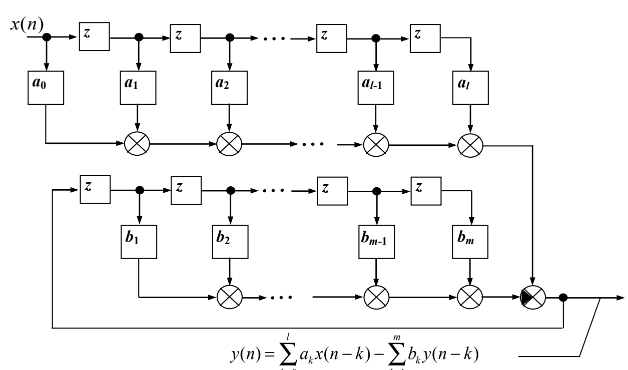

Fig. 1. Principal circuit of discrete filter

When constructing motion equations of the base tractor, we assume the following:

– a base tractor moves rectilinearly;

– joints of conditional shafts do not deform (energy loss for the deformation is insignificant);

– connection between the mounted equipment and the frame is absolutely rigid.

Uniform rectilinear motion of the base tractor, expressed in momenta, reduced to the conditional shaft of the tractor:

$$M_v = M_f + M_{ro}, \tag{14}$$

where M_v is the momentum on a conditional shaft of the tractor; M_f is the momentum of rolling resistance of the tractor; M_{ro} is the momentum of resistance created by the working body.

With respect to the uneven rectilinear motion due to the action of micro relief irregularities on the running equipment, this equation will take the following form:

$$M_v = (J_3 + J'_3)\frac{d\omega_2}{dt} + M_f + M_{ro} - M_\alpha, \tag{15}$$

where ω_2 is the angular velocity of a conditional shaft of the tractor; M_α is the momentum, reduced to the shaft of the tractor, which occurs due to the downhill motion of tractor (we consider a forward tilt of the tractor along the motion direction to be a positive angle); J_3 and J'_3 are the momenta of inertia of the tractor and the mounted equipment, respectively.

The tractor rolling resistance momentum, reduced to the shaft of the tractor:

$$M_f = \frac{r_k}{i_{tr}} P_f, \tag{16}$$

where P_f is the tangent rolling resistance force of the base tractor; i_{tr} is the transmission gear ratio; r_k is the radius of the drive wheel of the base tractor.

In rectilinear motion, force P_f depends on parameters of the engine, weight of the machine, actual motion speed and soil conditions. For a given tractor, at work on the given soil, with the given mounted equipment:

$$P_f = f(v_{tr}). \tag{17}$$

The equation that approximates dependence $P_f=f(v_{tr})$ for the tractor T-170 on the V category soil takes the form:

$$P_f = -0.05v_{tr}^2 + 1.15v_{tr} + 0.2. \tag{18}$$

Momentum of resistance that is created by the working body:

$$M_{ro} = \frac{r_k}{i_{tr}} P_{kr}, \tag{19}$$

where P_{kr} is the force of traction resistance.

A momentum arising due to the downhill motion of the tractor is derived from expression [15]:

$$M_\alpha = \frac{r_k}{i_{tr}} G_{ra}\sin\alpha, \tag{20}$$

where G_{ra} is the weight of the ripping unit; α is the inclination angle of the base tractor relative to the horizontal plane.

The actual motion speed of the base tractor is determined from expression [15]:

$$v_{tr} = \frac{r_k}{i_{tr}}(1-\delta)\omega_d, \tag{21}$$

where δ is the skid coefficient; ω_d is the angular velocity of a conditional engine shaft.

Dependence of skid coefficient on the traction resistance force, for a caterpillar ripper at work on the frozen soil, can be approximated by dependence:

$$\delta = a\left(\frac{P_{kr}}{P_{kr\ \max}}\right), \tag{22}$$

where a is the coefficient that depend on the type of engine and the surface of motion; $P_{kr\ \max}$ is the maximum force of traction resistance.

For the base tractor T-170, at work on the frozen loam without spurs, coefficient a can be taken equal to 0.06.

Thus, after substituting in equation (15) expressions (16), (18)–(20) and expression (22) in (21), we obtain a system of equations that describe uneven gradual motion of the base tractor:

$$\begin{cases} v_{tr} = \dfrac{r_k}{i_{tr}}\left(1 - \dfrac{aP_{kr}}{P_{kr\ \max}}\right)\omega_d; \\ M_v = (J_3 + J'_3)\dfrac{d\omega_2}{dt} + \left(\dfrac{r_k}{i_{tr}}\right)\times \\ \times\left[\left(-0.05v_{tr}^2 + 1.15v_{tr} + 0.2\right) + P_{kr} - G_{ra}\sin\alpha\right]. \end{cases}$$

The choice of an interaction model between running equipment of the ripping unit and soil is based on the following preconditions:

– determining linear and angular displacements of the ripping unit in a two-dimensional space;

– taking into consideration elastic-viscous properties of the suspension and the deformation of soil;

– taking into consideration the action of soil reaction force on displacement of the frame.

When constructing a model of interaction between the running equipment and soil, it is necessary to accept the following assumptions:

– elastic-viscous properties of soil are not accounted for due to their small magnitudes when working on frozen soils;

– effect of the mass of suspension elements on displacement of the frame are not considered;

– the profile of path under both caterpillars is the same;

– rolls are in constant contact with a caterpillar;

– frame of the tractor and elements of the mounted equipment are absolutely rigid;

– the angle of inclination of the line of loosening resistance action at the oscillations of the frame is constant;

– vertical load on the left and right caterpillars is the same.

In order to construct a model, we apply an estimation scheme, in which the caterpillar is divided into two semi-caterpillars, which interact with soil. They are joined together via the frame. Elastic-viscous properties of each semi-caterpillar are characterized by rigidity coefficients c_1, c_2 and damping coefficients p_1, p_2. Since we employ a flat estimation scheme, the coefficients of rigidity and damping are the sum of the rigidity and damping coefficients of the left and right caterpillar for each semi-caterpillar.

Micro relief is generated from correlation function [12]:

$$R_y(l) = \sigma^2 \cdot e^{-\alpha_1|l|}\cos\beta l, \quad (23)$$

where σ is the root-mean-square deviation, for the longitudinal profile σ=0.015...0.08 m, for the transverse profile σ=0.05...0.28 m; α_i are parameters that characterize correlation attenuation, for the longitudinal profile α==1.4...2.8 rad/s, for the transverse profile α=2.3...3.9 rad/s; β_i are parameters that characterize correlation periodicity, for the longitudinal profile β=1.0...1.5 rad/s, for the transverse profile β=1.2...3.6 rad/s; l is the length of the section.

For taking into consideration the levelling capability of caterpillars, we use an expression in the discrete form [9]:

$$y(n) = \frac{1}{M}\int_{m=n-k}^{n+k} y(m), \quad (24)$$

where k=0.5(M–1); M is the averaging interval; $y(m)$ are the ordinates of the non-levelled micro relief.

The micro relief, when levelled, is characterized by vertical coordinates under the front y_1 and the rear y_2 semi-caterpillars.

Coordinate origin is connected to the center of gravity of the ripping unit in its initial position. We consider an uphill direction to be an additional direction of the y axis, and the additional direction of angle φ is the forward tilt of the ripping unit.

Equilibrium conditions for the frame of a ripping unit based on the D'Alembert principle:

$$M\frac{d^2y}{dt^2} = \sum_{i=1}^{2} F_{ci} + \sum_{i=1}^{2} F_{pi} + F_v, \quad (25)$$

where M is the mass of the sprung part of the tractor; F_{ci} is the force that acts on the frame from the elastic element of the i-th semi-caterpillar; F_{pi} is the force that acts on the frame from the damping element of the i-th semi-caterpillars.

$$J_{ra}\frac{d^2\phi}{dt^2} = \sum_{i=1}^{2} M_{ci} + \sum_{i=1}^{2} M_{pi} + M_{Fro}, \quad (26)$$

where $J_{ra}=J_3+J_3'$ is the momentum of inertia of the tractor frame and working body relative to the transverse axis, which passes through the center of gravity; M_{ci} and M_{pi} are the momenta relative to the center of gravity from forces F_{ci} and F_{pi}; M_{Fro} is the momentum relative to the center of gravity from the force of soil reaction to the working body.

The forces acting on the frame from the elastic and damping elements:

$$F_{ci} = c_i \cdot y_i, \quad F_{pi} = p_i \cdot \frac{dy_i}{dt}, \quad (27)$$

where y_i is the vertical coordinate under the i-th semi-caterpillar:

$$y_i = y + \Delta y_i, \quad (28)$$

where Δy_i is a change in the vertical coordinate under the i-th semi-caterpillar.

With respect to expression (28):

$$\sum_{i=1}^{2} F_{ci} = c_1\cdot(y+\Delta y_1) + c_2\cdot(y+\Delta y_2), \quad (29)$$

$$\sum_{i=1}^{2} F_{pi} = p_1\cdot\frac{d(y+\Delta y_1)}{dt} + p_2\cdot\frac{d(y+\Delta y_2)}{dt}. \quad (30)$$

After substituting expressions (29) and (30) in equation (25) and following certain transforms, we obtain:

$$M\frac{d^2y}{dt^2} + (p_1+p_2)\frac{dy}{dt} + (c_1+c_2)y = \\ = p_1\frac{d\Delta y_1}{dt} + c_1\Delta y_1 + p_2\frac{d\Delta y_2}{dt} + c_2\Delta y_2 + F_v. \quad (31)$$

When converting differential equations into algebraic equations, equation (31) will be written in the form:

$$(T_{1y}p^2 + T_{2y}p + 1)y = \\ = (k_{1y}p + k_{2y})\Delta y_1 + (k_{3y}p + k_{4y})\Delta y_2 + k_{5y}F_v, \quad (32)$$

where T_{1y} and T_{2y} are the time constants; k_{1y}, k_{2y}, k_{3y}, k_{4y} and k_{5y} are the gain factors.

$$T_{1y} = \frac{M}{c_1+c_2}, \quad T_{2y} = \frac{p_1+p_2}{c_1+c_2}; \quad (33)$$

$$k_{1y} = \frac{p_1}{c_1+c_2}, \quad k_{2y} = \frac{c_1}{c_1+c_2}, \quad k_{3y} = \frac{p_2}{c_1+c_2},$$

$$k_{4y} = \frac{c_2}{c_1+c_2}, \quad k_{5y} = \frac{1}{c_1+c_2}. \quad (34)$$

Equation (32) shows that the vertical coordinate of the frame of a ripping unit is affected by changes in the vertical coordinates of micro relief under the left Δy_1 and the right Δy_2 semi-caterpillars, and vertical component of soil resistance on working body F_v. Applying the principle of superpositions, we obtain the following transfer functions:

$$W_y^{\Delta y_1} = \frac{y(p)}{\Delta y_1(p)} = \frac{k_{1y}p + k_{2y}}{T_{1y}p^2 + T_{2y}p + 1}, \quad (35)$$

$$W_y^{\Delta y_2} = \frac{y(p)}{\Delta y_2(p)} = \frac{k_{3y}p + k_{4y}}{T_{1y}p^2 + T_{2y}p + 1}, \quad (36)$$

$$W_y^{F_v} = \frac{y(p)}{F_в(p)} = \frac{k_{5y}}{T_{1y}p^2 + T_{2y}p + 1}. \quad (37)$$

Expressions (35)–(37) make it possible to represent a mathematical model of the vertical displacements of the frame due to a micro relief action in the form of a principal circuit shown in Fig. 2.

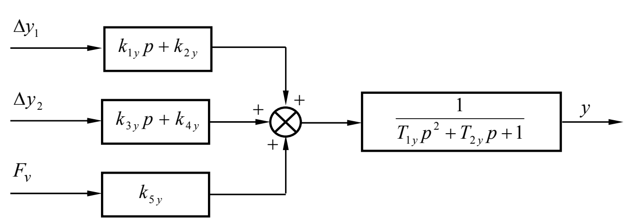

Fig. 2. Principal circuit of vertical displacements of the frame of ripping equipment

The momenta of forces acting on the frame from the elastic and damping elements:

$$M_{ci} = c_i \cdot y_i \cdot r_i, \quad M_{pi} = p_i \cdot \frac{dy_i}{dt} \cdot r_i, \tag{38}$$

where r_i is the distance from the center of gravity to the center of the i-th semi-caterpillar.

For rotational movements of the frame:

$$y_i = r_i \phi + \Delta y_i. \tag{39}$$

We shall obtain with respect to (39):

$$\sum_{i=1}^{2} M_{ci} = -c_1 \cdot (r_1 \cdot \phi + \Delta y_1) + c_2 \cdot (r_2 \cdot \phi + \Delta y_2), \tag{40}$$

$$\sum_{i=1}^{2} M_{pi} = -p_1 \cdot \frac{d(r_1 \cdot \phi + \Delta y_1)}{dt} + p_2 \cdot \frac{d(r_2 \cdot \phi + \Delta y_2)}{dt}. \tag{41}$$

After substituting expressions (40) and (41) in equation (26) and following certain transforms, we obtain the following equation:

$$\begin{aligned}
&(J_3 + J'_3)\frac{d^2\phi}{dt^2} + \\
&+(p_2 \cdot r_2^2 - p_1 \cdot r_1^2)\frac{d\phi}{dt} + (c_2 \cdot r_2^2 - c_1 \cdot r_1^2)\phi = \\
&= -(p_1 \cdot r_1 \cdot \frac{d\Delta y_1}{dt} + c_1 \cdot r_1 \cdot \Delta y_1) + \\
&+(p_2 \cdot r_2 \cdot \frac{d\Delta y_2}{dt} + c_2 \cdot r_2 \cdot \Delta y_2) + M_{Fro}.
\end{aligned} \tag{42}$$

When converting differential equations into algebraic equations, equation (42) will be written in the form:

$$\begin{aligned}
&(T_{1\phi} p^2 + T_{2\phi} p + 1)\phi = -(k_{1\phi} p + k_{2\phi})\Delta y_1 + \\
&+(k_{3\phi} p + k_{4\phi})\Delta y_2 + k_{5\phi} M_{Fro},
\end{aligned} \tag{43}$$

where $T_{1\varphi}$ and $T_{2\varphi}$ are the time constants; $k_{1\varphi}$, $k_{2\varphi}$, $k_{3\varphi}$, $k_{4\varphi}$ and $k_{5\varphi}$ are the gain factors.

$$T_{1\phi} = \frac{J_{\text{pa}}}{c_2 \cdot r_2^2 - c_1 \cdot r_1^2}, \quad T_{2\phi} = \frac{p_2 \cdot r_2^2 - p_1 \cdot r_1^2}{c_2 \cdot r_2^2 - c_1 \cdot r_1^2}; \tag{44}$$

$$k_{1\phi} = \frac{p_1 \cdot r_1}{c_2 \cdot r_2^2 - c_1 \cdot r_1^2}, \quad k_{2\phi} = \frac{c_1 \cdot r_1}{c_2 \cdot r_2^2 - c_1 \cdot r_1^2},$$

$$k_{3\phi} = \frac{p_2 \cdot r_2}{c_2 \cdot r_2^2 - c_1 \cdot r_1^2}, \quad k_{4\phi} = \frac{c_2 \cdot r_2}{c_2 \cdot r_2^2 - c_1 \cdot r_1^2},$$

$$k_{5\phi} = \frac{1}{c_2 \cdot r_2^2 - c_1 \cdot r_1^2}. \tag{45}$$

Equation (43) shows that angular oscillations of the frame of a ripping unit are affected by changes in the vertical coordinates of micro relief under the front Δy_1 and the right Δy_2 semi-caterpillars, and a momentum from soil reaction on working body M_{Fro}.

Applying the principle of superpositions, we obtain the following transfer functions:

$$W_{\phi}^{\Delta y_1} = \frac{\phi(p)}{\Delta y_1(p)} = \frac{k_{1\phi} p + k_{2\phi}}{T_{1\phi} p^2 + T_{2\phi} p + 1}, \tag{46}$$

$$W_{\phi}^{\Delta y_2} = \frac{\phi(p)}{\Delta y_2(p)} = \frac{k_{3\phi} p + k_{4\phi}}{T_{1\phi} p^2 + T_{2\phi} p + 1}, \tag{47}$$

$$W_{\phi}^{M_{Fro}} = \frac{\phi(p)}{M_{Fro}(p)} = \frac{k_{5\phi}}{T_{1\phi} p^2 + T_{2\phi} p + 1}. \tag{48}$$

Expressions (46)–(48) allow us to represent a mathematical model of angular oscillations of the frame from the action of micro relief in the form of a principal circuit, which is shown in Fig. 3.

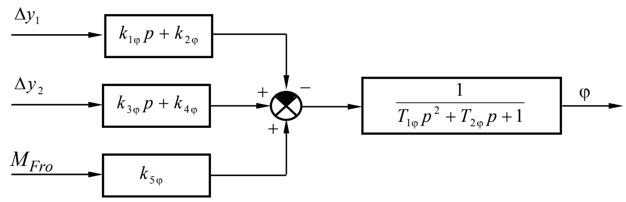

Fig. 3. Principal circuit of angular displacements of the frame of a ripping unit

In order to determine a change in the position of the working body depending on displacements of the frame of a ripping unit, it is possible to use a procedure from [10]. We shall represent changes in the position of the working body depending on displacements of the frame in the form of a dynamic link whose input is a change in the vertical coordinate of the center of gravity of frame Δy, and whose output is a change in the position of the working body Δy_{ro}. Transfer function of such a link is derived from ratio [10]:

$$W_{Yro}(p) = \frac{L[Y_{ro}(X)]}{L[Y(X)]}, \tag{49}$$

where L is a symbol of the Laplace transform.

In order to perform a Laplace transform, we accept $Y(X)$ in the form of a step function with a step height of h_{st} and we shall consider dependence $Y_{ro}(X)$ when a ripping unit overcomes such an obstacle. In doing so, we shall take into consideration that under practical conditions h_{st} is much less than a ripping unit's base L_b while a turning angle of the frame is very small.

Upon completing Laplace transforms (49), we obtain the following transfer function [10]:

$$W_{Yro}(p) = \frac{\Delta y_{ro}(p)}{\Delta y(p)} = k_{1ro} + \frac{k_{2ro}}{\text{p}}(1 - e^{-\tau_{ro} p}) - k_{3ro} e^{-\tau_{ro} p}, \tag{50}$$

where Δy_{ro} is a change in the vertical coordinate of the working body due to uncontrolled displacements of the frame; Δy is a change in the vertical coordinate of the center of gravity of the ripper due the action of micro relief on the running equipment; k_{1ro}, k_{2ro} and k_{3ro} are the gain factors; τ_{ro} is the time of delay.

$$k_{1\,ro} = \frac{L_b - x_{ro}}{L_b}, \quad k_{2\,ro} = \frac{L_b - x_{ro}}{L_b(L_b - L_{ts})}, \quad k_{3\,ro} = \frac{L_{ts} - x_{ro}}{L_b - L_{ts}}, \tag{51}$$

$$\tau_{ro} = \frac{L_{ts}}{v_{tr}}, \tag{52}$$

where L_b is the ripping unit's base; L_{ts} is the distance from the center of weight of the ripper to the point of overturning; $P(x_{ro}, y_{ro})$ are the coordinates of the point of applying the forces of resistance to loosening; v_{tr} is the motion speed of the base machine.

Transfer function (50) allows us to represent a mathematical model of change in the position of the ripper's working body depending on displacements of the frame in the form of a principal circuit shown in Fig. 4.

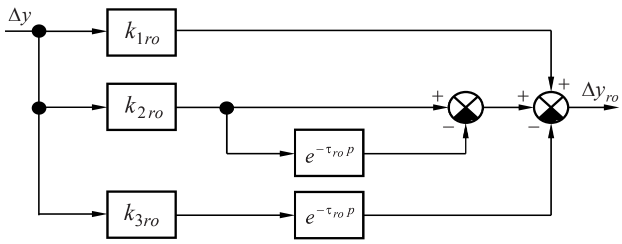

Fig. 4. Principal circuit of the model of change in the position of the working body depending on displacements of the frame

A general mathematical model of the action of micro relief on uncontrolled displacements of the working body can be represented in the form of a block diagram, which is shown in Fig. 5.

Block diagram (Fig. 5) is a mathematical model of the process of action of micro relief on uncontrolled displacements of the working body of a ripping unit, which cause a change in the depth of loosening and, therefore, a change in the momentum of resistance applied to the engine shaft. Micro relief is generated from correlation function (23), the levelling capability of caterpillars is taken into consideration in expression (24).

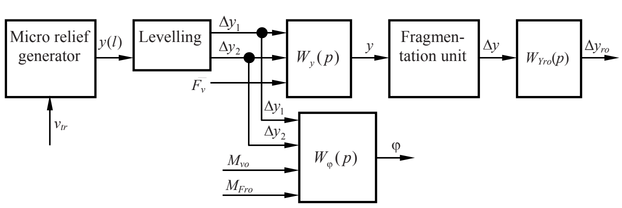

Fig. 5. Block diagram of a mathematical model for the action of micro relief on uncontrolled displacements of the working body

The obtained transfer functions of the vertical (35)–(37) and angular (46)–(48) displacements of the center of gravity of the frame allow us to take into consideration the elastic-viscous properties of suspension.

Transfer function (50) takes into consideration a change in the position of the ripper's working body when changing a position of the center of gravity of the frame.

5. Discussion of results of experimental study

To prove the adequacy of mathematical models of micro relief and working process of a ripping unit with actual operational processes, we conducted experimental study. The main task that requires a solution during experiment is to confirm the adequacy of a mathematical model.

The object of study is a ripping unit based on the tractor T-170 with the ripping equipment DZ-116V.10.000 (type DP-26S).

We chose the following parameters to be registered: angular speed of the crankshaft of the engine and motion speed of the base machine.

To measure angular velocity of the engine shaft, we used the digital tachometer CD 9902 in combination with the electromagnetic tachometric sensor of the type PD 2546 (Fig. 6).

Fig. 6. Digital tachometer CD 9902 with sensor PD 2546

Data from the digital tachometer were transferred to computer via an adapter to the COM port that comes as a bundle with the device.

The mathematical model must be adequate with the tested object or phenomenon. This is the most important condition for the legitimacy of findings obtained in the study based on a mathematical model. The model should reflect, with the required accuracy, characteristics of the examined process or object when changing its parameters and external impacts.

Adequacy is confirmed by comparing the results obtained by calculation based on the mathematical model with experimental data, the discrepancy between which, in order to solve the tasks set in the present study, must not exceed 10–18 %.

When estimating adequacy of the mathematical model of micro relief, it is expedient to choose a correlation function that describes the micro relief. Next, it is necessary to compare parameters σ (root-mean-square deviation), α (a parameter that characterizes correlation attenuation) and β (a parameter that characterizes correlation periodicity) of the correlation function of the obtained mathematical realization with corresponding parameters of the actual micro relief [16].

When conducting an experiment, it is necessary to level a 100-meter-long section with measurements taken every 0.5 meter.

Before estimating adequacy, we performed a statistical analysis on sample $y(l)$ – a random dependence of vertical coordinates of micro relief on horizontal coordinate (path), which allowed us to draw the following conclusions:

1) Mathematical expectation of the vertical coordinate of micro relief changes insignificantly, in the range from +0.003 to –0.003 meter, which makes it possible to accept the assumption on that a given process is centered [13, 17, 18].

2) Verification of a hypothesis on the normality of distribution law and the assessment of degree of consistency between statistical $F^*(y_i)$ and theoretical $F(y_i)$ were conducted using the Kolmogorov criterion $D=\max[F^*(y_i)-F(y_i)]$. It was established that the statistical distribution law (actual micro relief) is in good agreement with the theoretical normal, the values of probability $P(\lambda)=0.461...0.999>0.05$ (where 0.05 is the level of criterion significance [13, 17, 18]).

3) The homogeneity of a series of mutually independent variances $D^*_y(t_i)$, where i=1...200 was estimated by using the Bartlett criterion based on statistics M where the ratio M/C is distributed as the χ^2 Pearson criterion, where C is the coefficient dependent on the volume of the sample. The calculated magnitudes of χ^2 were compared with critical χ_a^2=222 for the number of cross-sections of 199. The value of the calculated magnitude χ_a^2=198 shows that the hypothesis $H_0|D_y(t_1)=D_y(t_2)=...D_y(t_{200})|$ on the homogeneity of a variance series is confirmed.

4) Conclusion about the ergodicity of random dependence $y(l)$ was drawn based on normalized correlation function; in this case, the ergodicity of the examined dependence was confirmed because condition $r_{ky}(\tau)\to 0$ is satisfied at increasing τ – a time shift.

5) Because random dependence $y(l)$ has a normal distribution law, in order to statistically estimate a given random process, it will suffice to obtain two statistics: mathematical expectation m_y and variance.

6) Random process $y(l)$ is centered, stationary, ergodic and has a normal distribution law.

Fig. 7 shows algorithm of adequacy verification of the mathematical model of soil micro relief; Table 1 gives results of comparison of statistical parameters of the actual and simulated micro relief.

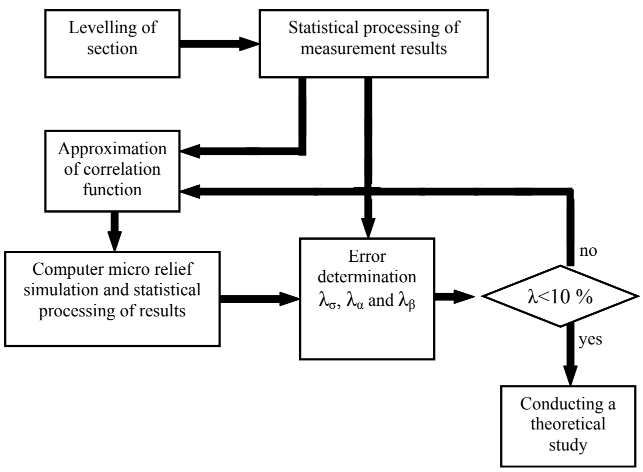

Fig. 7. Algorithm of adequacy verification of the mathematical model of soil micro relief

Table 1 shows that discrepancies for the root-mean-square deviation σ, attenuation coefficient α, and periodicity coefficient β do not exceed 10 %.

Good convergence of the normalized correlation functions of experimental and simulated micro reliefs also allows us to argue about the adequacy of the mathematical model of micro relief to the actual micro relief.

In order to estimate adequacy of the mathematical model of work process of a ripping unit, we performed a statistical analysis of the obtained data. Testing was carried out using the tractor T-170 with the ripping equipment DZ-116V.10.000 (the type DP-26S). To run the analysis, we selected samples of the function of angular velocity of the engine shaft $\omega_d(t)$ and motion speed of the base machine $v_{tr}(t)$ from N=30 independent implementations over the resulting interval equal to 150 seconds. The study was carried out at the initial depth of loosening h_0=0.4 m.

Table 1

Statistical parameters of micro relief

Parameter	Actual micro relief	Simulated micro relief	Divergence, %
σ, m	0.08	0.084	5.2
α, s^{-1}	0.118	0.110	6.8
β, s^{-1}	0.125	0.131	4.9

Based on the statistical analysis of sample $\omega_d(t)$, we drew the following conclusions:

1) The statistical distribution law of random dependence $\omega_d(t)$ agrees well with the theoretical normal, probability value is $P(\lambda)$=0.537...0.999>0.05 (0.05 is the level of criterion significance [13, 17, 18]).

2) Changes in the mathematical expectation of angular velocity of the engine shaft are insignificant (from +0.1 to −0,1 s^{-1}), the homogeneity of a series of mutually independent variances $D^*_\omega(t_i)$ is confirmed by compliance with the Bartlett criterion $\chi_a^2=731<\chi_a^2=794$ for 749 cross-sections, sampling discreteness is 0.2 s).

3) The fact of meeting the condition $r_{k\omega}(\tau)\to 0$ at increasing τ testifies to the ergodicity of the examined random process.

4) Random process $\omega_d(t)$ is ergodic and has a normal distribution law.

5) Sufficient characteristics of random process $\omega_d(t)$ are the mathematical expectation and variance.

Based on the statistical analysis of sampling $v_{tr}(t)$, we draw the following conclusions:

1) The statistical distribution of random dependence $v_{tr}(t)$ agrees well with the theoretical normal, probability value $P(\lambda)$=0.86...0.999>0.05 (0.05 is the level of criterion significance [13, 17, 18]).

2) Changes in the mathematical expectation of motion speed of the base machine are insignificant (from +0.002 to −0.002 m/s), the homogeneity of a series of mutually independent variances $D^*_v(t_i)$ is confirmed by compliance with the Bartlett criterion $\chi_a^2=708<\chi_a^2=794$ for 749 cross-sections, sampling discreteness is 0.2 s).

3) The fact of meeting the condition $r_{kv}(\tau)\to 0$ at increasing τ testifies to the ergodicity of the examined random process.

4) Random process $v_{tr}(t)$ is ergodic and has a normal distribution law.

5) Sufficient characteristics of random process $v_{tr}(t)$ are the mathematical expectation and variance.

Table 2 gives results of comparison of characteristics of the analyzed random processes, obtained experimentally and by simulating a work process of the ripping unit on a computer.

Table 2

Statistical parameters of the analyzed random processes

Parameter		m_x	Divergence, %	σ_x	Divergence, %
ω_d, s^{-1}	experiment	130.2	10.1	5.41	6.7
	simulation	143.3		5.77	
v_{tr}, m/s	experiment	2.59	11.3	0.185	4.2
	simulation	2.88		0.177	

Table 2 shows that the discrepancy between results of the experimental and theoretical studies does not exceed 10 %.

Good convergence of the normalized correlation functions of the experimental and simulated random processes also allows us to argue about the adequacy of the mathematical model of work process of the ripping unit to the actual work process of the examined machine.

6. Conclusions

1. The mathematical apparatus that we constructed made it possible to formulate conditions for the minimization of dynamic loads on the base machine through the substantiation of parameters of controlling signal that acts on the mounted equipment of a ripping unit.

2. Depending on the statistical analysis of terrain relief, by levelling the section, there occurs the possibility to make changes in the controlling signal to the mounted equipment of the working body, which would reduce dynamic loads.

3. The soil reactions during its destruction that were identified and described lead to uncontrolled displacement of the working body with low-frequency and high-frequency oscillations that act on the mounted equipment, reducing operational resource of the equipment, which necessitates enabling a controlling signal.

4. Adequacy of the proposed models of micro relief and work process of the ripping unit is achieved based on the statistical processing of soil relief, the introduction of a controlling signal for the motion of base machine and operational equipment.

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