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INVESTIGATION OF DYNAMIC PROCESSES IN THE PROPELLER OF MINITRACTOR

The article presents the results of theoretical investigations that were carried out by the authors during the development of the design of a crawler propulsion engine with an elastic caterpillars. A differential equation is derived that describes the dynamic process and allows us to investigate the transients in a complex mechanical system that is a motive.

Keywords: propeller, mechanical system, kinetic energy, general force, work, load, transient process.

Introduction. Creation of a crawler engine originates from 1818 when Frenchman Dubosh received a patent for the equipment of crews with moving rail tracks. As you know (Vasiliev V.V., 2008), crawler machines have several advantages over wheels, it is explained by its widespread usage, particularly in agriculture. Among the advantages of crawler engines it should be underlined:

- large area of the support, it allows to reduce the pressure on the support surface;
- high traction-coupling properties.

At the same time, the running systems of agricultural tractors have anthropogenic impact on the soil. Under the condition of multiple influence, its physical, mechanical and agronomic properties are under deterioration. Because of over-consolidation of the soil, the formation of the track deteriorates the quality of the implementation of technological operations related to soil cultivation, sowing and harvesting (Yemelianov, A.M., 2013). In order to reduce the negative influence of metal caterpillars, the engines rubber-metal elements (e.g., hinges), rubber-metal caterpillars, snowmobiles, rubber-reinforced caterpillars, elastic tracks of caterpillars are used (Candela M.V., Riabchenko V.N., Lipkan A.V., Yemelianov A.M., 2000; Tatalin B.F., Andreev G.V., Shiriaev V.I., Erohin A.P., 1977; Bumbar I.V., Kandel M.V., Candela N.M., Ryabchenko V.N., Shilko P.A., 2010; Abuzov, A.A., 2012).

The introduction of such constructive solutions is due to increase traction potential of tractors, reduce pressure on the soil, increase permeability and reduce dynamic loads in the elements of the crawler. The issue of improving crawler machines by constructing running systems with rubber elements is highlighted in researches by (Lapik V.P., 2015; Jinzheng Zhang, Qi Wang, Qich Jin, 2018; Bukharovskaia A.N., 2011; Takashi Fukushima, Eiji Inoue, Muneshi Mitsuoka , Shigeki Inaba, Takashi Okayasu, 2006; Ma Rabbani, Susumu Takeoka, Muneshi Mitsuoka, Eiji Inoue, Takashi Fukushima, Takashi Okayasu, 2010, Lapika V.P., 2010; Tolchynsky N.A., Teleshchev V.A. 1986; and others).

It has been established that the use of a propeller with rubber-wagon tracks allows to reduce the dynamic loads on the soil from the body of the machine by 2.5 times. During the movement of the machine on solid soils, the acceleration of the vibrations of submerged masses is reduced by 67%, that reduces the harmful effects of the car's vibrations on the soil (Lapik V.P., 2015). In addition, it has been found that the use of guns with rubber-reinforced caterpillars increases productivity and reduces the technogenic impact on soil (Bukharovskaia A.N., 2011).

The vibration characteristics of the rubber tracked system with the construction of a dynamic model are investigated by Jinzheng Zhang, Qi Wang, Qich Jin (2018). The authors formed a dynamic model based on theoretical analysis which allows to predict the actual state of motion and vibration characteristics of the rubber track system on the soil. The results of the experiment whose purpose is to determine changes in the vibration acceleration of the centre of gravity of the system of rubber caterpillars is also stated. The adequacy of the dynamic model recommended by the authors for predicting the vibration characteristics of the rubber track system has been experimentally confirmed. The study of the vibrational characteristics of a tractor with a rubber motive is also devoted to the work of Takashi Fukushima, Eiji Inoue, Muneshi Mitsuoka, Shigeki Inaba, Takashi Okayasu (2006). Deeper is numerical modeling, the results of which are presented by Ma Rabbani, Susumu Takeoka, Muneshi Mitsuoka, Eiji Inoue, Takashi Fukushima, Takashi Okayasu (2010).

The authors developed a two-dimensional model for predicting vibration characteristics, it differs from previous inputs of vertical dynamic force transmitted to guide rollers on a rubber track. The introduction of the vertical component into a mathematical model has allowed improving the prediction of the dynamics of loading forces on the elements of a crawler propeller with a rubber track. Despite the experience accumulated in agricultural engineering, the design of craftsmanship designs with rubber and rubber-reinforced elements requires the further implementation of a considerable amount of research work, both theoretical and experimental.

One of the most important directions is the study of transients in the propulsion system. When changing direction of movement, at the beginning of motion, braking, there are significant dynamic loads that exceed the static. The need for analysis of transients is connected particularly with the fact of the productivity and energy consumption of a machine that depends on the time of its occurrence (Smekhov A.A., Erofeev N.I., 1975).

In this article we will consider the beginning of the crawler movement for a mini tractor with an elastic caterpillar to obtain a differential that describes the dynamic process in the mechanical system.

Materials and methods. The basis of the research is the model (Nalobina O.O., Golotiuk M.V., Gavrysh V.S., Markova O.V., 2018), which is designed to solve the problem of increasing the pull-spring characteristics of the minitractor by even distribution of pressure from the crawler to the ground, increasing the smoothness of the course and maneuverability in the areas with a difficult relief.

Figure 1. shows the crawler engine of a mini tractor.

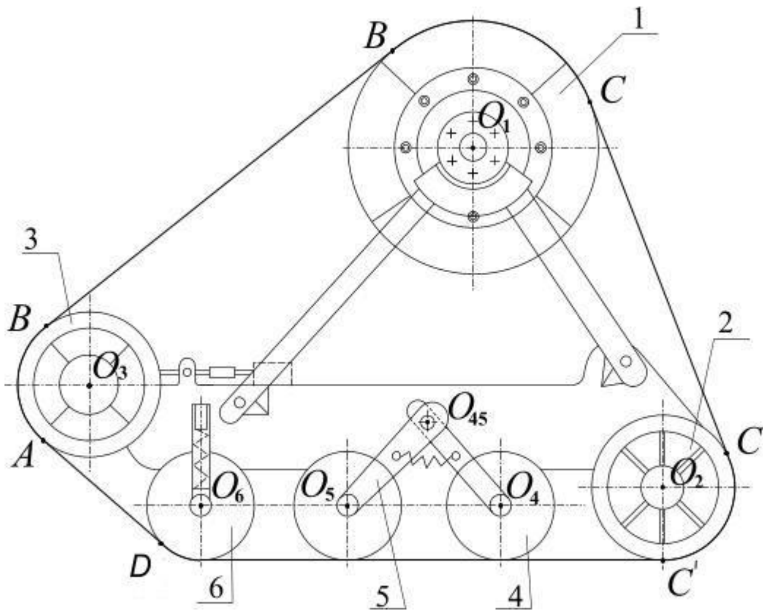

Fig. 1. Crawler thruster of a mini tractor: 1-drive wheel, 2-sprocket wheel, 3-stroke wheel, 4, 5, 6 - clamping rollers

Let's consider the beginning of the motion of the proposed propellant. During the start of the car there are significant dynamic loads, which proves the need for a dynamic calculation of the mechanical system.

We write down the equation in generalized coordinates:

$$\frac{d}{dt}\left(\frac{dE}{d\dot{s}}\right)-\frac{dE}{ds}=F_y,$$

where F_y – general force, $\dot{s}$ – general speed, which is the speed of an elastic caterpillar ($\dot{s}=\omega_1 r_1$,where ω_1, s^{-1} – angular speed of the driving wheel l; r_1, m – radius of this wheel).

During the tractor work is spent on moving the elastic track and overcoming the resistance resulting from friction in the supports of the wheels and rollers, the bend of the caterpillar, overcoming the resistance of the soil and resistance in the contact area with the bolts of the lower support unit. The following power factors apply to the elements of the mechanical system represented by the propulsion engine: the driving moments M_1, M_2, M_3 applied to the driving wheel 1, the steering wheel 2, the tensioner wheel 3, respectively.

Determine the general force F_y. It should be kept in mind that the elastic caterpillar in the process of movement overcomes the load due to its weight.

If the mass of the caterpillar is marked m_c, its length L_c, then the intensity of the distributed load $g_c = \frac{m_c g}{L_c}$, where g – acceleration of gravity.

The vector of this load is applied in the middle of the caterpillar by its width, directed downwards.

Components of the vector force g_c act along the pass line (left and right free branches that run in and out of the driving wheel) – g_{c1} and in the plane of the propulsion – g_{c2}.

$$\left. \begin{aligned} g_{c1} = g_c \cdot \cos\alpha_в = \frac{m_c g}{L_c}\cos\alpha_в; \\ g_{c2} = g_c \cdot \sin\alpha_в = \frac{m_c g}{L_c}\sin\alpha_в. \end{aligned} \right\} \tag{1}$$

where $\alpha_в$ – the inclination angle of the free branches of the elastic caterpillar to the horizontal; g_{c1} – component of the force vector g_c, which additionally loads the caterpillar within the areas AB, CD (Fig. 1);

g_{c2} – component of the force vector g_c, which is transmitted to the support of wheels.

The kinematic energy of the system consists of the product of the kinetic energies of the constituent systems. Consider them.

$$\left. \begin{aligned} &\text{Driving wheel 1: } E_{к1} = \frac{1}{2}\left(m_1V^2 + I_1\omega_1^2\right) = \frac{V^2}{2}\left(m_1 + \frac{I_1}{r_1^2}\right);\ \omega_1 = \frac{V}{r_1}. \\ &\text{Guide wheel 2: } E_{к2} = \frac{V^2}{2}\left(m_2 + \frac{I_2}{r_2^2}\right). \\ &\text{Tension wheel 3: } E_{к3} = \frac{V^2}{2}\left(m_3 + \frac{I_2}{r_2^2}\right). \\ &\text{Clamping rollers 4 and 5: } \frac{V^2}{2}\left(m_к + \frac{I_к}{r_к^2}\right), \text{ where: } к=4,5. \end{aligned} \right\} \tag{2}$$

Above information is valid provided that it moves along an even horizontal bearing surface.

If the caterpillar is found on the barrier, the centres O_4 and O_5 (fig. 1) rotate around the point O_{45} (fig. 2, d). The direction of rotation depends on the type of obstacle (its shape and height). To simplify the calculation we accept:

- the rotation is in the direction of movement of the tractor;

- at the fixed moment of time, the axis of the level $O_{45}O_5$ deviates from the initial position on the corner φ (fig. 2, d), $O_{45}O_4$ – for angle φ_1.

As $\varphi >> \varphi_1$, admit that centre movement O_5 relative to the centre O_{45} is insignificant and we ignore them. Then the magnitude of the absolute velocity of the point O_5 determines:

$$V_5^2 = V^2 + V_{O_5O_{45}}^2 + 2V \cdot V_{O_5O_{45}} \cos\varphi, \tag{3}$$

where $V_{O_5O_{45}} = \omega_{O_5}\left[O_5O_{45}\right]$.

Consider (3) write an expression for determining the kinetic energy of the roller 5:

$$E_{к5} = \frac{m_5\left(V^2 + V_{O_5O_{45}}^2 + 2V \cdot V_{O_5O_{45}} \cos\varphi\right)}{2} + \frac{I_5V^2}{2r_5^2}. \tag{4}$$

Roller 6 has an additional degree of freedom, which is conditioned by moving in a plane perpendicular to the lower supporting surface of the elastic track. Consider this, the absolute speed of the centre O_6 of roller determines:

$$V_6^2 = V^2 + V_p^2 + 2V \cdot V_p \cos\gamma, \tag{5}$$

where V_p – moving of the centre O_6 in the direction of compression of the spring, e.g. upwards;

γ – angle between velocity vectors V і V_p. (fig. 2, e).

The mechanical system of the propulsion, in addition to the above elements, contains an elastic caterpillar. Define its kinetic energy. To this end, conditionally split the contour of the elastic caterpillar into sections: ABC for which – $E_{ABC} = m_c V^2$ (here the velocity of the elastic caterpillar is equal to the derivative of the generalized coordinate s). At the site of the CD we have an increase in kinetic energy due to the need to overcome the friction between the surface of the elastic caterpillar and the soil, the value of which will be determined:

$$\Delta E = F_{fr} S , \tag{6}$$

where $F_{fr} = \mu m_c g$, here μ – coefficient of friction;

m_c – mass of elastic caterpillar (lower branch);

$g = 9{,}81 m/s^2$;

S – an area of soil on which work is done to overcome frictional forces $S = CD$.

Consider this, we have the expression for determining the kinematic energy of the reference track of the caterpillar:

$$E_{CD} = m_c V^2 + \mu m_c g S_{CD} = m_c \left(V^2 + \mu g S_{CD} \right). \tag{7}$$

We define a general force for the equality of elementary works.

In the functioning of the mechanical system, the work is spent on the transport of an elastic caterpillar, the bend of the caterpillar, the overcoming of resistance in the wheels of the wheels and rollers, and the resistance of the frictional forces between the bottom support track of the caterpillar and the ground.

Taking into account all the listed costs significantly complicates the calculations, but for optimal design of the engine there is a need for their maximum consideration. Therefore, the calculation of work wake up provided the most complete consideration of all factors, but with certain assumptions, which will be discussed below.

The elements of the mechanical system (propeller), as indicated above, have the following force factors (fig. 2): the driving moment M_1, applied to the driving wheel; moments M_2 , M_3, attached to guide and tensioning wheels; M_4 , M_5, M_6 – moments attached to rollers. M_2 , M_3, M_4 , M_5, M_6 – moments of resistance, which depend on the losses of friction in the supports, resistance to bending of the pass, radial and axial efforts. Radial forces depend, in turn, on the tension of an elastic caterpillar.

Radial forces transmitted to the wheels 2 and 3 are determined: $R_r = F_1 + F_2$, where $F_1 + F_2 = 2F_0 \sin \alpha_к / 2$, where $\alpha_к$ – the angle of the grip (contact) of the caterpillar and the wheels 2 and 3, where $2F_0 = 2EA(\varepsilon_1 + \varepsilon_2)$, here E – elastic module of elastic caterpillar material; A – cross-sectional area of the caterpillar; ε_1, ε_2 – relative elongation of caterpillar branches.

The moment of resistance of the wheels 1, 2, 3 can be presented in the form of calculation $\frac{M_к}{r_к} r_к$, where $\frac{M_к}{r_к}$ – the force that should be applied to the wheel to overcome the resistance. Provided that the resistance forces act in the plane of the wheel, they can be considered as resistance in the bearings, which according to (Artbolevskyi I.I., 1988): $1.22 K R_r \left(\frac{2}{d_к} + \frac{1}{r_в} \right)$, where K – coefficient of rolling friction, R_r – radial force acting in the plane of the wheel; $d_к$ – ball bearing diameter, $r_в$ – outer radius of inner bearing ring. Introduce the designation: $1{,}22 K \left(\frac{2}{d_к} + \frac{1}{r_в} \right) = K_n$, then:

$$\left. \begin{aligned} M_1 &= K_{n.1} r_1 R_{r_1}, \\ M_2 &= K_{n.2} r_2 R_{r_2}, \\ M_3 &= K_{n.3} r_3 R_{r_3}. \end{aligned} \right\} \tag{8}$$

Provided that the supports act not only in the plane of the wheel with force $R_к$, but also in the axial direction (perpendicular to the plane of the wheel) with force R_0, we have:

$$\left.\begin{aligned} M_2 &= K_{n.2} r_2 R_{r_2} + r_2 R_{O_2}, \\ M_3 &= K_{n.3} r_3 R_{r_3} + r_3 R_{O_3}, \\ M_1 &= K_{n.1} r_1 R_{r_1} + r_1 R_{O_1}. \end{aligned}\right\} \tag{9}$$

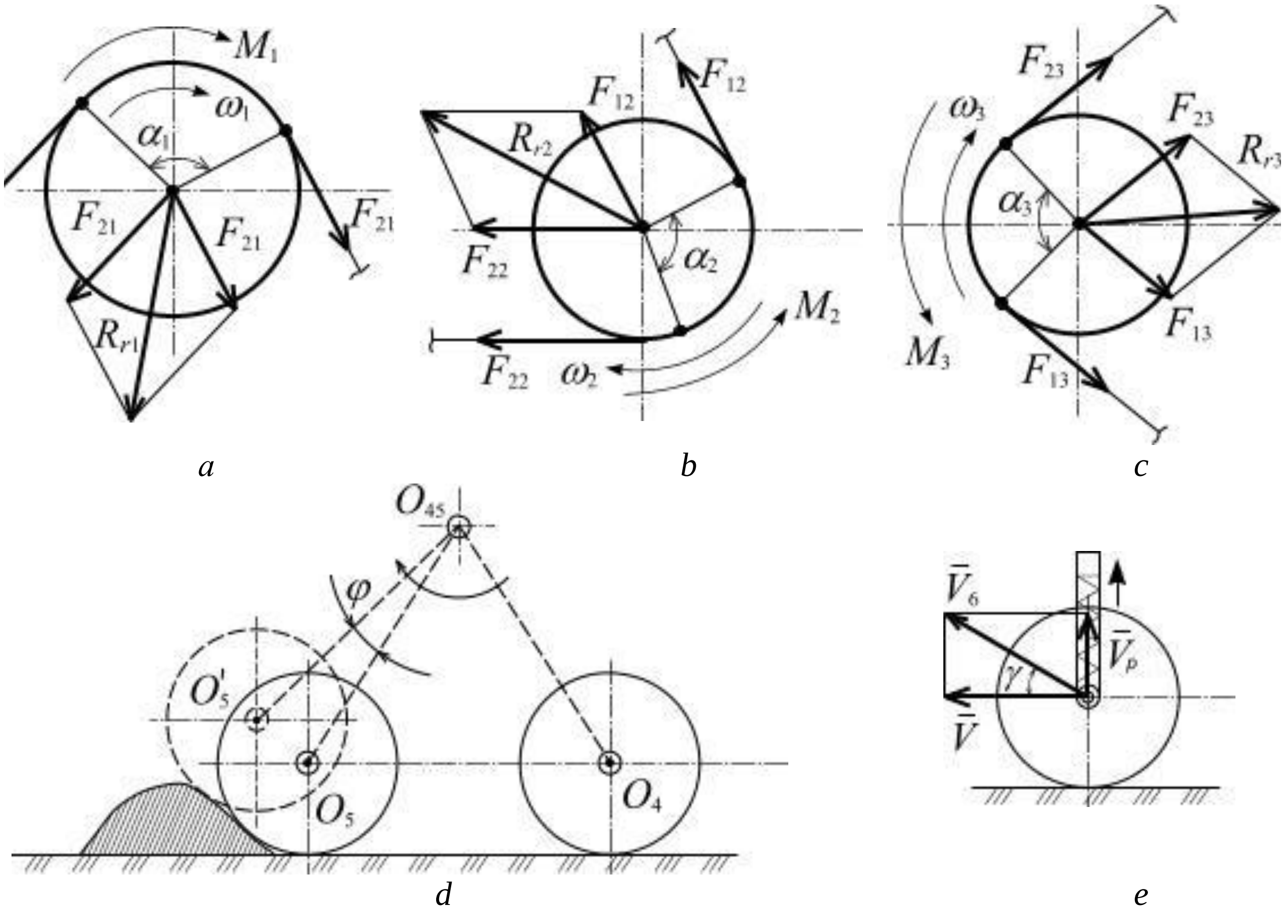

Fig. 2. Schemes for calculation: *a*, *b*, *c* – the forces acting on the branches of the elastic caterpillar and on the support of the wheels; *d* – scheme of mixing the roller 5 if the barrier is overcome; *e* – components of the vector of absolute speed of the centre O_6 of roller.

As it is seen from fig. 1 axial load of the wheel 1 is created due to the weight of the caterpillar $g_{г1}$: in general for all wheels:

$$R_{O_1} = \frac{m_c g}{L_c'} \cos\alpha_к, \tag{10}$$

where L_c' – the length of the section of the belt, the weight of which is transferred to the wheel resistance 1. Determine with high accuracy the fraction of the load, which is transmitted on the axle of wheels 1, 2, 3 is rather difficult. Therefore, in order to simplify the calculations, we assume that the part of the weight of the elastic track is transmitted to the axle of each wheel (1/3), that is approximately $\frac{m_c g}{3}\cos\alpha_к$.

The support of wheels 2 and 3 also transmits the load that arises in the segment of the CD from the weight of the rollers – $g_{ок}$. Denote the weight of one roller $m_к$, length of the plot СД – $L_{ок}$, then the intensity of the distributed load $g_{ок} = \frac{m_к n g}{L_{оп}}$, where n – number of rollers.

Assume that $1/2$ of the additional load from the impact of rollers on the support area of the caterpillar is transmitted to wheels 2 and 3. In addition, the force on the axis of the tensioned wheel 3 is transferred from the side of the hemisphere 7 (Fig. 1). Denote it R_n. This force is perpendicular to the axis of the wheel.

Results. Taking into account the information above, the axial loads on wheels 1, 2, 3 are determined:

$$\left.\begin{aligned} R_{O_1} &= \frac{m_c g}{3}\cos\alpha_1; \\ R_{O_2} &= \frac{m_c g}{3}\cos\alpha_2 + \frac{m_к n g}{2}s \quad \left(0 \le s \le s_к\right); \\ R_{O_3} &= \frac{m_c g}{3}\cos\alpha_3 + \frac{m_к n g}{2}s \quad \left(0 \le s \le s_A\right). \end{aligned}\right\} \qquad (11)$$

The change of the general coordinate s occurs from 0 to s_K or s_A; 0 – for wheel 2 relates to the point C; s_K – point K; for wheel 2 points B i A as well.

From (9), taking into account above information, we obtain the expressions for determining the moments:

$$\left.\begin{aligned} M_1 &= K_{n.1}r_1R_{r_1} + r_1R_{O_1} = K_{n.1}r_1 2EA\left(\varepsilon_1+\varepsilon_2\right) + r_1\frac{m_c g}{3}\cos\alpha_1 = \\ &= r_1\left[2EA\left(\varepsilon_1+\varepsilon_2\right)K_{під.1} + \frac{m_c g}{3}\cos\alpha_1\right]. \\ M_2 &= K_{n.2}r_2R_{r_2} + r_2R_{O_2} = 2K_{n.2}r_2EA\left(\varepsilon_1+\varepsilon_2\right) + r_2\left[\frac{m_c g}{3}\cos\alpha_2 + \frac{m_к g}{2}ns\right] = \\ &= r_2\left[2K_{n.2}EA\left(\varepsilon_1+\varepsilon_2\right) + g\left(\frac{m_c}{3}\cos\alpha_2 + \frac{m_к}{2}ns\right)\right]. \\ M_3 &= K_{n.3}r_3\left(R_{r_3}+R_n\right) + r_3R_{o3} = r_3\left(2K_{n.3}EA\left(\varepsilon_1+\varepsilon_2\right) + m_0 g\right) + r_3 g\left[\frac{m_c}{3}\cos\alpha_3 + \frac{m_k}{2}ns\right] = \\ &= r_3\left\{\left[2K_{n.3}EA\left(\varepsilon_1+\varepsilon_2\right) + m_0 g\right] + g\left[\frac{m_c}{3}\cos\alpha_3 + \frac{m_k}{2}ns\right]\right\}. \end{aligned}\right\} \qquad (12)$$

Introduce the replacement:

$$\left.\begin{aligned} a_i &= 2r_iEA\left(\varepsilon_1+\varepsilon_2\right)K_{n.i}, \\ b_i &= r_i\frac{m_c g}{3}\cos\alpha_i, \\ c_i &= r_i\frac{m_к g}{2}n, \\ d_3 &= m_0 g \cdot r_3. \end{aligned}\right\} \qquad (13)$$

We have:

$$\left.\begin{aligned} M_1 &= a_1 + b_1. \\ M_2 &= a_2 + b_2 \cdot s \\ M_3 &= a_3 + d_3 + b_3 \cdot s. \end{aligned}\right\}. \qquad (14)$$

We will determine the general force from the equality of the sum of the elementary effort of the operating forces of elementary work, which is spent under the condition of the generalized force. Let's make a sum of elementary works. To sum up, we assume that the analyzed technical system we has an elementary possible movement δs.

$$\sum\delta A = M_1\frac{\delta s}{r_1\eta} - M_2\frac{\delta s}{r_2} - M_3\frac{\delta s}{r_3} - q_{ok}s\cdot\delta s = F_y\delta s. \qquad (15)$$

Consider (13) we have:

$$F_y = \frac{a_1+b_1}{r_1\eta} - \frac{a_2+b_2\cdot s}{r_2} - \frac{a_3+d_3+b_3\cdot s}{r_3}. \qquad (16)$$

Consider (16), (2), (7), (4) write equations (1):

$$K\left(\sum_{k=1}^{6}\frac{I_k}{r_k^2} + m_k\right)\ddot{s} + 4m_c\ddot{s} + m_c\mu g\dot{s} - m_c\mu g\ddot{s} = \frac{a_1+b_1}{r_1\eta} - \frac{a_2+b_2\cdot s}{r_2} - \frac{a_3+d_3+b_3\cdot s}{r_3}, \qquad (17)$$

or

$$Ks\left(\sum_{k=1}^{6}\frac{I_k}{r_k^2}+m_k\right)+(4m_c-m_c\mu g)\ddot{s}+m_c\mu g\dot{s}=\frac{a_1+b_1}{r_1\eta}-\frac{a_2+b_2\cdot s}{r_2}-\frac{a_3+d_3+b_3\cdot s}{r_3}. \qquad (18)$$

Equation (18) – differential equation describing the dynamic process in the mechanical system. This equation allows us to investigate the transients in the mechanical system.

Conclusions. It is proposed the design of a crawler propulsion with elastic caterpillars in order to solve the problem of increasing the traction and spring characteristics of the mini tractor by uniformly distributing pressure from the track gun to the soil, increasing the smoothness of the course and maneuverability in the areas with difficult terrain.

A differential equation is obtained that allows to investigate the transients in a mechanical system, which is a motive. Moreover, the research will be continued in order to obtain equations that describe the dynamic processes during inhibition.

Using the results of research, you can improve the work of the propeller, subject to changes in loads on its elements.

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Налобіна О.О., Голотюк М.В., Бундза О.З., Герасимчук О.П., Пуць В.С., Шовкомуд О.В., Мартинюк В.Л. **Дослідження динамічних процесів у рушії мінітрактора.**

Ходові системи сільськогосподарських тракторів мають техногенний вплив на ґрунт. За умови багатократного впливу погіршуються його фізико-механічні та агротехнічні властивості. Внаслідок переущільнення ґрунту, утворення колії погіршується якість виконання технологічних операцій, пов'язаних із обробітком ґрунту, посівом та збиранням врожаю. З метою зменшення негативного впливу металевих гусениць на ґрунт застосовують рушії з гумовометалевими елементами (наприклад, шарнірами), гумовометалеві гусениці, пневмогусениці, гумовоармовані гусениці, еластичні траки гусениць.

Не зважаючи на досвід, накопичений у сільськогосподарському машинобудуванні, проектування конструкцій гусеничних рушіїв з гумовими та гумовоармованими елементами вимагає подальшого проведення значного об'єму науково-дослідних робіт як теоретичного так й експериментального характеру.

Одним із актуальних напрямків є дослідження перехідних процесів у системі рушія гусеничних машин. Під час зміни напрямку руху, на початку руху, гальмуванні виникають значні динамічні навантаження, що перевищують статичні. Потреба в аналізі перехідних процесів пов'язана, зокрема з тим, що продуктивність та енерговитрати машини залежать від часу їхнього протікання.

У даній статті розглянуто початок руху гусеничного рушія для мінітрактора з еластичною гусеницею з метою отримання диференційних рівнянь, які описують динамічний процес в механічній системі. В основу досліджень покладено розроблену авторами методику для вирішення задач підвищення тягово-пружинних характеристик мінітрактора шляхом рівномірного розподілу тиску з боку гусеничного рушія на ґрунт, підвищення плавності ходу та маневреності на ділянках із складним рельєфом.

Ключові слова: рушій, механічна система, кінетична енергія, узагальнена сила, робота, навантаження, перехідний процес.

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