Study of the oscillation processes of a front-mounted haulm harvester when it moves on the inequalities of the ground surface

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Abstract. *In the article the calculated mathematical model of oscillations of the haulm-harvesting machine frontally attached to a wheeled tractor is constructed. A nonlinear differential equation is obtained, which describes the oscillations of a haulm-harvesting machine in the longitudinal-vertical plane during the movement of its pneumatic copying wheels along the unevenness of the soil surface. On the basis of the received theoretical results rational constructive and kinematic parameters of the front-mounted hoisting machine which provide decrease in amplitude of the specified fluctuations are defined. So, at translational speed of movement of the haulm-harvesting unit* $V = 3.0\ m \cdot s^{-1}$, *the amplitude of oscillations of the rotor of the haulm harvester decreases in 1.2...1.5 times in comparison with height of roughnesses of a surface of the field* $h_o = \pm 0.04$ *m. At the amplitude of oscillations of the lower ends of the knives of the rotary cutting device up to 4 cm, the loss of the tip does not increase significantly. However, when increasing the values of the amplitude of these oscillations to 7 cm or more, the loss of the branch increases significantly and the maximum values of which exceed 12%.*
KEYWORDS*: HAULM, ROTARY CUTTING MACHINE, TRACTOR, OSCILLATIONS, DIFFERENTIAL EQUATIONS, RATIONAL PARAMETERS*

1. Introduction

The use of frontally hinged haulm harvesters with rotary haulm cutters, which carry out a pore-free cut, as well as a significant increase in working speeds of their movement cause intensive oscillations of these haulms in the longitudinal-vertical plane, which not only reduces the quality of cutting heads in general, but also causes significant losses of the haulm. Therefore, there is a need for analytical determination of the influence of kinematic and construction parameters of the mower, frontally mounted on a wheeled tractor, on the amplitude of oscillations in the longitudinal-vertical plane of the haulm cutting unit.

Front-mounted haulm harvesters are widespread in many beet-growing countries. However, fundamental analytical studies of their oscillatory motion over irregularities in the soil surface are virtually non-existent. In [1], a theoretical study of the vibrations of a frontally mounted mower harvester using the initial equations in the Lagrange form of the 2nd kind is given. However, this work does not take into account all the forces acting on this dynamic system, so the resulting mathematical model of its motion is not adequate to the real process. Applying the same technique [2], we can build a more accurate mathematical model of the movement of this machine on the uneven ground surface, which will allow us to study the influence of its construction and kinematic parameters on the considered movement along the lines of sugar beet roots.

The aim of the study is the theoretical substantiation of the construction and kinematic parameters of the front-mounted on the wheeled aggregating tractor rotary machine, ensuring its stable and steady movement in the longitudinal-vertical plane.

2. Materials and Methods

To ensure stable and steady movement in the longitudinal-vertical plane of the rotary haulm harvester, frontally mounted on a wheeled aggregating tractor, a new universal haulm harvester was developed, which performs the technological process on the principle of a mower-shredder. This machine uses a rotary topper in which the cutting blades are pivotally mounted on the drive drum, have an arc-shaped form and, when rotating in a longitudinal-vertical plane, provide a non-supporting, copiless cut of the main mass of the haulm across the entire width of the capture [3-11].

It should be noted that the quality performance of the technological process of harvesting the haulm will be determined by the stability of the movement of its rotary cutter in the longitudinal-vertical plane, the efficiency of copying the unevenness of the ground surface in the area of its width, as well as the overall construction parameters, including the parameters of the connecting mechanism of the aggregating tractor.

To determine the influence of structural and kinematic parameters of the haulm harvester, frontally mounted on the aggregating wheel tractor, on the vibrations in the longitudinal-vertical plane of the pre-implement, it is necessary to build its mathematical model, that is to make the differential equations of its oscillatory motion.

For this purpose, analytically consider the movement of the haulm harvester over the irregularities of the ground surface in the longitudinal-vertical plane, which most significantly affects the uniformity of cutting the haulm from the heads of root crops. Based on [1], first of all, we make an equivalent diagram of the movement of a wheeled aggregating tractor mounted frontally on a halm harvester (Fig. 1).

In this case, we will show the harvester in an equivalent diagram in its two positions, when the copying wheels in front of the machine only run over the uneven surface of the ground and when they are already on the top of this uneven surface.

As shown in Fig. 1 haulm harvester is connected to the aggregate tractor by means of two lower thrusts OK and one upper thrust DM the hitching mechanism of the implement tractor, which has pivots at the points of O, D, M and K. The radii of the copying wheels and the cutting device are denoted by r and r_1. The mass of the entire harvesting machine is denoted by M; the mass of the two copying wheels – through $m = m_1 + m_2$ (where m_1 – the mass of the first copy wheel, m_2 – mass of the second copying wheel). Mass m of the both copy wheels on the equivalent circuit will be centered at the point B.

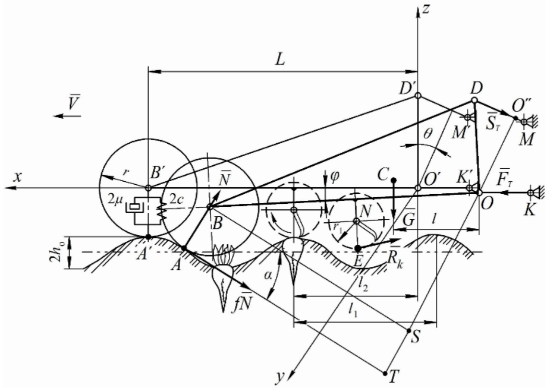

Figure 1. *Equivalent scheme of a front-mounted harvesting machine on a tractor*

Let's represent pneumatic copying wheels in the form of elastic-damping models with the total rigidity coefficient $2c$ and the total damping coefficient 2μ.

At the same time the pneumatic copying wheel, moving in interrows of crops of sugar beet and crumpling the top most loose layer of soil, contacts with roughness of a surface of a field in a point A. In addition, the irregularities of the ground surface (in a smoothed state) can be represented in the form of a harmonic function, i.e. by such analytical expression [3]:

$$h = h_o\left(1 - \cos\frac{2\pi x}{l_1}\right), \qquad (1)$$

where h – the ordinate of the height of the unevenness of the soil surface, m, h_o – half the height of the unevenness of the soil surface, m, l_1 – step of unevenness of the soil surface, m; $x = Vt$ – current coordinate, m; V – forward speed of the haulm harvester, m·s^{-1}.

Let us further characterize the influence of the forces shown in the equivalent diagram (Fig. 1) on the occurrence of vertical angular oscillations of the haulm harvester frame when it moves over irregularities of the ground surface. The main forces in this case are normal $\bar{N}$ and tangent $f\bar{N}$ soil reactions applied at the point A contact of the copying wheel with the ground. Here f – coefficient of resistance to rolling of the copying wheel on the soil surface. These forces are external active forces that are transmitted to the frame of the harvesting machine from the surface of the ground. It should be noted that each copying wheel performs deformation of the ground while moving in the inter-row of sugar beet crops.

The force of gravity also has a significant effect on the angular oscillations of the frame $\bar{G}$ of the harvester that attached to its center of mass (point *C*).

Also at point *E* the resistance reaction $\bar{R}_k$ of the rotor cutter is acting against the cutting of the haulm, as shown in the equivalent diagram. In addition, along the lower link OK of the hitch the tractor pulling force $\bar{F}_T$ acts from point K to point O, and along the upper link DM of the hitch the pulling force $\bar{S}_T$ acts from point D to point M, which also have a certain effect on the oscillating process under consideration. To take into account the elastic-damping properties of the tires, it is necessary to determine the potential energy P and the dissipative function R of this dynamic system.

We will use differential equations of motion in the form of Lagrangian form of type II [2] to compose the differential equations of motion of the harvester mounted on the aggregating wheel tractor over the unevenness of the soil surface.

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}}\right) - \frac{\partial T}{\partial \varphi} = Q_\varphi - \frac{\partial P}{\partial \varphi} - \frac{\partial R}{\partial \dot{\varphi}}, \qquad (2)$$

wghere T – kinetic energy of the considered dynamic system; Q_φ – generalized force; P – potential energy of the system; R – dissipative function (Rayleigh function); φ – generalized coordinate; $\dot{\varphi}$ – generalized speed.

Further, we define the components included in equation (2). The kinetic energy T of this dynamic system consists of kinetic energy T_1 of the forward motion of the haulm harvester, the kinetic energy T_2 angular movement of the machine frame around the point O, kinetic energy T_3 of vertical oscillations of its copying wheels and kinetic energy T_4 of rotation of the pneumatic copying wheels around the axes on which they are mounted. Therefore, in general, kinetic energy T will be equal:

$$T = \sum_{i=1}^{4} T_i = T_1 + T_2 + T_3 + T_4. \qquad (3)$$

Determine the values of the components included in expression (5). Accordingly, they will be equal:

$$T_1 = \frac{MV^2}{2}, \qquad (4)$$

where M – weight of the haulm harvesting machine, kg; V – the speed of translational motion of the center of mass of the machine, m·s^{-1}.

$$T_2 = \frac{I_{oy}\dot{\varphi}^2}{2}, \qquad (5)$$

where I_{oy} – the moment of inertia of the frame of the harvester relative to the axis Oy, which is perpendicular to the longitudinal-vertical plane and passes through the point O, kg·m^2; $\dot{\varphi}$ – angular velocity of rotation of the machine frame, s^{-1}.

$$T_3 = \frac{m\dot{z}^2}{2}, \qquad (6)$$

where m – weight of copying wheels kg; $\dot{z}$ – speed of vertical oscillations of copying wheels m·s^{-1}, або:

$$T_3 = \frac{mL^2 \cdot \dot{\varphi}^2}{2}, \qquad (7)$$

and

$$T_4 = \frac{I_k\omega^2}{2}, \qquad (8)$$

where I_k – moment of inertia of the copy wheels relative to the axis of rotation (total for both copy wheels), kg·m^2; ω – angular rotation speed of the copying wheel, s^{-1}.

Substituting expressions (4), (5), (7), and (8) into expression (3), we obtain the final expression for determining the kinetic energy of the considered dynamic system:

$$T = \frac{MV^2}{2} + \frac{I_{oy}\dot{\varphi}^2}{2} + \frac{m \cdot L^2 \cdot \dot{\varphi}^2}{2} + \frac{I_k\omega^2}{2}. \qquad (9)$$

The potential energy P of this dynamic system will be equal to the work of the elastic deformation forces of the pneumatic tires of both copying wheels and therefore defined by the following expression:

$$P = c \cdot L^2 \cdot \varphi^2, \qquad (10)$$

where c – coefficient of stiffness of pneumatic tires of the copying system wheels, N·m^{-1}; L – distance from the axis of the harvesting machine suspension (point O) to the axis of its copying wheels (point B), m.

We define the dissipative function R of this dynamic system through the viscous drag force, which is proportional to the velocity of displacement, and therefore equal to:

$$R = \mu \cdot L^2 \cdot \dot{\varphi}^2, \qquad (11)$$

where μ – the damping coefficient of the copying wheels, N·s·m^{-1}.

These viscous resistance forces are also due to the pneumatic tires of the copying wheels of the haulm harvesting machine.

Determine the necessary partial derivatives that are included in the expression (2).

The first partial derivative of kinetic energy T on the generalized speed $\dot{\varphi}$ equal:

$$\frac{\partial T}{\partial \dot{\varphi}} = \left(I_{oy} + m \cdot L^2\right)\dot{\varphi}, \qquad (12)$$

then

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}}\right) = \left(I_{oy} + m \cdot L^2\right)\ddot{\varphi}. \qquad (13)$$

Given that:

$$\frac{\partial T}{\partial \varphi} = 0, \qquad (14)$$

we obtain that the left-hand side of equation (2) is equal to:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}}\right) - \frac{\partial T}{\partial \varphi} = \left(I_{oy} + m \cdot L^2\right)\ddot{\varphi}. \qquad (15)$$

Similarly, we find partial derivatives for potential energy P and for dissipative function R. We have:

$$\frac{\partial P}{\partial \varphi} = 2c \cdot L^2 \cdot \varphi, \qquad (16)$$

and

$$\frac{\partial R}{\partial \dot{\varphi}} = 2\mu \cdot L^2 \cdot \dot{\varphi} . \quad (17)$$

Further, we define the generalized force Q_φ on the generalized coordinate φ. To determine the generalized force Q_φ we use the expression for the elementary work of active forces on a possible displacement $\delta\varphi$. We will have:

$$\begin{aligned} &\delta A_\varphi = -N \cdot BS \cdot \delta\varphi + fN \cdot TO \cdot \delta\varphi + R_k \cos\varphi \cdot EN \cdot \delta\varphi + \\ &+G \cdot l \cdot \cos\varphi \cdot \delta\varphi - S_T \cdot OO'' \cdot \delta\varphi, \end{aligned} \quad (18)$$

where BS, TO, $EN \cdot \cos\varphi$, $l \cdot \cos\varphi$ and OO'' – shoulders of force $\bar{N}$, $f\bar{N}$, $\bar{R}_k$, $\bar{G}$ and $\bar{S}_T$ relative to the point O respectively (Fig. 2).

Then the generalized force Q_φ by angular coordinate φ equal:

$$\begin{aligned} &Q_\varphi = \frac{\delta A_\varphi}{\delta\varphi} = -N \cdot BS + fN \cdot TO + R_k \cos\varphi \cdot EN + \\ &+G \cdot l \cdot \cos\varphi - S_T \cdot OO''. \end{aligned} \quad (19)$$

This generalized force Q_φ is actually the sum of the algebraic moments of all active forces with respect to the point O, acting on the given dynamical system.

We determine the necessary arms of all the forces in expression (19). As can be seen from Fig. 2:

$$BS = L \cdot \cos(\alpha + \varphi) , \quad (20)$$

where α – the angle of inclination of the tangent to the cosine given by the expression (1).

It is known that the tangent of the angle of inclination tangent to the curve $h = f(x)$ at this point is equal to the derivative of the equation of this curve on the variable x at this point, ie: $\tan\alpha = h'_x$.

Given expression (1), we obtain:

$$\dot{h}_x = \frac{2\pi h_o}{l_1} \cdot \sin\frac{2\pi x}{l_1} , \quad (21)$$

then:

$$\alpha = \arctan\left[\frac{2\pi h_o}{l_1} \cdot \sin\frac{2\pi x}{l_1}\right]. \quad (22)$$

Next, from Fig. 2 we get the value of the other shoulders:

$$TO = r + L \cdot \sin(\alpha + \varphi) , \quad (23)$$

$$OO'' = OD \cdot \cos(\theta + \varphi) , \quad (24)$$

Substituting expressions (20), (23) and (24) into expression (19), we obtain the value of the generalized force Q_φ, that equal:

$$\begin{aligned} &Q_\varphi = -N \cdot L \cdot \cos(\alpha + \varphi) + fN \cdot \left[r + L\sin(\alpha + \varphi)\right] + \\ &+ R_k \cdot EN \cdot \cos\varphi + G \cdot l \cdot \cos\varphi - S_T \cdot OD \cdot \cos(\theta + \varphi), \end{aligned} \quad (25)$$

where EN, OD – set constructive parameters.

Next, substituting expressions (15), (16), (17), (25), in equation (2), we obtain:

$$\begin{aligned} &\left(I_{oy} + m \cdot L^2\right)\ddot{\varphi} + 2c \cdot L^2 \cdot \varphi + 2\mu \cdot L^2 \cdot \dot{\varphi} = \\ &= -N \cdot L \cdot \cos(\alpha + \varphi) + fN \cdot \left[r + L\sin(\alpha + \varphi)\right] + \\ &+R_k \cdot EN \cdot \cos\varphi + G \cdot l \cdot \cos\varphi - S_T \cdot OD \cdot \cos(\theta + \varphi). \end{aligned} \quad (26)$$

The obtained differential equation (26) is a differential equation of angular oscillations of the harvester frame in the longitudinal-vertical plane.

We transform the system (26) into the following form:

$$\begin{aligned} &\ddot{\varphi} + \frac{2L^2}{I_{oy} + m \cdot L^2}\left(c \cdot \varphi + \mu \cdot \dot{\varphi}\right) = \\ &= \frac{1}{I_{oy} + m \cdot L^2}\Big\{-N \cdot L \cdot \cos(\alpha + \varphi) + \\ &+ fN \cdot \Big[r + L\sin(\alpha + \varphi)\Big] + R_k \cdot EN \cdot \cos\varphi + \\ &+G \cdot l \cdot \cos\varphi - S_T \cdot OD \cdot \cos\Big(\theta + \varphi\Big)\Big\}. \end{aligned} \quad (27)$$

Thus, the nonlinear differential equation (27) is obtained with respect to the unknown generalized coordinate φ, which is a computational mathematical model of the movement of a frontally attached wheeled aggregating tractor harvester.

The initial conditions for the differential equation (32) are as follows:

at $t = 0$: $\varphi = 0$ and $\dot{\varphi} = 0$. (28)

Differential equation (27) with initial conditions (28) can be solved on a PC by the adapted Runge-Kutta method in the MathCAD system.

However, the resulting system of differential equations (27) includes the unknown normal reaction $\bar{N}$, acting from the ground on the copying wheels, as well as $\bar{R}_k$ force of resistance to shearing the haulm.

In first approximation, the normal reaction $\bar{N}$ can be determined by the equality to zero of the algebraic sum of the moments of all forces acting on the system relative to the point O. Such an equation can be obtained from equation (27) provided that $Q_\varphi = 0$. We will have:

$$\begin{aligned} &-N \cdot L \cdot \cos(\alpha + \varphi) + fN \cdot \left[r + L\sin(\alpha + \varphi)\right] + \\ &+R_k \cdot EN \cdot \cos\varphi + G \cdot l \cdot \cos\varphi - S_T \cdot OD \cdot \cos(\theta + \varphi) = 0. \end{aligned} \quad (29)$$

However, the angles α and φ, included in equation (29) depend on time, so it is convenient to consider the time moment t, when thhe angles α and φ equal to zero. As can be seen from Fig. 2, this is the moment of time t when the copying wheel is on a horizontal surface, for example, at the maximum point of the cosine (1). Then at $\alpha = 0$ and $\varphi = 0$ from expression (29) we obtain:

$$-N \cdot L + fN \cdot r + R_k \cdot EN + G \cdot l - S_T \cdot OD \cdot \cos\theta = 0 . \quad (30)$$

Next, from equation (30) we find the value of the desired normal reaction $\bar{N}$:

$$N = \frac{G \cdot l + R_k \cdot EN - S_T \cdot OD \cdot \cos\theta}{L - f\,r} . \quad (31)$$

By determining the coordinate φ of the angular displacement of the haulm harvester frame by solving differential equation (27), we can determine the vertical displacement of the rotor blade of the haulm harvester (point E, Fig. 2) at any time moment t by the following expression:

$$z_E(t) = l_2 \cdot \varphi(t) , \quad (32)$$

where l_2 – distance from the attachment point M of the knife to the frame to the point O of the harvester's suspension to the lower link OK.

The vertical displacement of the center of mass (point C) of the haulm harvester can be determined from the following expression:

$$z_C(t) = l \cdot \varphi(t) , \quad (33)$$

where l – the distance from the vertical axis passing through the point C, to the point O.

3. Results and discussions

When making numerical calculations on a PC, the forward speed of the tractor with which the harvester is coupled, varied from V = 10 km·h^{-1} and V = 12 km·h^{-1}. Different values of the moment of inertia of the harvester were also used I_{oy} (taking into account the weight of the haulm inside the machine), which depend on M – mass of the harvester (M = 948 kg) and L – distances from the copying wheels axis to the point O of the suspension (L = 1.8 m) (Fig. 2). In the calculations were selected several values of moments of inertia: from I_{oy} = 30 kg·m^2 to I_{oy} = 60 kg·m^2.

For calculations and numerical modeling on PC the initial constructive and kinematic parameters of the three-row haulm harvester, frontally mounted on a wheeled tractor, are the following: the weight of the machine and the haulm inside the machine G = 9300 N; weight of copying wheels $G_k = G_{k1} + G_{k2} = 480$ N; weight of copying wheels $m = m_1 + m_2 = 48.9$ kg; the distance from the axis of suspension of the machine to the axis of the cutting device $l_2 = 1.1$ m and to the center of mass $l = 0.8$ m; stiffness coefficient of pneumatic tires of copying wheels $2c$ = 4000 N·m^{-1}; damping coefficient of pneumatic tires of copying wheels 2μ = 150 N s·m^{-1}; half the height of the unevenness of the soil surface h_o = 0.04 m; step of its inequality l_1 = 0.7 m; coefficient of friction f = 0.3; the total cutting force of the haulm R_k = 300 N; normal reaction N = 4117 N; the radius of the rotor of the cutting machine r_1 = 0.3 m; copy wheel radius r = 0.368 m; effort in the upper thrust S_T = 209 N and lower F_T = 1750 N of the hinged mechanism.

The results of numerical simulation on PC based on the developed mathematical model are shown in Fig. 2-4.

The graph shown in Fig. 2 shows that, at the initial moment of the harvester's motion, the amplitude of angular oscillations of the frame reaches a significant value (up to 0.02 rad). However, later, due to the inertial properties of the oscillating masses, this amplitude decreases and the oscillatory process stabilizes.

The graphical dependencies shown in Fig. 3 show that increasing the width of the main tillage unit, which forms a cosine profile of the soil surface, as well as improving the quality of the subsequent preparation of the field surface significantly reduces the oscillations of the front-mounted on the tractor harvester, especially at the speed of this harvester unit up to 2.5 m·s^{-1}.

The graphs shown in Fig. 4 show that the frequency of oscillations of the haulm cutting rotor in the longitudinal-vertical plane will not exceed 22 s^{-1} in the whole range of agrotechnical speeds of the harvesting machine at a step of inequalities greater than 0.9 m.

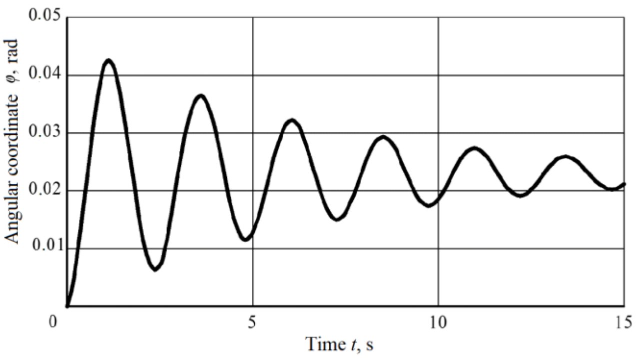

Figure 2. *Dependence of the angular coordinate φ oscillations of the frame of the hoeing machine from time to time t at the initial moment of movement*

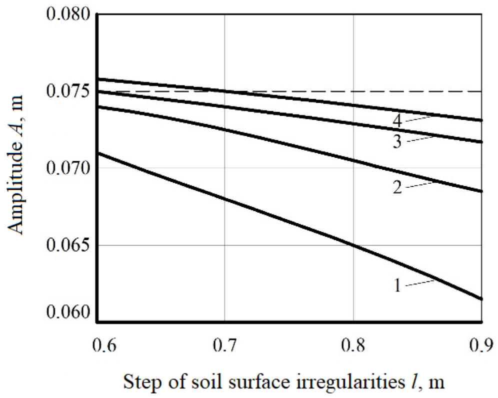

Figure 3. *Dependence of the oscillation amplitude A of the rotor of a haulm harvester on the unevenness of the ground surface l at different speeds of the machine: 1 – V_1 = 1.5 m·s^{-1}; 2 – V_2 = 2.0 m·s^{-1}; 3 – V_3 = 2.5 m·s^{-1}; 4 – V_4 = 3.0 m·s^{-1}*

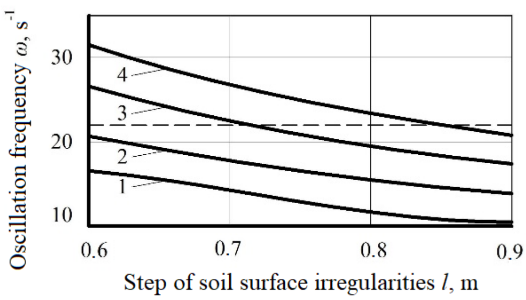

Figure 4. *Dependence of the frequency ω of forced oscillations of the shear rotor in the longitudinal-vertical plane of the harvester on the pitch of the uneven ground surface l at different speeds of the machine: 1 – V_1 = 1.5 m·s^{-1}; 2 – V_2 = 2.0 m·s^{-1}; 3 – V_3 = 2.5 m·s^{-1}; 4 – V_4 = 3.0 m·s^{-1}*

To verify the compliance of the theoretical calculations with the real process, as well as to determine the losses of sugar beet haulm during harvesting with the given haulm harvester, its experimental research in the field directly during the harvesting of the haulm was carried out. For this purpose, the harvester was equipped with appropriate instruments and experimental equipment to record the amplitude of vertical oscillations of its rotary cutting apparatus, progressive speed of the machine, also equipment was prepared to measure and record the uncut haulm residues on the heads of root crops, prepared scoring sections.

According to the developed methodology, the study of the quality indicators of the harvesting machine front-mounted on the tillage wheeled aggregating tractor was carried out in fivefold repetition for each mode of operation.

4. Conclusion

1. It has been established that the harvester mounted frontally on a wheeled aggregating tractor makes angular oscillations in the longitudinal-vertical plane when moving over the irregularities of the ground surface, which are kinematic disturbances.

2. On the basis of the differential equation in the Lagrange form of the 2nd kind the nonlinear differential equation of the angular oscillations of the frame frontally mounted on the aggregating tractor wheel of the rotary type, which represents a mathematical model of its motion is obtained.

3. Numerical simulation of angular vibrations in the longitudinal-vertical plane of the frame frontally attached to the wheeled aggregating tractor of the rotary tillage machine showed that the given vibrating system is able to damp the disturbing effects from the unevenness of the soil surface under the assumed construction parameters. Thus, at the forward speed of the haulm

harvester, $V = 3.0$ m·s^{-1}, the amplitude of oscillations of the rotor of the haulm harvester decreases in 1.2...1.5 times in comparison with height of roughnesses of a surface of a field $h_o = \pm 0.04$ m.

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