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Modeling and Research of the Controllability of Wheeled Tractors

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Abstract**:** ***In this paper we considered the issues of controllability and stability of wheeled tractors on the slopes with the help of mathematical modeling and optimal control. The well-known methods of modeling and research for improving the stability of the tractor do not allow solving the problem of stable motion of the tractor on the slopes, as they do not provide sufficient correction of the moving direction, which depends on the character of external disturbances. The application of modern optimal control methods allows to investigate this problem at the design phase of the machine with using mathematical models. To solve the problem, we created the equations of motion of a wheeled tractor using the Lagrange equations of the second kind. On the basis of the equations of motion we developed models and algorithms for optimal control of a wheeled tractor. The necessary conditions for optimal control of the motion using the Pontryagin maximum principle were investigated. With the help of auxiliary functions of Hamilton-Pontryagin, we have determined the coefficients of stiffness and viscous resistance of wheel tractor tires. The boundary value problem of the maximum principle to determine the transient process motion of the tractor is formulated and on its basis the equations of horizontal and vertical oscillations of the tractor were solved at an uneven distribution of mass between the front and rear driven wheels and the coefficient of adhesion of the wheels and the lateral slip of the tractor in turning were calculated.***

Keywords**:** ***wheeled tractor, modeling, optimal control, wheel adhesion, lateral slip.***

I. INTRODUCTION

Improving the technical levels and consumer properties of technical means for agricultural production, in particular the development of an improved tractor to ensure optimal technological modes of operation of machine-tractor units in agricultural production and other sectors of the economy is important [1-4].

As known, the factors that negatively affect the performance of units with wheeled tractors during curvilinear movement is the removal of the pneumatic tires of the driving and guide wheels of the tractor.

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The impact of tire drift is exacerbated by the steady trend towards higher operating speeds of the aggregates. Due to the lateral drift of tires, the traction characteristics of the driving wheels and the tractor as a whole deteriorate, and, of course, the driving stability, the quality of work and the handling of the unit. To ensure the requirements for the quality of the work of machine-tractor units, it is necessary to investigate the main indicators of driving stability, handling and pressure in contact of the tires with the soil and others [5-9].

II. DEVELOPMENT OF MATHEMATICAL MODELS OF HORIZONTAL AND VERTICAL OSCILLATIONS OF A FOUR-WHEEL UNIVERSAL-TILLED TRACTOR WITH STEPLESSLY ADJUSTABLE CLEARANCE

One of the ways to solve such problems is the controllability of a 4-wheeled tractor through mathematical modeling and optimal control of the tractor under various driving conditions.

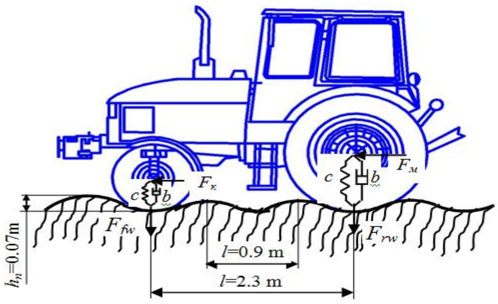

Fig. 1. Tractor design model.

In accordance with the design scheme given in Fig. 1, let's build a generalized mathematical model of horizontal and vertical oscillations of a 4-wheeled tractor in the process of moving over the roughness on the headland of the cotton field in the form of the Lagrange equations of the second kind:

- for horizontal oscillations:

$$\left.\begin{aligned}
m_t\ddot{x}_t &= F_x - b_1(\dot{x}_t-\dot{x}_{Lrw}) - c_1(x_t-x_{Lrw}) - b_2(\dot{x}_t-\dot{x}_{Rrw}) - c_2(x_t-x_{Rrw}) - \\
&\quad - b_3(\dot{x}_t-\dot{x}_{Lfw}) - c_3(x_t-x_{Lfw}) - b_4(\dot{x}_t-\dot{x}_{Rfw}) - c_4(x_t-x_{Rfw}) \\
m_{Lrw}\ddot{x}_{Lrw} &= b_1(\dot{x}_t-\dot{x}_{Lrw}) + c_1(x_t-x_{Lrw}) - m_{Lrw}\frac{2\pi^2V_{Lrw}^2}{l_{gr}^2}h_s\sin\frac{2\pi V_{Lrw}}{l_{gr}}t \\
m_{Rrw}\ddot{x}_{Rrw} &= b_2(\dot{x}_t-\dot{x}_{Rrw}) + c_2(x_t-x_{Rrw}) - m_{Rrw}\frac{2\pi^2V_{Rrw}^2}{l_{gr}^2}h_s\sin\frac{2\pi V_{Rrw}}{l_{gr}}t \\
m_{Lfw}\ddot{x}_{Lfw} &= b_3(\dot{x}_t-\dot{x}_{Lfw}) + c_3(x_t-x_{Lfw}) - m_{Lfw}\frac{2\pi^2V_{Lfw}^2}{l_{gr}^2}h_s\sin\frac{2\pi V_{Lfw}}{l_{gr}}t \\
m_{Rfw}\ddot{x}_{Rfw} &= b_4(\dot{x}_t-\dot{x}_{Rfw}) + c_4(x_t-x_{Rfw}) - m_{Rfw}\frac{2\pi^2V_{Rfw}^2}{l_{gr}^2}h_s\sin\frac{2\pi V_{Rfw}}{l_{gr}}t
\end{aligned}\right\} \quad (1)$$

- for vertical oscillations

$$\left.\begin{aligned}
&m_t\ddot{y}_t = F_y - b_1\frac{B}{2}(\dot\varphi_t-\dot\varphi_{Lrw}) - c_1\frac{B}{2}(\varphi_t-\varphi_{Lrw}) - b_2\frac{B}{2}(\dot\varphi_t-\dot\varphi_{Rrw}) - c_2\frac{B}{2}(\varphi_t-\varphi_{Rrw}) - \\
&\quad - b_3\frac{B}{2}(\dot\varphi_t-\dot\varphi_{Lfw}) - c_3\frac{B}{2}(\varphi_t-\varphi_{Lfw}) - b_4\frac{B}{2}(\dot\varphi_t-\dot\varphi_{Rfw}) - c_4\frac{B}{2}(\varphi_t-\varphi_{Rfw}) \\
&m_{Lrw}\ddot{y}_{Lrw} = b_1\frac{B}{2}(\dot\varphi_t-\dot\varphi) + c_1\frac{B}{2}(\varphi_t-\varphi_{Lrw}) - m_{Lrw}\frac{2\pi^2V_{Lrw}^2}{l_n^2}h_s\left(1-\cos\frac{2\pi V_{Lrw}}{l_n}t\right) \\
&m_{Rrw}\ddot{y}_{Rrw} = b_2\frac{B}{2}(\dot\varphi_t-\dot\varphi_{Rrw}) + c_2\frac{B}{2}(\varphi_t-\varphi_{Rrw}) - m_{Rrw}\frac{2\pi^2V_{Rrw}^2}{l_n^2}h_s\left(1-\cos\frac{2\pi V_{Rrw}}{l_n}t\right) \\
&m_{Lfw}\ddot{y}_{Lfw} = b_3\frac{B}{2}(\dot\varphi_t-\dot\varphi_{Lfw}) + c_3\frac{B}{2}(\varphi_t-\varphi_{Lfw}) - m_{Lfw}\frac{2\pi^2V_{Lfw}^2}{l_n^2}h_s\left(1-\cos\frac{2\pi V_{Lrw}}{l_n}t\right) \\
&m_{Rfw}\ddot{y}_{Rfw} = b_4\frac{B}{2}(\dot\varphi_t-\dot\varphi_{Rfw}) + c_4\frac{B}{2}(\varphi_t-\varphi_{Rfw}) - m_{Rfw}\frac{2\pi^2V_{Rfw}^2}{l_n^2}h_n\left(1-\cos\frac{2\pi V_{Rfw}}{l_n}t\right) \\
&j_t\ddot\varphi_t = e m_{Lws}\ddot{y}_t - h_c k_c m_{Rws}\ddot{y}_t \sin\frac{2\pi V_t}{l_n}t
\end{aligned}\right\} \qquad (2)$$

where F_x, F_y - tractor pulling forces; $\dot{x}_i$ and $\ddot{x}_i$ - linear speeds and acceleration of tractor for front and rear wheels of the tractor under horizontal oscillation; $\dot{y}_i$ and $\ddot{y}_i$ - linear speeds and acceleration of tractor for front and rear wheels of the tractor under vertical oscillations; V_i – speed of tractor and its wheels under horizontal and vertical oscillation; b_i, c_i - coefficients of viscous resistance and rigidity of the wheel tire of a tractor; m_i - distributed mass on supports of tractor wheels; h_n − height of the road roughness; l_n – distance between the support and road roughness.

III. RESEARCHING OF THE NECESSARY CONDITIONS FOR OPTIMAL CONTROL AND SOLUTION OF THE PROBLEM OF OPTIMAL CONTROL OF THE WHEEL TRACTOR MOVEMENT

To solve the problem, the theory of optimal systems is used. The statement of the optimal control problem is as follows [1,2,12,13].

At the initial time, the test object is in the following state:

$$q_i(0)=q_0(0), \qquad \dot q_i(0)=\dot q_0(0), \qquad V_i(0)=V_0(0) \qquad (3)$$

It is required to choose such a control $u(t)$, which will transfer the test object to a predetermined final state

$$q_i(t)=q_0(t),\;\; \dot q_i(t)=\dot q_0(t),\;\; V_i(t)=V_0(t)\;\; (i=\overline{1,n}),\quad 0\le t\le T. \qquad (4)$$

Time of the transition process should be the shortest.

Then the goal of control is reduced to minimizing the functional with $q=x_i$, $q=y_i$ [1−5].

$$J(q_0,u(t),q(t)) = \int_{t_0}^{T} f^0(q(t),u(t),t)dt + g^0(q_0,g(T))\,. \qquad (5)$$

at the conditions equations (3)-(4)

$$\dot q(t) = f(q(t),u(t),t). \qquad (6)$$

Let the functions be set as:

$$g^i(q_0,q(T))\le 0, \quad i=1,\ldots,m;$$

$$g^i(q_0,q(T))=0, \quad i=m+1,\ldots,s; \qquad (7)$$

$$u\in U, \quad t_0\le t\le T, \qquad (8)$$

where $f(q(t),u(t),t)$ is the continuously differentiable function with its derivatives; $u(t)$ is a piecewise continuous function on the interval $[t_0, T]$.

In machine testing under specified operating conditions, the performance criterion can be an evaluation of the speed of operation.

To study necessary conditions for optimal control, the Pontryagin maximum principle [12,13] is used.

To formulate the maximum principle, we introduce the Hamilton – Pontryagin function

$$H=(q,u,t,\psi_i,\psi_0)=-f^0(q,u,t)+\langle\psi,u\rangle \qquad (9)$$

and a conjugated system for horizontal oscillations:

$$\left.\begin{aligned}
&\frac{d\psi_1}{dt}=-\frac{\partial H_t}{\partial x_1}=-m_t^{-1}(c_1+c_2+c_3+c_4)\psi_2, \\
&\frac{d\psi_2}{dt}=-\frac{\partial H_t}{\partial x_2}=-\psi_1+m_t^{-1}(b_1+b_2+b_3+b_4)\psi_2 \\
&\frac{d\psi_1}{dt}=-\frac{\partial H_{Lrw}}{\partial x_3}=-m_{Lrw}{}^{-1}c_1\psi_2, \quad \frac{d\psi_2}{dt}=-\frac{\partial H_{Lrw}}{\partial x_4}=-\psi_1+m_{Lrw}{}^{-1}b_1\psi_2 \\
&\frac{d\psi_1}{dt}=-\frac{\partial H_{Rrw}}{\partial x_5}=-m_{Rrw}{}^{-1}c_2\psi_2, \quad \frac{d\psi_2}{dt}=-\frac{\partial H_{Rrw}}{\partial x_6}=-\psi_1+m_{Rrw}{}^{-1}b_2\psi_2 \\
&\frac{d\psi_1}{dt}=-\frac{\partial H_{Lfw}}{\partial x_7}=-m_{Lfw}{}^{-1}c_3\psi_2, \quad \frac{d\psi_2}{dt}=-\frac{\partial H_{Lfw}}{\partial x_8}=-\psi_1+m_{Lfw}{}^{-1}b_3\psi_2 \\
&\frac{d\psi_1}{dt}=-\frac{\partial H_{Rfw}}{\partial x_9}=-m_{Rfw}{}^{-1}c_4\psi_2, \quad \frac{d\psi_2}{dt}=-\frac{\partial H_{Rfw}}{\partial x_{10}}=-\psi_1+m_{Rfw}{}^{-1}b_4\psi_2
\end{aligned}\right\} \qquad (10)$$

with restriction on control $|u|\le 1$.

To solve the problem under consideration, the following necessary condition must be met:

$$H(q_i(t),u(t),t,\psi_i,\psi_0)=\max_{u\in U} H(q_i(t),u,t,\psi_i(t),\psi_0) \qquad (11)$$

Proceeding to determining the optimal control of tractor based on (9), the following function for horizontal oscillations is formed as:

$$\left.\begin{aligned}
&x_{м}=x_1,\dot x_{м}=x_2,\dot x_2=u_x-m_{м}^{-1}[b_1(x_2-x_4)-c_1(x_1-x_3)- \\
&\quad -b_2(x_2-x_6)-c_2(x_1-x_5)-b_3(x_2-x_8)-c_3(x_1-x_7)- \\
&\quad -b_4(x_2-x_{10})-c_4(x_1-x_9)] \\
&x_{кзл}=x_3,\dot x_{кзл}=x_4,\dot x_4=m_{кзл}{}^{-1}[b_1(x_2-x_4)+c_1(x_1-x_3)]-u_1 \\
&x_{кзп}=x_5,\dot x_{кзп}=x_6,\dot x_6=m_{кзп}{}^{-1}[b_2(x_2-x_6)+c_2(x_1-x_5)]-u_2 \\
&x_{кпл}=x_7,\dot x_{кпл}=x_8,\dot x_8=m_{кпл}{}^{-1}[b_3(x_2-x_8)+c_3(x_1-x_7)]-u_3 \\
&x_{кпп}=x_9,\dot x_{кпп}=x_{10},\dot x_{10}=m_{кпп}{}^{-1}[b_4(x_2-x_{10})+c_4(x_1-x_9)]-u_4
\end{aligned}\right\} \qquad (12)$$

If $f^0\equiv 1$, $g^0\equiv 0$, then $J(q_0,u(t),q(t))=T-t_0$, in this case the problem presented by equations (5)-(8) is called the problem of operation speed.

The object under consideration is a stationary system and the problem (5) means that f and U do not explicitly depend on time, i.e.

$$f(t,q,u)=f(q,u), \qquad U(t)=U\,. \qquad (13)$$

If the stationary problems (5), (13) have an optimal control $u(t)$ and an optimal path $q_0(t)$, then there exists a non-zero vector of conjugate variables $(\psi_1(t),\ \psi_2(t))$, $\psi(t)\in R^n$ satisfying conditions by equation (3), i.e. the maximum condition is satisfied equation (11)

$$\psi_0(t)=const\le 0\,. \qquad (14)$$

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Since conjugate system (10) are homogeneous relative to ψ_i, a constant in equation (14) can be arbitrarily chosen as:

$$\psi_0(t) = -1 \qquad 0 \le t \le T. \qquad (15)$$

From the condition $\max\limits_{|u|\le 1} H$ follows $u = sign\psi_2$ at $\psi_2 \ne 0$, then the boundary value problem of the maximum principle for horizontal oscillations is written in the following form:

$$\left.\begin{aligned}
\ddot{x}_2 &= sign\psi_2 - m_t^{-1}[b_1(x_2-x_4) - c_1(x_1-x_3) - \\
&\quad - b_2(x_2-x_6) - c_2(x_1-x_5) - b_3(x_2-x_8) - \\
&\quad - c_3(x_1-x_7) - b_4(x_2-x_{10}) - c_4(x_1-x_9)] \\
\ddot{x}_4 &= m_{Lrw}^{-1}[b_1(x_2-x_4) + c_1(x_1-x_3)] - sign\psi_2 \\
\ddot{x}_6 &= m_{Rrw}^{-1}[b_2(x_2-x_6) + c_2(x_1-x_5)] - sign\psi_2 \\
\ddot{x}_8 &= m_{Lfw}^{-1}[b_3(x_2-x_8) + c_3(x_1-x_7)] - sign\psi_2 \\
\ddot{x}_{10} &= m_{Rfw}^{-1}[b_4(x_2-x_{10}) + c_4(x_1-x_9)] - sign\psi_2
\end{aligned}\right\} \quad (16)$$

The boundary value problem of the maximum principle in this case consists of system equation (16), boundary conditions (3) and (4) resulting from equation (11), and condition (15).

Hamilton-Pontryagin function [3, 5] for horizontal oscillations was composed as:

$$\left.\begin{aligned}
H_t &= \psi_0 + \psi_1 x_2 + \psi_2 \ddot{x}_2 \\
H_{Lrw} &= \psi_0 + \psi_1 x_4 + \psi_2 \ddot{x}_4 \\
H_{Rrw} &= \psi_0 + \psi_1 x_6 + \psi_2 \ddot{x}_6 \\
H_{Lfw} &= \psi_0 + \psi_1 x_8 + \psi_2 \ddot{x}_8 \\
H_{Rfw} &= \psi_0 + \psi_1 x_{10} + \psi_2 \ddot{x}_{10}
\end{aligned}\right\}. \quad (17)$$

Condition (11) will mark out the function $u = sign\psi_2$, $\psi_2 \ne 0$. The boundary value problem (16) in this case has the form

$$H_i = -f^0 u + \psi_2(t) u_d \qquad (18)$$

Let us proceed to investigate equations (10), (18) in the area of following:

$$u_k = sign\psi_2(t) = \begin{cases} 1, & \psi_2(t) > 1 \\ -1, & \psi_2(t) < 1 \end{cases}, \quad \kappa = 2, 4, \square, 2\nu, \qquad (19)$$

that is, the control $u_k(t)$ can have only one switch point.

Thus, from the Pontryagin maximum principle, we obtain the structure of optimal control of motion of the tractor guide wheels.

To determine the auxiliary functions (10), the conjugate system with variation in design parameters b_i, c_i, m_i has been investigated by a numerical method.

IV. EXPERIMENTAL RESULTS

As a result, graphical dependences of the rates and accelerations of tractor oscillations, the maximum values of the H-function have been obtained and presented on Fig. 2-5 and in Tables I-VI.

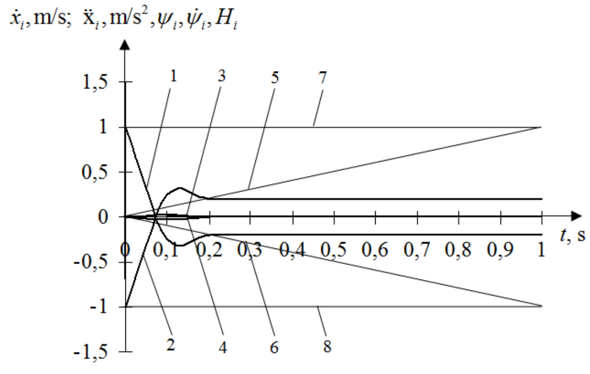

Fig. 2. Graphs of transient processes: 1 – accelerations $\ddot{x}_m, \ddot{x}_{rwl}, \ddot{x}_{rwr}, \ddot{x}_{fwl}, \ddot{x}_{fwr}$; 3- velocities $\dot{x}_m, \dot{x}_{rwl}, \dot{x}_{rwr}, \dot{x}_{fwl}, \dot{x}_{fwr}$; auxiliary functions: 5 - ψ_1, ψ_2; 7- $\dot{\psi}_1$, $\dot{\psi}_2$; H_i at u(t)=+1; 2 – accelerations $\ddot{x}_m, \ddot{x}_{rwl}, \ddot{x}_{rwr}, \ddot{x}_{fwl}, \ddot{x}_{fwr}$; 3 - velocities $\dot{x}_m, \dot{x}_{rwl}, \dot{x}_{rwr}, \dot{x}_{fwl}, \dot{x}_{fwr}$; auxiliary functions: 6 - ψ_1, ψ_2; 8- $\dot{\psi}_1$, $\dot{\psi}_2$; H_i at u(t)= -1 for horizontal oscillations of tractor.

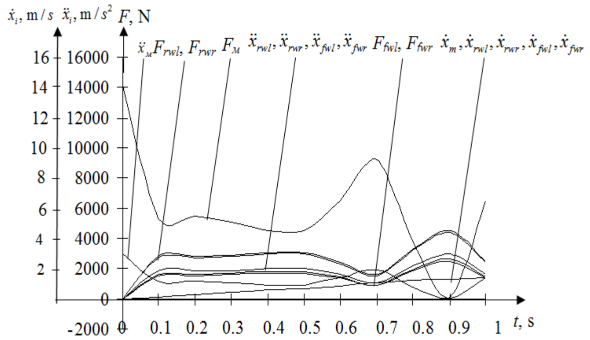

Fig. 3. The character of the motion parameters change of four-wheeled universal tractors with stepless adjustable clearance for horizontal oscillation at h_t=0.01m

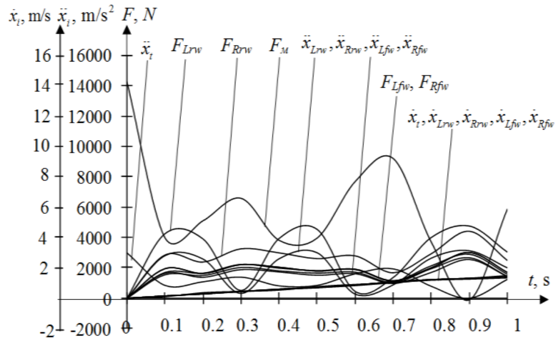

Fig. 4. The character of the change of the motion parameters of four-wheeled universal tractors with stepless adjustable clearance for horizontal oscillations at ht=0.02 m

Systems (1), (2), (10), (16) are solved using the Runge-Kutta numerical method. The control $u_k(t)$, bringing the maximum of function (11), is defined in area (19).

Table-I: Values of speeds and accelerations in the transition process of the beginning of the tractor movement

T, s	$\dot{x}_t$, m/s	$\ddot{x}_t$, m/s²	$\dot{x}_{Lrw}$, m/s	$\ddot{x}_{Lrw}$, m/s²	$\dot{x}_{Rrw}$, m/s	$\ddot{x}_{Rrw}$, m/s²	$\dot{x}_{Lfw}$, m/s	$\ddot{x}_{Lfw}$, m/s²	$\dot{x}_{Rfw}$, m/s	$\ddot{x}_{Rfw}$, m/s²	$\dot{x}_t$, m/s	$\ddot{x}_t$, m/s²	$\dot{x}_{Lrw}$, m/s	$\ddot{x}_{Lrw}$, m/s²	$\dot{x}_{Rrw}$, m/s	$\ddot{x}_{Rrw}$, m/s²	$\dot{x}_{Lfw}$, m/s	$\ddot{x}_{Lfw}$, m/s²	$\dot{x}_{Rfw}$, m/s	$\ddot{x}_{Rfw}$, m/s²
	u=+1										u=-1									
0	0	1	0	-1	0	-1	0	-1	0	-1	0	-1	0	1	0	1	0	1	0	1
0.1	0.03	-0.24	-0.03	0.24	-0.03	0.24	-0.03	0.24	-0.03	0.24	-0.03	0.24	0.03	-0.24	0.03	-0.24	0.03	-0.24	0.03	-0.24
0.2	0.0008	-0.2	-0.0008	0.2	-0.0008	0.2	-0.0008	0.2	-0.0008	0.2	-0.0008	0.2	0.0008	-0.2	0.0008	-0.2	0.0008	-0.2	0.0008	-0.2
0.3	0.0002	-0.2	-0.0002	0.2	-0.0002	0.2	-0.0002	0.2	-0.0002	0.2	-0.0002	0.2	0.0002	-0.2	0.0002	-0.2	0.0002	-0.2	0.0002	-0.2
0.4	0	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2
0.5	0	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2
0.6	0	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2
0.7	0	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2
0.8	0	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2
0.9	0	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2
1	0	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2

Table-II: The values of conjugate systems and hamilton-pontryagin functions in the transition process of the beginning of the tractor movement

T, s	ψ_1	$\dot{\psi}_1$	ψ_2	$\dot{\psi}_2$	H_t	ψ_1	$\dot{\psi}_1$	ψ_2	$\dot{\psi}_2$	H_t
	u=+1					u=-1				
0	0	0.98	0	0.98	0.99	0	-0.98	0	-0.98	-0.99
0.1	0.098	0.98	0.09	0.98	0.99	-0.098	-0.98	-0.09	-0.98	-0.99
0.2	0.196	0.98	0.185	0.98	0.99	-0.196	-0.98	-0.185	-0.98	-0.99
0.3	0.29	0.98	0.278	0.98	0.99	-0.29	-0.98	-0.278	-0.98	-0.99
0.4	0.39	0.98	0.37	0.98	0.99	-0.39	-0.98	-0.37	-0.98	-0.99
0.5	0.49	0.98	0.46	0.98	0.99	-0.49	-0.98	-0.46	-0.98	-0.99
0.6	0.588	0.98	0.556	0.98	0.99	-0.588	-0.98	-0.556	-0.98	-0.99
0.7	0.686	0.98	0.649	0.98	0.99	-0.686	-0.98	-0.649	-0.98	-0.99
0.8	0.785	0.98	0.74	0.98	0.99	-0.785	-0.98	-0.74	-0.98	-0.99
0.9	0.885	0.98	0.835	0.98	0.99	-0.885	-0.98	-0.835	-0.98	-0.99
1	0.98	0.98	0.928	0.98	0.99	-0.98	-0.98	-0.928	-0.98	-0.99

Table-III: The values of operation parameters for horizontal oscillations at the tire deflection of h_t=0.01m

T, s	$\dot{x}_t$, m/s	$\ddot{x}_t$, m/s²	F_x, N	$\dot{x}_{Lrw}$, m/s	$\ddot{x}_{Lrw}$, m/s²	F_{Lrw}, N	$\dot{x}_{Rrw}$, m/s	$\ddot{x}_{Rrw}$, m/s²	F_{Rrw}, N	$\dot{x}_{Lfw}$, m/s	$\ddot{x}_{Lfw}$, m/s²	F_{Lfw}, N	$\dot{x}_{Rfw}$, m/s	$\ddot{x}_{Rfw}$, m/s²	F_{Rfw}, N
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	2.98	14190	0	0	0	0	0	0	0	0	0	0	0	0
0.1	0.15	1.126	5351.02	0.145	1.86	2837.7	0.145	1.86	2744.7	0.145	1.86	1665.4	0.145	1.86	1591.01
0.2	0.299	1.15	5480.28	0.296	1.83	2796.2	0.296	1.83	2704.6	0.296	1.83	1641.1	0.296	1.83	1567.7
0.3	0.443	1.08	5129.6	0.44	1.9	2899.2	0.44	1.9	2804.1	0.44	1.9	1701.5	0.44	1.9	1625.46
0.4	0.578	0 .96	4577.9	0.576	2.02	3085.9	0.576	2.02	2984.8	0.576	2.02	1811.1	0.576	2.02	1730.17
0.5	0.7	0.96	4578.2	0.7	2.02	3085.8	0.7	2.02	2984.7	0.7	2.02	1811.06	0.7	2.02	1730.1
0.6	0.850	1.37	6530.4	0.853	1.6	2459.1	0.853	1.6	2378.5	0.853	1.6	1443.2	0.853	1.6	1378.7
0.7	1.040	1.93	9184.1	1.048	1.05	1607.1	1.048	1.05	1554.4	1.048	1.05	943.2	1.048	1.05	901.06
0.8	1.210	0.8	3847.3	1.2	2.17	3320.5	1.2	2.17	3211.6	1.2	2.17	1948.7	1.2	2.17	1861.6
0.9	1.290	0.019	92.6	1.28	2.96	4526.01	1.28	2.96	4377.6	1.28	2.96	2656.2	1.28	2.96	2537.5
1	1.378	1.37	6510.9	1.388	1.6	2465.3	1.388	1.6	2384.5	1388	1.6	1446.9	1.388	1.6	1382.2

Table-IV: The values of operation parameters for horizontal oscillations at the tire deflection of h_t=0.02 m

T, s	$\dot{x}_t$, m/s	$\ddot{x}_t$, m/s²	F_x, N	$\dot{x}_{Lrw}$, m/s	$\ddot{x}_{Lrw}$, m/s²	F_{Lrw}, N	$\dot{x}_{Rrw}$, m/s	$\ddot{x}_{Rrw}$, m/s²	F_{Rrw}, N	$\dot{x}_{Lfw}$, m/s	$\ddot{x}_{Lfw}$, m/s²	F_{Lfw}, N	$\dot{x}_{Rfw}$, m/s	$\ddot{x}_{Rfw}$, m/s²	F_{Rfw}, N
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	3.0	14250	0	0	0	0	0	0	0	0	0	0	0	0
0.1	0.16	0.83	3965.1	0.097	2.78	4246.6	0.148	1.94	2861.02	0.15	1.7	1524.9	0.148	1.93	1652.3
0.2	0.28	1.07	5086.7	0.36	2.56	3904.4	0.286	1.62	2393.5	0.28	1.65	1477.2	0.28	1.62	1388.1
0.3	0.447	1.38	6570.9	0.44	3.3	513.9	0.437	2.2	3270.6	0.437	2.23	1997.8	0.437	2.2	1896.7
0.4	0.59	0.799	3796.4	0.52	2.58	3934.3	0.59	2.03	3002.6	0.59	1.98	1777.3	0.59	2.03	1739.2
0.5	0.7	0.83	3943.7	0.75	2.97	4531.5	0.7	1.77	2623.3	0.7	1.82	1629.6	0.7	1.78	1521.78
0.6	0.85	1.6	7673.1	0.89	0.29	453.2	0.85	1.9	2804.4	0.85	1.89	1693.7	0.85	1.9	1625.4
0.7	1.05	1.93	9199.8	1.0	0.89	1371.6	1.07	1.14	1685.9	1.06	1.135	1015.8	1.07	1.14	976.77
0.8	1.22	0.77	3680.7	1.2	2.62	3997.07	1.2	1.99	2944.2	1.2	2.14	1917.6	1.2	2.0	1710.3
0.9	1.29	-0.029	-137.66	1.29	3.1	4753.08	1.28	3.0	4433.57	1.28	2.9	2632.2	1.28	3.0	2568.7
1	1.37	1.23	5851.5	1.46	1.99	3040.4	1.39	1.69	2498.8	1.38	1.58	1413.7	1.39	1.69	1445.4

Computational experiment has been conducted at the following parameters:

-for horizontal oscillations at the tire deflection of h_t=0.01m: $c_1=c_{Lrw}$=1496025 N/m; $b_1=b_{Lrw}$=110480 N·s/m; $c_2=c_{Rrw}$=1446975 N/m; $b_2=b_{Rrw}$=106856.8 N·s/m; $c_3=c_{Lfw}$=877995 N/m; $b_3=b_{Lfw}$=64838.85 N·s/m; $c_4=c_{Rfw}$=838755 N/m; $b_4=b_{Rfw}$=61940.7 N·s/m; m_t=4750kg; m_{Lrw}=1525 кг; m_{Rrw}=1475 kg; m_{Lfw}=895 kg; m_{Rfw}=855kg; $r_{кз}$=0.785m; r_{fr}=0.43 m; h_n =0.07m; V_t=1.38 m/s; $F_x = 14190$ N.

-for horizontal oscillations at the tire deflection of h_t=0.02m: $c_1=c_{Lrw}$=748012.5 N/m; $b_1=b_{Lrw}$=55239.55 Ns/m; $c_2=c_{Rrw}$=723487.5 N/m; $b_2=b_{Rrw}$=53428.4 Ns/m; $c_3=c_{Lfw}$=438997.5 N/m; $b_3=b_{Lfw}$=32419.27 N·s/m; $c_4=c_{Rfw}$=419377.5 N/m; $b_4=b_{Rfw}$=30970.26 N·s/m; m_t=4750 kg; m_{Lrw}=1525 kg; m_{Rrw}=1475 kg; m_{Lfw}=895 kg; m_{Rfw}=855kg; r_{rw}=0.785m; r_{fr}=0.43 m; h_n =0.07m; V_t=1.38 m/s; $F_x = 14250$ N.

- for vertical oscillations at the tire deflection of h_t=0.01m: $c_1=c_{Lrw}$=1496025 N/m; $b_1=b_{Lrw}$=110480 Ns/m; $c_2=c_{Rrw}$=1446975 N/m; $b_2=b_{Rrw}$=106856.8 Ns/m; $c_3=c_{Lfw}$=877995 N/m; $b_3=b_{Lfw}$=64838.85 Ns/m; $c_4=c_{Rfw}$=838755 N/m; $b_4=b_{Rfw}$=61940.7 Ns/m; m_t=4750kg; m_{Lrw}=1525 kg; m_{Rrw}=1475 kg; m_{Lfw}=895 kg; m_{Rfw}=855 kg; $r_{кз}$=0.785m; r_{fr}=0.43 m; h_n =0.07m; V_t=1.38 m/s; $F_y = 10033.845$ N.

- for vertical oscillations at the tire deflection of h_t=0.02 m: $c_1=c_{Lrw}$=748012.5 N/m; $b_1=b_{Lrw}$=55239.55 Ns/m; $c_2=c_{Rrw}$=723487.5 N/m; $b_2=b_{Rrw}$=53428.4 Ns/m; $c_3=c_{Lfw}$=438997.5 N/m; $b_3=b_{Lfw}$=32419.27 Ns/m; $c_4=c_{Rfw}$=419377.5 N/m; $b_4=b_{Rfw}$=30970.26 Ns/m; m_t=4750 kg; m_{Lrw}=1525 kg; m_{Rrw}=1475 kg; m_{Lfw}=895 kg; m_{Rfw}=855kg; r_{rw}=0.785m; r_{fr}=0.43 m; h_n =0.07m; V_t=1.38 m/s; $F_y = 10076.27$ N.

Table-V: The values of tractor operation parameters for vertical oscillations at the tire deflection of h_t=0.01 m

T, s	$\dot y_t$, m/s	$\ddot y_t$, m/s²	F_y, N	$\dot y_{Lrw}$, m/s	$\ddot y_{Lrw}$, m/s²	F_{Lrw}, N	$\dot y_{Rrw}$, m/s	$\ddot y_{Rrw}$, m/s²	F_{Rrw}, N	$\dot y_{Lfw}$, m/s	$\ddot y_{Lfw}$, m/s²	F_{Lfw}, N	$\dot y_{Rfw}$, m/s	$\ddot y_{Rfw}$, m/s²	F_{Rfw}, N
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	2.11	10033.8	0	0	0	0	0	0	0	0	0	0	0	0
0.1	0.1	0.79	3787.5	0.1	1.3	2500.4	0.1	1300	1939.6	0.1	1.3	1176.9	0.1	1.3	1124.3
0.2	0.2	0.83	3943.5	0.2	1.28	1955.3	0.2	1280	1891.2	0.2	1.28	1147.5	0.2	1.28	1096.25
0.3	0.3	0.8	3931.1	0.3	1.284	1959.33	0.3	1284	1895	0.3	1.284	1149.9	0.3	1.284	1098.5
0.4	0.419	0.77	3678	0.418	1.338	2040.5	0.418	1338	1973.6	0.418	1.338	1197.5	0.418	1.338	1144.05
0.5	0.5	0.63	2696.3	0.5	1.48	2259.4	0.5	1480	2185.3	0.5	1.48	1326	0.5	1.48	1266.7
0.6	0.59	0.418	1985.6	0.59	1.69	2583.9	0.59	1690	2499.2	0.59	1.69	1516.45	0.59	1.69	1448.68
0.7	0.65	0.25	1193.9	0.65	1.86	2838.8	0.65	1860	2745.03	0.65	1.86	1665.6	0.65	1.86	1591.2
0.8	0.7	0.248	1181.5	0.7	1.863	2842.06	0.7	1863	2748.8	0.7	1.863	1667.9	0.7	1.863	1593.4
0.9	0.773	0.47	2270.2	0.775	1.63	2492.5	0.775	1630	2410.8	0.775	1.63	1462.8	0.775	1.63	1397.45
1	0.864	0.837	3977.7	0.867	1.27	1944.3	0.867	1270	1880.5	0.867	1.27	1141.09	0.867	1.27	1090.09

Table-VI: The values of tractor operation parameters for vertical oscillations at the tire deflection of h_t=0.02 m

T, s	$\dot y_t$, m/s	$\ddot y_t$, m/s²	F_y, N	$\dot y_{Lrw}$, m/s	$\ddot y_{Lrw}$, m/s²	F_{Lrw}, N	$\dot y_{Rrw}$, m/s	$\ddot y_{Rrw}$, m/s²	F_{Rrw}, N	$\dot y_{Lfw}$, m/s	$\ddot y_{Lfw}$, m/s²	F_{Lfw}, N	$\dot y_{Rfw}$, m/s	$\ddot y_{Rfw}$, m/s²	F_{Rfw}, N
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	2.12	10076.27	0	0	0	0	0	0	0	0	0	0	0	0
0.1	0.1	0.728	3460.2	0.098	1.39	2124.1	0.098	1.39	2054.45	0.098	1.39	1246.6	0.098	1.39	1190.8
0.2	0.2	0.8	3878.1	0.2	1.3	1989.9	0.2	1.3	1924.7	0.2	1.3	1167.8	0.2	1.3	1115.6
0.3	0.3	0.83	3973.3	0.3	1.29	1970.7	0.3	1.29	1906.16	0.3	1.29	1156.6	0.3	1.29	1104.9
0.4	0.42	0.78	3707.5	0.42	1.34	2444.7	0.42	1.34	1977.6	0.42	1.34	1200	0.42	1.34	1146.37
0.5	0.5	0.64	3033.8	0.5	1.48	2260.9	0.5	1.48	2186.86	0.5	1.48	1326.9	0.5	1.48	1267.6
0.6	0.59	0.42	2006.22	0.59	1.7	2590.9	0.59	1.7	2505.9	0.59	1.7	1520.5	0.59	1.7	1452.6
0.7	0.658	0.247	1174.9	0.654	1.87	2857.7	0.654	1.87	2764.08	0.654	1.87	1677.18	0.654	1.87	1602.2
0.8	0 .7	0.238	1133.04	0.7	1.88	2871.2	0.7	1.88	2777.1	0.7	1.88	1685.1	0.7	1.88	1609.78
0.9	0.776	0.47	2241.9	0.779	1.649	2515.2	0.779	1.649	2432.7	0.779	1.649	1476.1	0.779	1.649	1410.18
1	0.867	0.85	4040.38	0.874	1.27	1937.8	0.874	1.27	1874.3	0.874	1.27	1137.3	0.874	1.27	1086.46

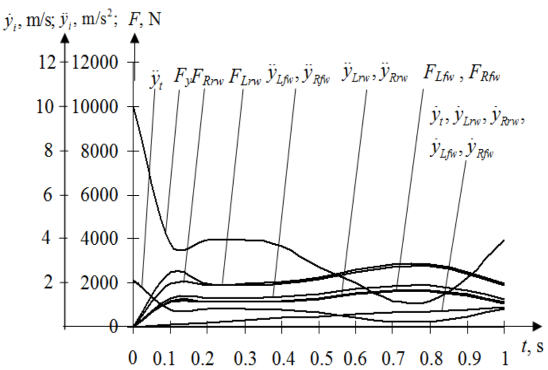

Fig. 5. The character of the change of the motion parameters of four-wheeled universal tractors with stepless adjustable clearance for vertical oscillations at h_t=0.01 mm

V. RESEARCHING OF THE CONTROLLABILITY OF THE TRACTOR WHEELS IN MOTION ON ROUGHNESS ROAD

In real operating conditions of the curvilinear movement of the tractor, in which the side wheel drive is always present. However, we first consider in what proportions the angles of rotation of various wheels should be on the assumption: the wheels are rigid in the lateral direction, i.e.

there is no skidding and the wheels roll in the plane of their rotation [3,4,14].

In our case, when the wheels of only one axle are controlled by a two-axle machine, we get:

$$\frac{CO}{BC}=ctg\alpha_2\,;\quad \frac{DO}{AD}=ctg\alpha_1\,,$$

$$AD=a=c\cdot\sin\alpha_2=2678\cdot0.5=1339\,\text{mm};$$

$$DO=b=c\cdot\cos\alpha_2=2678\cdot0.866=2319.216\,\text{mm};$$

$$CO=b+l_0=2319.216+1800=4119.216\,\text{mm}.$$

Subtracting from the first equality the second, mean $AD=BC$, we get:

$$ctg\alpha_2-ctg\alpha_1=\frac{l_0}{L}=\frac{1800}{2678}=0.672\,,$$

where l_0 – the distance between the axles of the pivot pin.

With the existing real ratios $\frac{l_0}{L}$ the difference in the angles of rotation of the inner and outer steered wheels is on average a fraction of a degree, so in most cases you can make calculations with sufficient accuracy for practice, take the average angle of rotation of the wheels and consider the so-called cycling turning scheme in which two wheels of the same axis as if united in one. The advantage of this scheme is a reduction by about 2 times the number of equations describing the movement of a machine [3,4,14,15].

The turning radius, called the kinematic radius, is defined as

$$R=\frac{L}{tg(\frac{\alpha_2+\alpha_1}{2})}=\frac{L}{tg\alpha}=\frac{2678}{tg35^0}=\frac{2678}{0.7}=3825.7\ \text{mm},$$

$$R_2=\frac{L}{tg\alpha_2}=\frac{2678}{tg40^0}=\frac{2678}{0.839}=3191.895\ \text{mm}\,,$$

$$R_1=\frac{L}{tg\alpha_1}=\frac{2678}{tg30^0}=\frac{2678}{0.57735}=4638.434\ \text{mm}\,,$$

where L – the base of the tractor; α – the average angle of rotation of the driven wheels; O – the center of rotation of the tractor.

The determination of the turning radius of the tractor as the main operational indicator of the curvilinear motion of the machine-tractor unit (MTU) requires a number of additional systematic refinements. The classic assumptions about the kinematic motion of turning a wheeled tractor are based on a number of assumptions. The main assumptions are aimed at clarifying the concept of correctness of rotation, in which the wheels roll without sliding and there is no lateral wheel drive of the tractor.

As known, with the curvilinear movement of the tractor, an additional component of the lateral force increases, and tire slippage on the supporting surface occurs. In this case, the uniformity of motion is influenced not only by the speed of rotation, but also by the elastic and damping characteristics of the entire steering gear and tires. Consider the kinematic scheme of turning the tractor with rear driving and front driven wheels (Fig. 6). Let us assume that the tractor moves at a low constant speed, when the centrifugal force can be neglected [11,14,15,20].

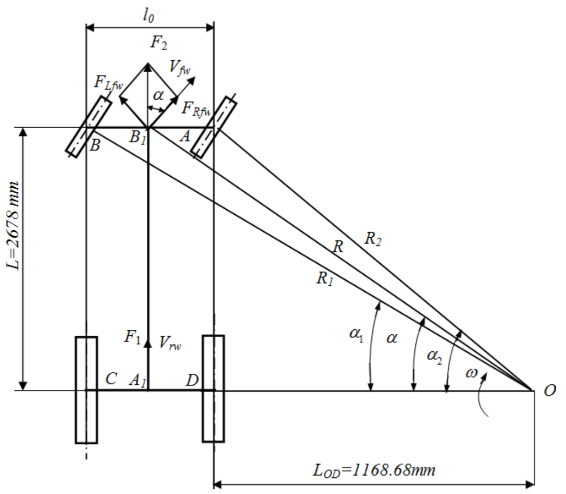

Fig. 6. Kinematic scheme of tractor turning.

Tangential force of the front axle F_1 attached at point A_1 and directed along the longitudinal axis of the tractor. At the same time, point A_1 moves at a speed v_1 in the direction of the thrust force of the rear axle, since in the absence of lateral forces there are no reasons for its change. The steering wheels of the front axle, rotated at the middle angle $\alpha=35^o$, move under the action of the pushing force $F_{2L}=m_{Lfw}\&\&_{Lfw}$ $F_{2R}=m_{Rfw}\&\&_{Rfw}$ transmitted by the rear axle from the tractor's longitudinal frame. The pushing force is applied at point B_1 and acts along the longitudinal frame of the tractor. We decompose this force into two components: $F_{Lfw}=F_{2L}\cos\alpha$, directed at an angle to the longitudinal axis of the machine and a force $F_{Rfw}=F_{2R}\cdot\sin\alpha$, perpendicular to the force F_{Lfw}.

Analyzing the obtained results, we can note the following: with the curvilinear movement of the tractor, the main parameters defining the rotation of the machine are the base of the tractor, the average angle of rotation of the steered wheels and the angles of lateral withdrawal of the front and rear axle. Moreover, it should be noted that the angles of lateral withdrawal of the front and rear axles of the tractor, their value and change will have a significant impact on the kinematics of the rotation of the machine. The impact will be exerted to a greater degree in the conditions of tractor movement on unstable soils: in the early spring period, in the period of over moistening of the soil, etc. In addition, lateral skid is the very parameter that reflects the impact on the car of external force factors accompanying the curvilinear motion.

In real operating conditions, the angles δ_i of side drift can reach from 7^0 to 12^0 [12, 14]. For our case accept $\delta=7^0$.

In the general case, taking into account the angle of the lateral skid, you can determine the coefficient of resistance to the lateral skid of the steering wheels by the formula [15, 20]

$$K_L=F_{Lfw}\cdot\delta\,,\quad K_{Rfw}=F_{Rfw}\cdot\delta\ ,\tag{20}$$

As known, the amount of lateral skid when turning the tractor will be influenced by sideways sliding motion and lateral deformation of the elements of movement.

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Table-VII:The values of the resistance coefficients of the steering wheels to the lateral skid

T, s	When deflection tires h_t=0.01 m				When deflection tires h_t=0.02 m			
	F_{Lfw}, N	F_{Rfw}, N	K_L	K_R	F_{Lfw}, N	F_{Rfw}, N	K_L	K_R
0	0	0	0	0	0	0	0	0
0.1	1363.72	912.2	9546	6385.37	1246.4	946.5	8724.89	6625.68
0.2	1341.7	897.48	9392	6282.38	1209.75	794.49	8468.27	5561.45
0.3	1393	931.8	9751.3	6522.69	1635	1078.94	11445	7552.59
0.4	1481	990.66	10367.2	6934.65	1451.7	995.568	10161.93	6968.98
0.5	1481	990.66	10367.2	6934.65	1334.4	872.96	9340.76	6110.73
0.6	1173.1	784.68	8211.66	5492.79	1385.7	931.81	9700	6522.69
0.7	769.84	514.95	5388.9	3604.64	832.16	559.08	5825.147	3913.6
0.8	1591	1064.23	11137	7449.6	1569	980.85	10983.1	6865.99
0.9	2170.2	1451.66	15191.57	10161.67	2126.23	1471.28	14883.64	10298.99
1	1173.1	784.68	8211.66	5492.79	1158.43	828.82	8109	5801.76

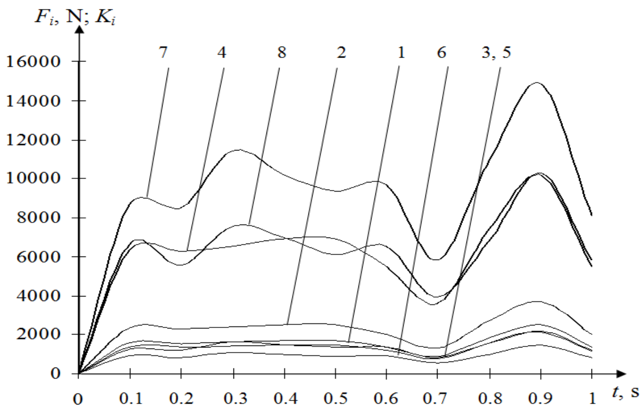

Fig. 7. Graphs of changes the resistance coefficients of tractor wheels: 1,5- forces of lateral skid of the left front wheel of the tractor at h_t=0.01 m, h_t=0.02 m; 2,6- forces of lateral leads of the right front wheel of the tractor at h_t=0.01 m, h_t=0.02 m; 3,7- coefficient of resistance to the lateral skidding of the left front wheel of the tractor at h_t=0.01 m, h_t=0.02 m; 4.8 - coefficient of resistance to the lateral skidding of the right front wheel of the tractor at h_t=0.01 m, h_t=0.02 m.

Substituting the values of the forces obtained by solving the system (1) and (2) we obtain the values of the adhesion coefficient of wheel (see Tables VIII-IX)

$$K_{ad} = \frac{F_{x_i}}{F_{y_i}} < K_{giv.},$$

where F_{x_i} и F_{y_i} – longitudinal and transverse force of the tractor and it wheels.

Table-VIII: The value of adhesion coefficient of the tractor wheels at the tire deflection h_t=0.01 m

T, s	$K_{ad.t}$	$K_{ad.Lrw}$	$K_{ad.Rrw}$	$K_{ad.Lfw}$	$K_{ad.Rfw}$
0	1.41422	0	0	0	0
0.1	1.412811	1.134898416	1.415086	1.415073	1.415112
0.2	1.3897	1.430061883	1.430097	1.430153	1.430057
0.3	1.304876	1.479689486	1.479736	1.479694	1.479709
0.4	1.244671	1.51232541	1.512363	1.512401	1.51232
0.5	1.697956	1.365760821	1.365808	1.365807	1.365832
0.6	3.28888	0.951700917	0.951705	0.951696	0.951694
0.7	7.69252	0.566119487	0.56626	0.566282	0.566277
0.8	3.256284	1.168342681	1.168364	1.168355	1.168319
0.9	0.040789	1.815851555	1.815829	1.815833	1.815807
1	1.63685	1.267962763	1.268014	1.267998	1.267969

Table-IX: The value of coefficient of adhesion of the tractor wheels at the tire deflection h_t =0.02 m

T, s	$K_{ad.t}$	$K_{ad.Lrw}$	$K_{ad.Rrw}$	$K_{ad.Lfw}$	$K_{ad.Rfw}$
0	1.41422	0	0	0	0
0.1	1.412811	1.134898416	1.415086	1.415073	1.415112
0.2	1.3897	1.430061883	1.430097	1.430153	1.430057
0.3	1.304876	1.479689486	1.479736	1.479694	1.479709
0.4	1.244671	1.51232541	1.512363	1.512401	1.51232
0.5	1.697956	1.365760821	1.365808	1.365807	1.365832
0.6	3.28888	0.951700917	0.951705	0.951696	0.951694
0.7	7.69252	0.566119487	0.56626	0.566282	0.566277
0.8	3.256284	1.168342681	1.168364	1.168355	1.168319
0.9	0.040789	1.815851555	1.815829	1.815833	1.815807
1	1.63685	1.267962763	1.268014	1.267998	1.267969

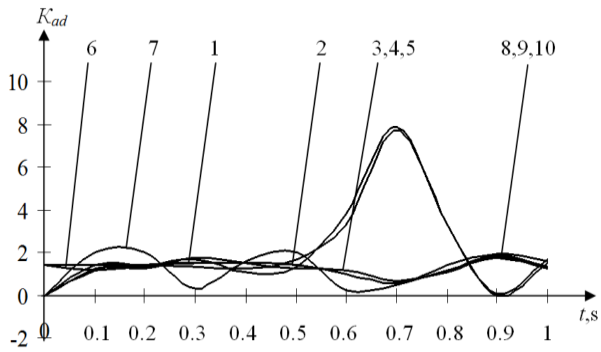

Fig. 8. Graphs of changes of the adhesion coefficients of tractor wheels: 1,6- total coefficient of adhesion of tractor wheel $K_{ad.t}$ at h_t=0.01 m, h_t=0.02 m; 2,7- coefficient of adhesion of the left rear wheel of the tractor $K_{ad.Lrw}$ at h_t=0.01 m, h_t=0.02 m; 3,8- coefficient of adhesion of the right rear wheel of the tractor $K_{ad.Rrw}$ at h_t=0.01 m, h_t=0.02 m; 4,9- coefficient of adhesion of the left front wheel of the tractor $K_{ad.Lfw}$ at h_t=10 mm, h_t=20 mm; 5,10- coefficient of adhesion of the right front wheel of the tractor $K_{ad.Rfw}$ at h_t=0.01 m, h_t=0.02 m.

In order for the driven wheels to move in the plane of rotation, the pulling force must not be greater than the force of their adhesion to the supporting surface [12, 14].

As can be seen from Fig. 8, the value of the coefficient of adhesion of the wheels increases when overcoming an obstacle.

VI. CONCLUSION

The results of computational experiments show that the value of the tractor oscillation increases with h_t=0.02 m. It is revealed that the uneven distribution of mass between the rear leading and the front driven wheels leads to disruption of the movement of the wheels of the tractor.

Thus, the smoothness of tractor motion depends on the mass and parameters of the controlled axes, the values of which are determined by numerical solution of the systems (1), (2) and the conjugate system (10) with variation in motion parameters F_i and design parameters b_i, c_i, m_i for given road roughness.

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