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Modeling and optimal control of motion of cotton harvester MH-2.4 under horizontal oscillations

Azimov B.M., Yakubjanova D.K., KubaevS.T.

Professor, Scientific and Innovation Center of Information and Communication Technologies under Tashkent IT University, Tashkent, Uzbekistan
Senior Lecturer, Samarkand branch of Tashkent university of Informational technology, Samarkand, Uzbekistan
assistant professor, Samarkand branch of Tashkent university of Informational technology, Samarkand, Uzbekistan

ABSTRACT: The article presents the equations of motion of cotton harvester (HUM) MH-2.4. On the basis of the equations of motion, the models and algorithms for optimal control of cotton harvester HUM MH-2.4 are developed. Necessary conditions for optimal control of HUM MX-2.4 motion are investigated using the Pontryagin maximum principle. The values of horizontal oscillations of HUM MH-2.4 are determined. The shortcomings of the method of rotation of HUM MH-2.4 with rear steering wheels are revealed: the difficulty of steering gear, the equal distribution of weight between the front leading and rear steering wheels.

KEYWORDS: cotton harvesting machine, modeling, optimal control.

I.INTRODUCTION

The problem of modeling and optimal control of motion of cotton harvester MH-2.4 under horizontal oscillations, considered and solved in this paper, is related to the derivation of the equation of motion of a cotton harvester. This is specified by the development of the model and algorithm for optimal control of the cotton harvester MH-2.4, and, in turn, requires qualitative research and assessment of necessary conditions for optimal control of the HUM MH-2.4 motion by applying the Pontryagin maximum principle.

It should be noted that the problems and tasks related to the assessment of technical parameters of operation of cotton harvesters with hitching devices are, in general, caused by the creation of effective and practical models, methods and control algorithms. The studies performed in this aspect predetermine the complex statement of problem; its structuring is formalized by the solution of the following tasks:

-study of the principles of formation of a control model for the identification ofperformance capability indices of cotton harvesters;

- parametric identification and evaluation of dynamic loads on the hitching systems of machine-tractor unit;
- concepts formation of structural identification of models of machine-tractor units with hitching systems;
- analysis and evaluation of technical characteristics of the hitching systems of machine-tractor units;
- research and development of an algorithm for estimating the parameters of the operation of hitching systems of machine-tractor units.

The produced two-row vertical-spindle cotton harvester (HUM) MH-2.4 is assembled with the TTZ-LS 100HC tractor in a semi-hitched way, the front guide wheels are dismantled, the unit is made on a four-wheel arrangement with two rear guide wheels.

It should be noted that the existing engineering models do not describe the real dynamic processes that occur during the operation of machines. The real dynamic processes the engineers and designers deal with are very complex and difficult to analyze in full volume. The difficulty lies in the fact that to obtain a solution the model must be simple enough and at the same time it should reflect the essence of the problem so that the results obtained would reflect the real physical meaning [2-7].

II. LITERATURE SURVEY

When developing the algorithm and the model of optimal control for the cotton harvesting machine MX-2.4 a number of published papers in this field were studied.

Yu.A. Sudnik notes that at present high demand on the quality and efficiency of technological operations in the agricultural sector dictates the need to address the problem of improving the technological and ecological levels of mobile units in agricultural machinery.

M.M. Makhmutov considers and solves the problems of traction-coupling properties increase in wheeled movers of mobile machine and tractor units by using anti-skid devices that reduce the compressing effect of wheels on soil.

S.V. Tarasova notes that the implementation of modern mobile energy resources requires solving major problematic and prospective issues in the theory of tractor construction and the development of innovative areas that contribute to the increase in the level of scientific and technological progress in the agrarian industrial complex. At the research level, the problem of justifying the mode of motion of wheeled vehicles during agricultural operations on inclined support surfaces is actualized.

P.Yu. Yakovlev determines that if the motion stability of the machine-tractor unit with a front hitching is inadequate, it is sometimes impossible to achieve high technical and economic indices, and it is difficult to ensure the agro-technical performance of the machine-tractor unit, which in turn makes their use more difficult or economically inexpedient. It is stated that the use of elastic element in the design of front hitching mechanism ensures an elastic coupling of the unit to the tractor.

Z.Ya. Lurie and E.N.Centa discuss the existing ways to reduce the force of weight and mass of the working units of mobile machines (based on the fundamental laws of physics) to the axis of motion sources. To study hydraulic aggregate of the tractor hitching, the equations of reduced force of weight and mass are obtained, taking into account losses, based on equality of powers and kinetic energy. The influence of these parameters on the quality of working process is assessed.

G.B. Shipilovsky notes that the effectiveness of automatic, remote or manual control of the machine-tractor unit depends on how fully the requirements imposed on the regularities of developed algorithm are met. One of the most important roles plays the properties of tractor or machine-tractor unit as a control object. An exact mathematical description of all characteristics and properties of machine-tractor unit is quite a complicated task. At the same time it is determined that from the point of view of creating an effective control system, a complete and exact solution of this task is not compulsory.

III. PROBLEM STATEMENT AND METHODS OF SOLUTION

Bearing in mind the above-stated and in accordance with design scheme presented in Figure 1, a general mathematical model of horizontal oscillations of HUM MH-2.4 in the course of motion along the roughness of headlands of cotton fields in the form of Lagrange equations of the second kind is derived [2, 5-7]:

$$\left.\begin{aligned} m_{м}\ddot{x}_{м} &= F_{м} - b_1(\dot{x}_{м} - \dot{x}_{к_1}) - c_1(x_{м} - x_{к_1}) - b_2(\dot{x}_{м} - \dot{x}_{к_2}) - c_2(x_{м} - x_{к_2}) \\ m_1\ddot{x}_{к_1} &= b_1(\dot{x}_{м} - \dot{x}_{к_1}) + c_1(x_{м} - x_{к_1}) - m_1\frac{2\pi^2 V_{м}^2}{l_5^2} h_n \sin\frac{2\pi V_{k_1}}{l_5}t \\ (m_2 - m_3)\ddot{x}_{к_2} &= b_2(\dot{x}_{м} - \dot{x}_{к_2}) + c_2(x_{м} - x_{к_2}) - (m_2 - m_3)\frac{2\pi^2 V_{м}^2}{l_5^2} h_n \sin\frac{2\pi V_{k_2}}{l_5}t \end{aligned}\right\}, \quad (1)$$

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where $\dot{x}_i$ и $\ddot{x}_i$ – are the linear velocities and acceleration of machine; b_i, c_i– are the coefficients of viscous resistance and stiffness of machine wheel tire ;m_i is the mass of machine distributed on machine supports and the distributed mass along the supports of the machine; $h_ш$– is the height of road roughness; V_i –speed of machines, front and rear wheels.

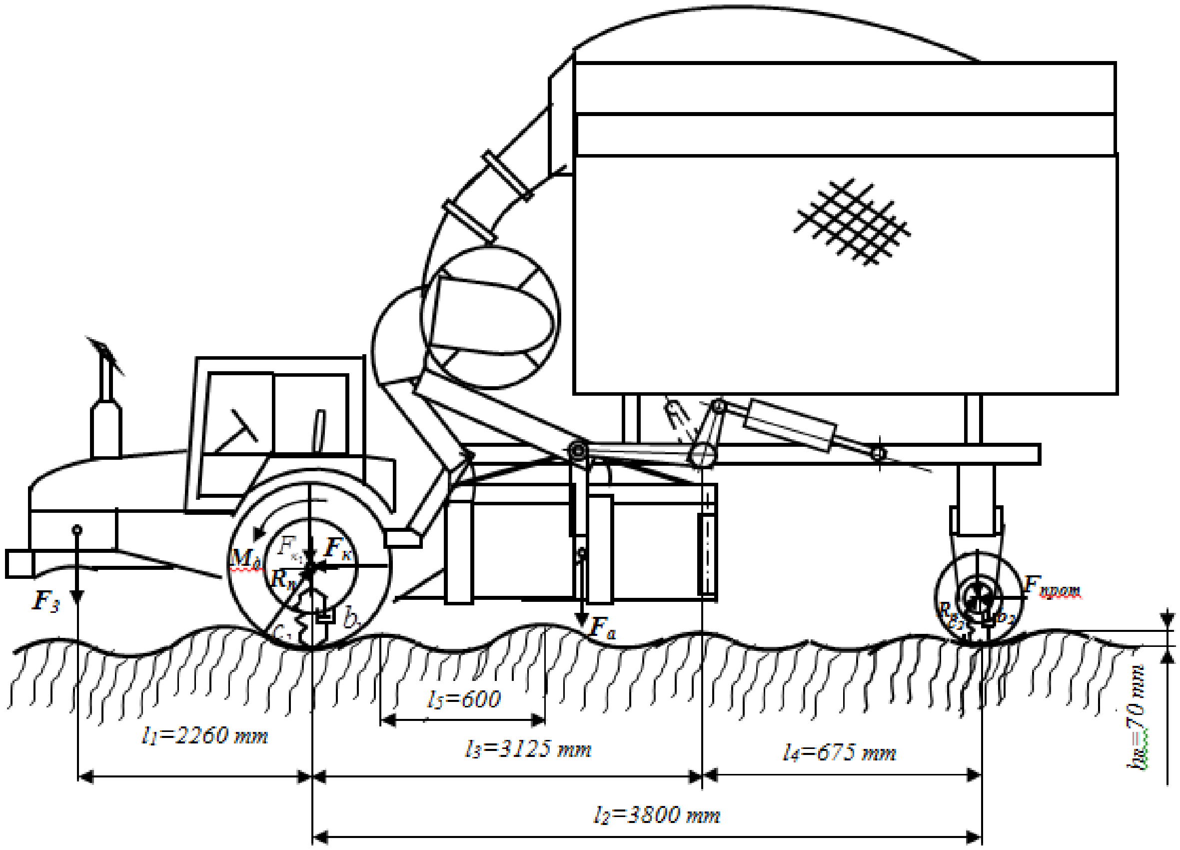

Figure. 1. Design scheme of HUM MH-2.4

Solution of this problem is based on the theory of optimal systems. Consider the statement of the problem of optimal control in a general form.

At the initial moment of time the test object is in the following state

$$q_i(0) = q_0(0), \qquad \dot{q}_i(0) = \dot{q}_0(0), \quad V_i(0) = V_0(0). \tag{2}$$

It is required to select a control *u(t)* that will transfer the test object to a predetermined final state

$$q_i(t) = q_0(t), \ \ \dot{q}_i(t) = \dot{q}_0(t), \ \ V_i(t) = V_0(t) \ \ (i = \overline{1,n}), \quad 0 \le t \le T. \tag{3}$$

This requires the time of the transient process to be the smallest [4-9].

The aim of control is reduced to minimizing the functional considering q=x_i, q=y_i

$$J(q_0, u(t), q(t)) = \int_{t_0}^{T} f^0(q(t), u(t), t)dt + g^0(q_0, g(T)). \tag{4}$$

Under conditions (2)-(5)

$$\dot{q}(t) = f(q(t), u(t), t). \quad (5)$$

Let there be given the functions

$$g^i(q_0, q(T)) \le 0, \text{ i=1,…,m}; \quad g^i(q_0, q(T)) = 0, \quad i = m+1, ..., s, \quad (6)$$

$$u \in U, \qquad t_0 \le t \le T, \quad (7)$$

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

At machine testing under given operating conditions, the quality criterion can be the speed of operation.

When investigating the necessary conditions for optimal control, the Pontryagin maximum principle is used [8,9].

To formulate the maximum principle, the Hamilton-Pontryagin function is introduced

$$H = (q, u, t, \psi_i, \psi_0) = -f^0(q, u, t) + \langle \psi, u \rangle \quad (8)$$

and conjugated system

$$\left.\begin{aligned} &\frac{d\psi_1}{dt} = -\frac{\partial H_м}{\partial x_1} = -m_м^{-1}(c_1 + c_2)\psi_2, \quad \frac{d\psi_2}{dt} = -\frac{\partial H_м}{\partial x_2} = -\psi_1 + m_м^{-1}(b_1 + b_2)\psi_2 \\ &\frac{d\psi_1}{dt} = -\frac{\partial H_1}{\partial x_3} = -m_1^{-1} c_1 \psi_2, \quad \frac{d\psi_2}{dt} = -\frac{\partial H_1}{\partial x_4} = -\psi_1 + m_1^{-1} b_1 \psi_2 \\ &\frac{d\psi_1}{dt} = -\frac{\partial H_2}{\partial x_5} = -(m_2 - m_3)^{-1} c_2 \psi_2, \quad \frac{d\psi_2}{dt} = -\frac{\partial H_2}{\partial x_6} = -\psi_1 + (m_2 - m_3)^{-1} b_2 \psi_2 \end{aligned}\right\} \quad (9)$$

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

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

$$H(q_i(t), u(t), t, \psi_i, \psi_0) = \max_{u \in U} H(q_i(t), u, t, \psi_i(t), \psi_0). \quad (10)$$

Passing to the definition of the optimal control of machine based on (8), the following function is formed

$$\left.\begin{aligned} &x_м = x_1, \dot{x}_м = y_2, \dot{x}_2 = u_y - m_м^{-1}[b_1(x_2 - x_4) - c_1(x_1 - x_3) - \\ &\qquad - b_2(x_2 - x_6) - c_2(x_1 - x_5)] \\ &x_{к_1} = x_3, \dot{x}_{к_1} = x_4, \dot{x}_4 = m_1^{-1}[b_1(x_2 - x_4) + c_1(x_1 - x_3)] - u_1 \\ &x_{к_2} = x_5, \dot{x}_{к_2} = x_6, \dot{x}_6 = (m_2 - m_3)^{-1}[b_2(x_2 - x_6) + c_2(x_1 - x_5)] - u_2 \end{aligned}\right\} . \quad (11)$$

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 (4) - (7) is called the speed of operation problem.

The object under consideration is a stationary system and problem (4) means that f and U do not depend explicitly on time, i.e.

$$f(t, q, u) = f(q, u), \quad U(t) = U . \quad (12)$$

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If stationary problems (4), (12) have optimal control *u(t)* and an optimal trajectory $q_0(t)$, then there exists a nonzero vector of conjugate variables $(\psi_1(t),\ \psi_2(t)),\ \ \psi(t)\in R^n$ satisfying conditions (2), i.e. the maximum condition (10) is satisfied

$$\psi_0(t) = const \le 0\,. \tag{13}$$

Since the conjugate system (9) is homogeneous with respect to ψ_i, a constant in equation (13) is chosen arbitrary, so that

$$\psi_0(t) = -1 \qquad 0 \le \mathrm{t} \le \mathrm{T}\,. \tag{14}$$

From conditions $\max\limits_{|u|\prec 1} H$ it follows that $u = sign\psi_2$ at $\psi_2 \ne 0.$

The boundary-value problem of the maximum principle is written in the following form

$$\left.\begin{aligned} \dot{x}_2 &= sign\psi_y - m_м^{-1}[b_1(x_2 - x_4) - c_1(x_1 - x_3) - b_2(x_2 - x_6) - c_2(x_1 - x_5)] \\ \dot{x}_4 &= m_1^{-1}[b_1(x_2 - x_4) + c_1(x_1 - x_3)] - sign\psi_1 \\ \dot{x}_6 &= (m_2 - m_3)^{-1}[b_2(x_2 - x_6) + c_2(x_1 - x_5)] - sign\psi_2 \end{aligned}\right\}. \tag{15}$$

The boundary-value problem of the maximum principle in these cases will consist of system (15), boundary conditions (2) and (3) following from (10), and condition (14).

Formulate the Hamilton-Pontryaginfunction in the following form [5-9]:

$$\left.\begin{aligned} H_м &= \psi_0 + \psi_1 y_2 + \psi_2 \dot{y}_2 \\ H_1 &= \psi_0 + \psi_1 y_4 + \psi_2 \dot{y}_4 \\ H_2 &= \psi_0 + \psi_1 y_6 + \psi_2 \dot{y}_6 \end{aligned}\right\}. \tag{16}$$

Hence it is clear that the condition (10) singles out the function

$$u = sign\psi_2, \quad \psi_2 \ne 0.$$

The boundary value problem (15) in this case has the form

$$H_i = -f^0 u + \psi_2(t) u_д\,. \tag{17}$$

Proceed to the study of (9), (17) in the region

$$u_k = sign\,\psi_2(t) = \begin{cases} 1, & \psi_2(t) > 1 \\ -1, & \psi_2(t) < 1 \end{cases}, \quad k=2,4,\dots,2n\,, \tag{18}$$

the control $u_k(t)$ can have only one switching point.

Thus, from the Pontryagin maximum principle, the structure of the optimal control of the motion of guide wheels of a cotton harvester is obtained.

To determine the auxiliary functions (9), a conjugate system with variation of design parameters b_i, c_i,m_i,$j_i$is studied numerically.

IV. Results of computational experiment

As a result, graphical dependences of velocities and accelerations of cotton harvester oscillations and the maximum values of the *H*-function are obtained (Figures 2-8, Tables 1-6).

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Table 1.Values of velocities and accelerations in the transition process in HUM MH -2.4

T,s	$\dot{x}_м$, m/s	$\ddot{x}_м$, m/s²	$\dot{x}_{\kappa_1}$, m/s	$\ddot{x}_{\kappa_1}$, m/s	$\dot{x}_{\kappa_2}$, m/s	$\ddot{x}_{\kappa_2}$, m/s²	$\dot{x}_м$, m/s	$\ddot{x}_м$, m/s²	$\dot{x}_{\kappa_1}$, m/s	$\ddot{x}_{\kappa_1}$, m/s	$\dot{x}_{\kappa_2}$, m/s	$\ddot{x}_{\kappa_2}$, m/s²
	u=+1						u=-1					
0	0	1	0	-1	0	-1	0	-1	0	1	0	1
0.1	-	-0.16	-0.0004	0.2	-	0.37	0.0004	0.16	0.000	-0.2	0.00005	-0.37
0.2	-	-	-0.0009	0.2	-	0.37	0.0009	0.159	0.000	-0.2	0.00009	-0.37
0.3	-	-	-0.0014	0.2	-	0.37	0.0014	0.159	0.001	-0.2	0.00013	-0.37
0.4	-	-	-0.0019	0.2	-	0.37	0.0019	0.159	0.001	-0.2	0.00017	-0.37
0.5	-	-	-0.0024	0.2	-	0.37	0.0024	0.159	0.002	-0.2	0.00022	-0.37
0.6	-	-	-0.0029	0.2	-	0.37	0.0029	0.159	0.002	-0.2	0.00028	-0.37
0.7	-	-	-	0.2	-	0.37	0.0033	0.159	0.003	-0.2	0.00034	-0.37
0.8	-	-	-0.0038	0.2	-	0.37	0.0038	0.159	0.003	-0.2	0.0004	-0.37
0.9	-	-	-0.0043	0.2	-	0.37	0.0043	0.159	0.004	-0.2	0.00047	-0.37
1	-	-	-0.0048	0.2	-	0.37	0.0048	0.159	0.004	-0.2	0.00054	-0.37

Table 2.Values of conjugate systems and the Hamilton-Pontryagin function in the transition process in HUMMH-2.4

T.s	ψ_1	$\dot{\psi}_1$	ψ_2	$\dot{\psi}_2$	H_u	ψ_1	$\dot{\psi}_1$	ψ_2	$\dot{\psi}_2$	H_u
	u=+1					u=-1				
0	0	-1	0	-1	-1	0	1	0	1	1
0.1	-0.09	-1	-0.1	-1	-1	0.09	1	0.1	1	1
0.2	-0.2	-1	-0.2	-1	-1	0.2	1	0.2	1	1
0.3	-0.3	-1	-0.32	-1	-1	0.3	1	0.32	1	1
0.4	-0.4	-1	-0.43	-1	-1	0.4	1	0.43	1	1
0.5	-0.5	-1	-0.538	-1	-1	0.5	1	0.538	1	1
0.6	-0.6	-1	-0.64	-1	-1	0.6	1	0.64	1	1
0.7	-0.7	-1	-0.75	-1	-1	0.7	1	0.75	1	1
0.8	-0.8	-1	-0.86	-1	-1	0.8	1	0.86	1	1
0.9	-0.9	-1	-0.96	-1	-1	0.9	1	0.96	1	1
1	-1	-1	-1	-1	-1	1	1	1	1	1

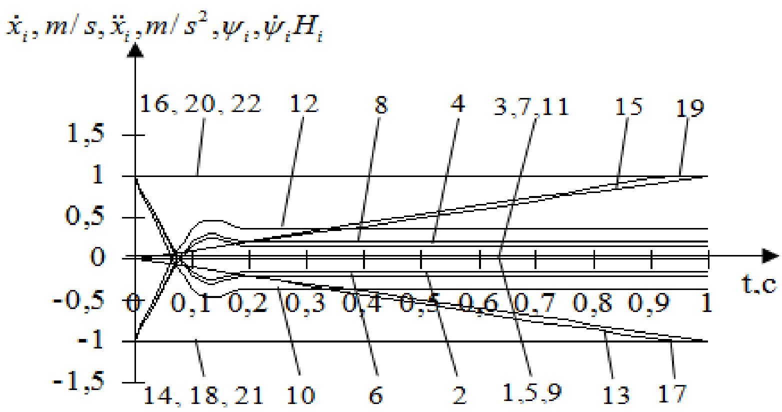

Figure. 2. Graphs of transition processes: 1,3,5,7,9,11 − velocities $\dot{x}_м, \dot{x}_{\kappa_1}, \dot{x}_{\kappa_2}$; 2,4,6,8.10,12,14 - accelerations $\ddot{x}_м, \ddot{x}_{\kappa_1}, \ddot{x}_{\kappa_2}$; auxiliaryfunctions13,15 - ψ_1, 17,19-ψ_2, 14,16- $\dot{\psi}_1$, 18, 20 -$\dot{\psi}_2$; 21,22 − H functions of horizontal oscillations of cotton harvester MH-2.4 1,2,5,6,9,10,13,14,17,18,21 - u(t)= +1; 3,4,7,8,11,12,15,16,19,20,22 - at u(t)= -1.

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Systems (1), (9), (15) are solved using the Runge-Kutta numerical methods. The control $u_k(t)$, causing the maximum of function (10), is defined in the region (18).

Computational experiment has been carried out at the following values of parameters:

- at tire deflection$h_ш$=30 mm=0.03m:

c_1=843333.33 N/m; b_1=74090 Nf/m; c_2=1738333.3 N/m; b_2=152719.82 Nf/m; c_3=626037.55 Nm/rad; b_3=57477.5 Nmf/m; $m_м$=7745 kg; m_1=2530 kg; m_2=5215 kg; m_3=1200 kg; m_a=675 kg; $r_{к1}$=0.75 m; $r_{к2}$=0.415 m; h_n =0.07 m; $V_м$=1.11m/s; $F_м = 16060$ N .

Table 3.Values of HUMMH-2.4 operation parameters under horizontaloscillations at *h = 30 mm*

T, s	$\dot{x}_м$, m/s	$\ddot{x}_м$, m/s^2	$F_м$, N	$\dot{x}_{к_1}$, m/s	$\ddot{x}_{к_1}$, m/s	$F_{к1}$, N	$\dot{x}_{к_2}$, m/s	$\ddot{x}_{к_2}$, m/s^2	$F_{к2}$, N
1	2	3	4	5	6	7	8	9	10
0	0	2.07	16060	0	0	0	0	0	0
0.1	0.12	0.818	6336.68	0.096	1.5	3739.15	0.1	1.476	5926.87
0.2	0.227	0.88	6814.82	0.219	1.4	3580.65	0.22	1.39	5590.4
0.3	0.335	0.86	6714.38	0.332	1.3	3294.03	0.332	1.42	5718.98
0.4	0.44	0.81	6291.15	0.437	1.236	3126.97	0.437	1.49	5996.72
0.5	0.54	0.85	6592.25	0.54	1.33	3369.87	0.54	1.44	5791.75
0.6	0.658	1.14	8831.2	0.666	1.64	4165.03	0.664	1.09	4401.63
0.7	0.796	1.2	9301.53	0.799	1.37	3479.68	0.798	1.04	4194.53
0.8	0.9	0.5	3963.22	0.886	0.82	2075.14	0.889	1.87	7526.6
0.9	0.97	0.58	4544.9	0.969	1.44	3650.86	0.97	1.72	6906.82
1	1.111	1.68	13027.9	1.13	1.6	4069.68	1.13	0.44	1768.57

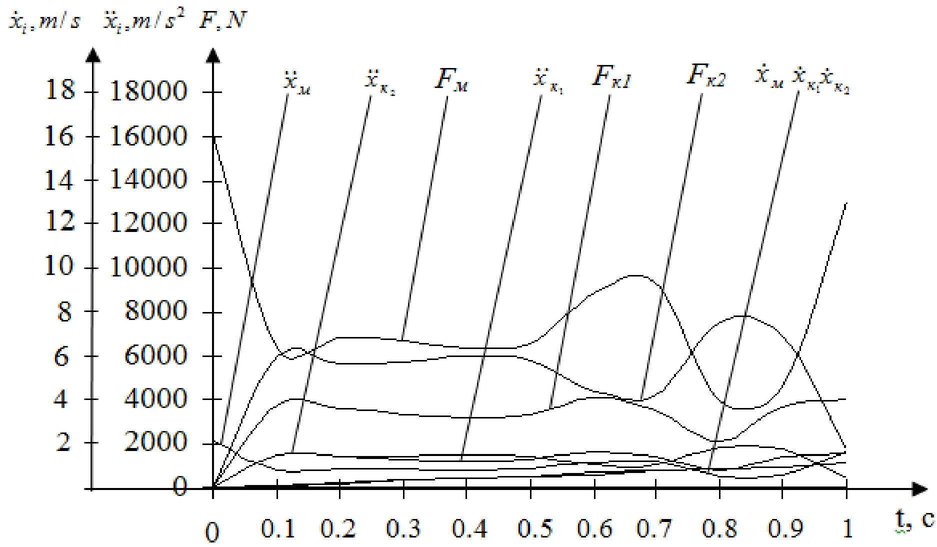

Figure.3. Pattern of change in HUM MH-2.4 motion parameters under horizontal oscillations at$h_ш$=30 mm

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- at tire deflection $h_{ш}$=40 mm=0.04m:
c_1=620482.5 N/m; b_1=33814.912 Nf/m; c_2=1278978.75 N/m; b_2=69701.5 Nf/m; $m_м$=7745 kg; m_1=2530 kg; m_2=5215 kg; m_3=1200 kg; m_a=675 kg; $r_{к1}$=0.75 m; $r_{к2}$=0.415 m; h_n =0.07 m; $V_м$=1.11 m/s; $F_м = 16060$ N .

Table 4.Values of the HUMMH-2.4 operation parameters under horizontal oscillations at *h=40 mm*

T, s	$\dot{x}_м$, m/s	$\ddot{x}_м$, m/s²	$F_м$, N	$\dot{x}_{к_1}$, m/s	$\ddot{x}_{к_1}$, m/s	$F_{к1}$, N	$\dot{x}_{к_2}$, m/s	$\ddot{x}_{к_2}$, m/s²	$F_{к2}$, N
1	2	3	4	5	6	7	8	9	10
0	0	2.0878	16170	0	0	0	0	0	0
0.1	0.13	0.695	5383.6	0.0827	1.58	4009.36	0.095	1.687	6774.96
0.2	0.227	0.8	6319.36	0.219	1.56	3963.15	0.227	1.448	5813.27
0.3	0.335	0.9	6973.9	0.338	1.3	3315.14	0.336	1.37	5531.63
0.4	0.44	0.83	6435.13	0.44	1.2	3057.68	0.44	1.5	6021.58
0.5	0.545	0.84	6517.9	0.546	1.35	3414.58	0.546	1.48	5947.7
0.6	0.66	1.13	8768.3	0.67	1.7	4338.7	0.67	1.1	4472.45
0.7	0.8	1.27	9882.63	0.8	1.27	3214.67	0.8	0.96	3881.9
0.8	0.9	0.56	4338.16	0.88	0.75	1901.81	0.88	1.85	7463.52
0.9	0.98	0.44	3432.48	0.97	1.65	4185.95	0.98	1.9	7649.52
1	1.11	1.72	13327.44	1.15	1.38	3511.73	1.15	0.3	1274.37

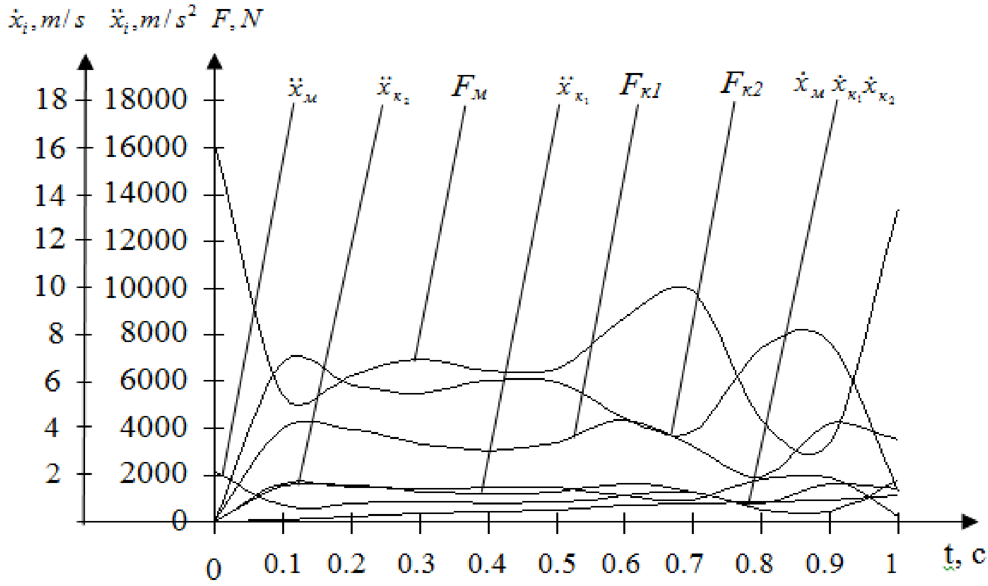

Figure4. Pattern of change in the HUM MH-2.4 motion parameters under horizontaloscillations at$h_{ш}$=*40 mm*

V.CONCLUSION

Thus, the uniformity of machine motion depends on the mass and parameters of the steering axles; their values are determined by numerical solution of the system (1) and the conjugate system (9) with the variation of motion parameters of F_i, M_i and design parameters *b*, *c*, m_i, j_i for given road roughness.

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Physical meaning of the results obtained can be formulated as follows. If conditions (2) - (7) are satisfied at the initial moment of time, then the optimal speed of operation is achieved at the following control values. On the time interval [t_0, t], the transportation force $u_n(t)$=+1 has a maximum value. Hence, on the segment [t_0, t], the mode is "full speed ahead" and machine speed will increase to $V_м$=*1.11 m/s*, and at that moment the wheels of the machine will rise to the upper edge of the roughness. On the interval [t, T] machine descends, and at that moment the transportation force switches to $u_д(t)$=-1, i.e. there is a mode "full speed astern" providing uniformity of motion of guide wheels of a cotton harvester.

The results obtained by solving mathematical models of horizontal oscillations of HUM MH-2.4 and the hitching systems in the course of motion along the roughness on the headlands of a cotton field are in satisfactory agreement with the experimental data [1]. Results of computational experiments show that the oscillations values of machine decreases at $h_ш$ = *40 mm.* The shortcomings of the way of turning HUM MX-2.4 with rear steerable wheels are revealed: the complexity of the steering drive, the uneven distribution of the mass between the front, driving and rear steerable wheels.

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