

OPTIMAL CONTROL OF THE MOTION OF FAN DRIVE MECHANISMS OF A COTTON-PICKING MACHINE

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Abstract:

The article formulates the equations of motion of the drives of the pneumatic system of technological machines. Based on the obtained equations of motion, algorithms for optimal control of the drives of the pneumatic system have been developed. Using Pontryagin's maximum principle, the necessary conditions for optimal control of the motion of the drives of the pneumatic system have been studied. By solving the coupled systems, the optimal values of the stiffness coefficients, the viscous resistance of the drive belts, and the moments of inertia corresponding to the rotating mechanisms of the pneumatic system have been found. The values of transient processes and torsional vibrations during the startup process of the pneumatic system drives have been determined.

Keywords: pneumatic system drive, hydraulic motor, hydraulic pump, optimal control.

Introduction

For the normal operation of a pneumatic system, drive mechanisms consisting of elastic elements are of great importance. They are precisely the main source of failure of the working parts. For this reason, ensuring the stability of the system's operation largely depends on optimizing the parameters of its belt transmissions. For the normal operation of a pneumatic system, motion mechanisms composed of elastic elements are of great importance. They are the main sources of failure of the working parts. For this reason, ensuring stable operation is largely associated with optimizing the parameters of the belt transmission of the pneumatic system [1], [2], [3], [4], [5].

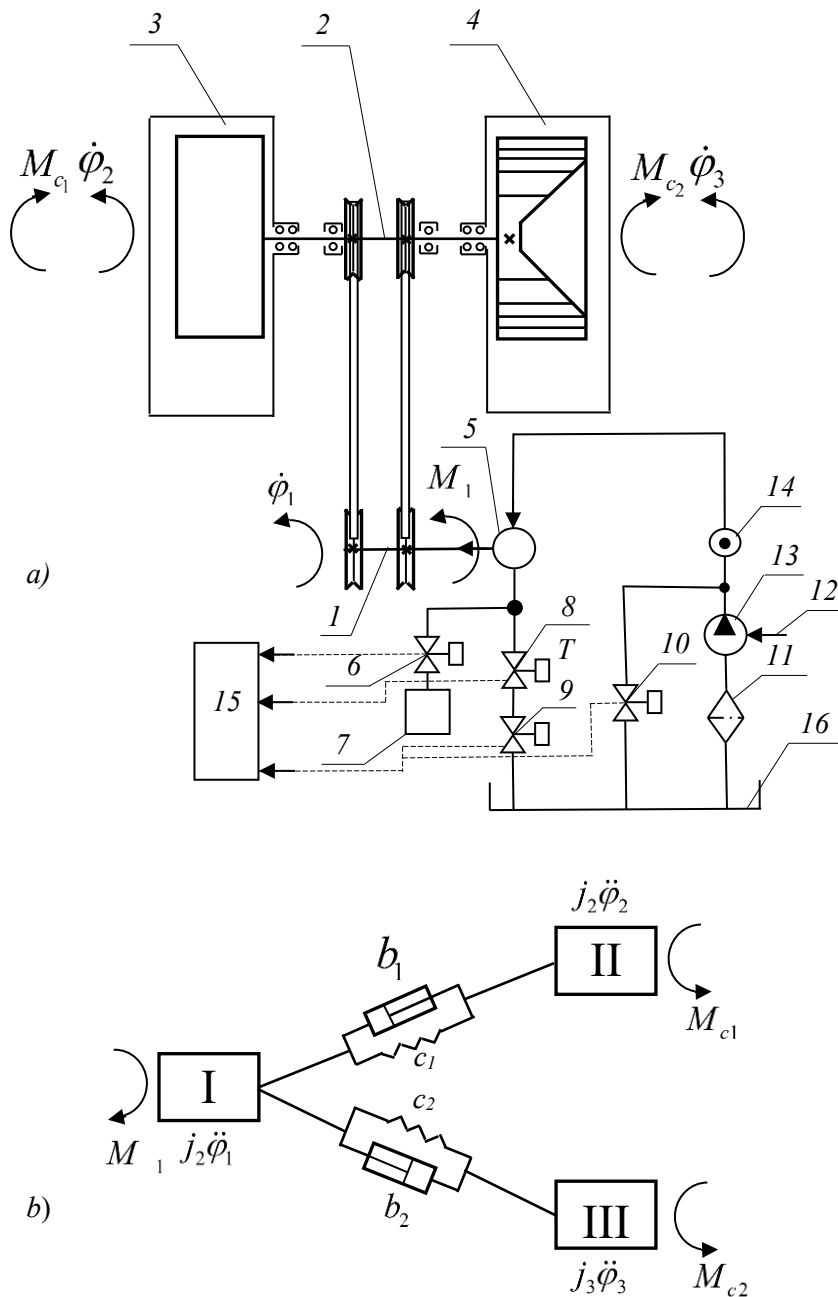


Figure 1. Kinematic diagram (a) and dynamic model (b) of the drive of the pneumatic system of technological machines

Here: 1 – belt drive; 2 – belt transmission; 3, 4 – fans; 5 – hydraulic motor; 6, 9, 10 – electromagnetic valve; 7 – radiator; 8 – temperature sensor; 11 – filter; 12 – power take-off shaft; 13 – hydraulic pump; 14 – pressure gauge; 15 – microcontroller; 16 – crankcase.

$$\left. \begin{aligned} j_1 \ddot{\varphi}_1 &= M_1 - b_1 (\dot{\varphi}_1 - i_1 \dot{\varphi}_2) - c_1 (\varphi_1 - i_1 \varphi_2) - b_2 (\dot{\varphi}_1 - i_2 \dot{\varphi}_3) - c_2 (\varphi_1 - i_2 \varphi_3); \\ j_2 \ddot{\varphi}_2 &= i_1 b_1 (\dot{\varphi}_1 - i_1 \dot{\varphi}_2) + i_1 c_1 (\varphi_1 - i_1 \varphi_2) - M_2; \\ j_3 \ddot{\varphi}_3 &= i_2 b_2 (\dot{\varphi}_1 - i_2 \dot{\varphi}_3) + i_2 c_2 (\varphi_1 - i_2 \varphi_3) - M_3. \end{aligned} \right\} \quad (2.1)$$

Materials and Methods

Here j_i - moments of inertia of the rotating mechanisms of the pneumatic system, $N \cdot m \cdot s^2$; M_1 - torque of the driving mechanism, $N \cdot m$; M_2, M_3 - resistance torques, $N \cdot m$; $\varphi_i, \dot{\varphi}_i, \ddot{\varphi}_i$ - angular displacement, angular velocity, and angular acceleration of the rotating mechanisms of the pneumatic system, $rad, rad/s, rad/s^2$; i - transmission ratio in the belt drives of the rotating mechanisms of the pneumatic system; c_1, c_2 - stiffness coefficients of the belt, $N \cdot m / rad$; b_1, b_2 - viscosity coefficients of the belt, $N \cdot m \cdot s / rad$.

To calculate the parameters of the units controlling the pneumatic system and to optimally control them, software-algorithmic tools based on the required stiffness and viscosity coefficients and a mathematical model have been developed.

Optimal control algorithm. The main goal of controlling the operation of the drives of the pneumatic system is to determine the optimal modes of transient processes, wherein minimizing the energy consumed during the transient process is required. From this standpoint, the task is set of selecting the optimal control action $u(t)$ that brings the motion parameters of the drives of the pneumatic system to the specified values in the shortest possible time. In this case, to evaluate the operating efficiency of the system, a periodic operation indicator is adopted as the main criterion, expressed in the form of minimizing a functional;

$$J(\varphi_0, u(t), \varphi(t)) = \int_{t_0}^T f^0(\varphi(t), u(t), t) dt + g^0(\varphi_0, g(T)), \quad (2)$$

where $\int_{t_0}^T f^0(\varphi(t), u(t), t) dt$ – is the Lagrange problem for the transient process;

$g^0(\varphi_0, g(T))$ – is the Mayer problem for the final moment of motion.

based on the condition

$$\varphi_i(0) = \varphi_0(0), \quad \dot{\varphi}_i(0) = \dot{\varphi}_0(0), \quad \varphi_i(0) = 0, \quad \dot{\varphi}_i(0) = 0 \quad (3)$$

where $\varphi_i(0), \dot{\varphi}_i(0)$ - is the state at $t = 0$.

$$\varphi_i(t) = \varphi_0(t), \quad \dot{\varphi}_i(t) = \dot{\varphi}_0(t), \quad 0 \leq t \leq T, \quad (i = \overline{1, n}), \quad (4)$$

where $\varphi_0(t), \dot{\varphi}_0(t)$ – is the state of the system at the final point, n - is the number of equations.

$$\dot{\varphi}_i(t) = f(\varphi_i(t), u(t), t), \quad (5)$$

$$u \in U, \quad t_0 \leq t \leq T, \quad (6)$$

where $f(\dots)$ - is a continuous, differentiable function; $u(t)$ - is a piecewise-continuous function on the interval $[t_0, T]$.

In order to study the necessary conditions for optimal control of the actuating mechanisms of the pneumatic system under consideration, Pontryagin's maximum principle is applied. To formulate the maximum principle, Pontryagin's Hamiltonian function is introduced for the drives of the pneumatic system.

$$H(\varphi, u, t, \psi_i, \psi_0) = f^0(\varphi, u, t) + \langle \psi, u \rangle, \quad (7)$$

and the adjoint system

$$\left. \begin{aligned} \frac{d\psi_{1H}}{dt} &= -\frac{\partial H_H}{\partial y_i} = j_i^{-1} c \psi_{2H}; \\ \frac{d\psi_{2i}}{dt} &= -\frac{\partial H_i}{\partial y_{i+1}} = -\psi_{1i} + j_i^{-1} b \psi_{2i}. \end{aligned} \right\} \quad (8)$$

with the constraint $|u| \leq 1$ imposed on the control action.

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

$$H(\varphi_i(t), u(t), t, \psi_i, \psi_0) = \max_{u \in U} H(\varphi_i(t), u, t, \psi_i(t), \psi_0), \quad (9)$$

Results

Proceeding from expression (7) to determining the optimal control, the following function is formulated [6].

$$\left. \begin{aligned} \varphi_1 &= y_1, \quad \dot{\varphi}_1 = y_2, \quad \dot{y}_2 = u_1 - j_1^{-1} \left[\begin{aligned} &b_1(y_2 - i_1 y_4) + c_1(y_1 - i_1 y_3) + \\ &+ b_2(y_2 - i_2 y_6) + c_2(y_1 - i_2 y_5) \end{aligned} \right]; \\ \varphi_2 &= y_3, \quad \dot{\varphi}_2 = y_4, \quad \dot{y}_4 = j_2^{-1} \left[i_1 b_1(y_2 - i_1 y_4) + i_1 c_1(y_1 - i_1 y_3) \right] - u_2; \\ \varphi_3 &= y_5, \quad \dot{\varphi}_3 = y_6, \quad \dot{y}_6 = j_3^{-1} \left[i_2 b_2(y_2 - i_2 y_6) + i_2 c_2(y_1 - i_2 y_5) \right] - u_3. \end{aligned} \right\} \quad (10)$$

Similarly, if $f^0 \equiv 1$, then the functional takes the form $J(\varphi_0, u(t), \varphi(t)) = T - t_0$. In this case, problem (2)–(6) is called a time-optimal problem [7].

The object under consideration is a stationary system, and problem (4) means that the functions f and U do not depend explicitly on time, i.e., they are not expressed in explicit form with respect to the time parameter [8].

$$f(t, y, u) = f(y, u), \quad U(t) = U. \quad (11)$$

If the stationary problem (4), (11) has an optimal control $u(t)$ and an optimal trajectory $\varphi_0(t)$, then there exists a nonzero, nontrivial vector of adjoint variables $(\psi_1(t), \psi_2(t))$, $\psi(t) \in R^n$ that satisfies conditions (9), as a result of which the maximum condition (7) is satisfied [9].

$$\psi_0(t) = \text{const} \leq 0. \quad (12)$$

Similarly, since the adjoint system (8) is homogeneous with respect to ψ_i , the constant value in equation (9) can be chosen arbitrarily, so that

$$\psi_0(t) = -1 \quad 0 \leq t \leq T. \quad (13)$$

For $\psi_2 \neq 0$, from the condition $\max_{|u| \leq 1} H$ it follows that $u = \text{sign} \psi_2$, if $\psi_2 \neq 0$, then the boundary-value problem of the maximum principle is written in the following form [10], [11]:

$$\left. \begin{aligned} \varphi_1 = y_1, \dot{\varphi}_1 = y_2, \dot{y}_2 &= \text{sign}\psi_2 - j_1^{-1} \left[b_1(y_2 - i_1 y_4) + c_1(y_1 - i_1 y_3) + \right. \\ &\quad \left. + b_2(y_2 - i_2 y_6) + c_2(y_1 - i_2 y_5) \right]; \\ \varphi_2 = y_3, \dot{\varphi}_2 = y_4, \dot{y}_4 &= j_2^{-1} \left[i_1 b_1(y_2 - i_1 y_4) + i_1 c_1(y_1 - i_1 y_3) \right] - \text{sign}\psi_2; \\ \varphi_3 = y_5, \dot{\varphi}_3 = y_6, \dot{y}_6 &= j_3^{-1} \left[i_2 b_2(y_2 - i_2 y_6) + i_2 c_2(y_1 - i_2 y_5) \right] - \text{sign}\psi_2. \end{aligned} \right\} \quad (14)$$

We construct the Pontryagin–Hamilton function, which has the following form

$$\left. \begin{aligned} H_1 &= \psi_0 + \psi_1 y_2 + \psi_2 \dot{y}_2; \\ H_2 &= \psi_0 + \psi_1 y_4 + \psi_2 \dot{y}_4; \\ H_3 &= \psi_0 + \psi_1 y_6 + \psi_2 \dot{y}_6. \end{aligned} \right\} \quad (15)$$

From this it follows that condition (9) determines the control function in the case $u = \text{sign}\psi_2$, $\psi_2 \neq 0$. As a result, function (12) consists of the following [12].

$$H_i = -f^0 u + \psi_2(t) u_d. \quad (16)$$

In this case

$$u_i = \text{sign}\psi_2(t) = \begin{cases} 1, & \psi_2(t) > 1 \\ -1, & \psi_2(t) < 1 \end{cases}, \quad i=2,4,\dots,2n, \quad (17)$$

is valid, i.e., the control action $u_k(t)$ can have only one switching point [13].

To determine the auxiliary functions (8), a numerical method is used, in which the adjoint system is studied by varying the design parameters b_i, c_i and j_i .

The system of equations (1), (8), and (14) was solved using Runge-Kutta numerical methods. The control action $u_k(t)$ ensuring the maximum value of function (9) was determined in region (17). Analysis of the solution results of system (8) showed that changes in the moments of inertia and elastic-dissipative forces sharply change the function of the variables $\psi_1, \dot{\psi}_1, \psi_2, \ddot{\psi}_2$, i.e., they have a significant effect on the motion of the pneumatic system drive of the cotton-picking machine. Therefore, it is a matter of determining the adjoint system variables ensuring the normal operation of the drives of the pneumatic system of the cotton-picking machine [14].

Discussion

The results of the numerical solutions of systems (1), (8), and (14) are presented in Tables 1, 2, 3 and in Figures 3 and 4, on the basis of which it is possible to determine the following optimal values of the parameters of the drives of the pneumatic system of the cotton-picking machine; these values are given in Table 2.4.

Table 1.

For the pneumatic system drives of the cotton-picking machine, the values of the auxiliary variables $\psi_1, \dot{\psi}_1, \psi_2, \dot{\psi}_2$ and the function H obtained as a result of solving the adjoint system in accordance with Pontryagin's maximum principle

T, s	ψ_1	$\dot{\psi}_1$	ψ_1	$\dot{\psi}_1$	ψ_2	$\dot{\psi}_2$	ψ_2	$\dot{\psi}_2$	H
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	u=+1		u=-1		u=+1		u=-1		u=+1	u=-1
0	0	-1	0	1	0	-1	0	1	-1	1
0.1	-0.1	-1	0.1	1	-0.1	-1	0.1	1	-1	1
0.2	-0.2	-1	0.2	1	-0.2	-1	0.2	1	-1	1
0.3	-0.3	-1	0.3	1	-0.3	-1	0.3	1	-1	1
0.4	-0.4	-1	0.4	1	-0.4	-1	0.4	1	-1	1
0.5	-0.5	-1	0.5	1	-0.5	-1	0.5	1	-1	1
0.6	-0.6	-1	0.6	1	-0.6	-1	0.6	1	-1	1
0.7	-0.7	1	0.7	1	-0.7	-1	0.7	1	-1	1
0.8	-0.8	1	0.8	1	-0.8	-1	0.8	1	-1	1
0.9	-0.9	-1	0.9	1	-0.9	-1	0.9	1	-1	1
1	-1	-1	1	1	-1	-1	1	1	-1	1

Table 2

Values of the velocity and acceleration of the transient processes obtained as a result of solving the boundary-value problem according to Pontryagin's maximum principle for the pneumatic system drives of the cotton-picking machine

T, s	$\dot{\varphi}_1, s^{-1}$	$\ddot{\varphi}_1, s^{-2}$	$\dot{\varphi}_1, s^{-1}$	$\ddot{\varphi}_1, s^{-2}$	$\dot{\varphi}_2, s^{-1}$	$\ddot{\varphi}_2, s^{-2}$	$\dot{\varphi}_2, s^{-1}$	$\ddot{\varphi}_2, s^{-2}$	$\dot{\varphi}_3, s^{-1}$	$\ddot{\varphi}_2, s^{-2}$	$\dot{\varphi}_3, s^{-1}$	$\ddot{\varphi}_2, s^{-2}$
	u=+1		u=-1		u=+1		u=-1		u=+1		u=-1	
0	0	1	0	-1	0	-1	0	1	0	-1	0	1
0.1	-0.03	-0.56	0.03	0.56	-0.03	-0.18	0.03	0.18	-0.03	-0.18	0.03	0.18
0.2	-0.06	-0.57	0.06	0.57	-0.06	-0.17	0.06	0.17	-0.06	-0.17	0.06	0.17
0.3	-0.09	-0.57	0.09	0.57	-0.09	-0.17	0.09	0.17	-0.09	-0.17	0.09	0.17
0.4	-0.12	-0.57	0.12	0.57	-0.12	-0.17	0.12	0.17	-0.12	-0.17	0.12	0.17
0.5	-0.15	-0.57	0.15	0.57	-0.15	-0.17	0.15	0.17	-0.15	-0.17	0.15	0.17
0.6	-0.18	-0.57	0.18	0.57	-0.18	-0.17	0.18	0.17	-0.18	-0.17	0.18	0.17
0.7	-0.21	-0.57	0.21	0.57	-0.21	-0.17	0.21	0.17	-0.21	-0.17	0.21	0.17
0.8	-0.25	-0.57	0.25	0.57	-0.25	-0.17	0.25	0.17	-0.25	-0.17	0.25	0.17
0.9	-0.28	-0.57	0.28	0.57	-0.28	-0.17	0.28	0.17	-0.28	-0.17	0.28	0.17
1	-0.31	-0.57	0.31	0.57	-0.31	-0.17	0.31	0.17	-0.31	-0.17	0.31	0.17

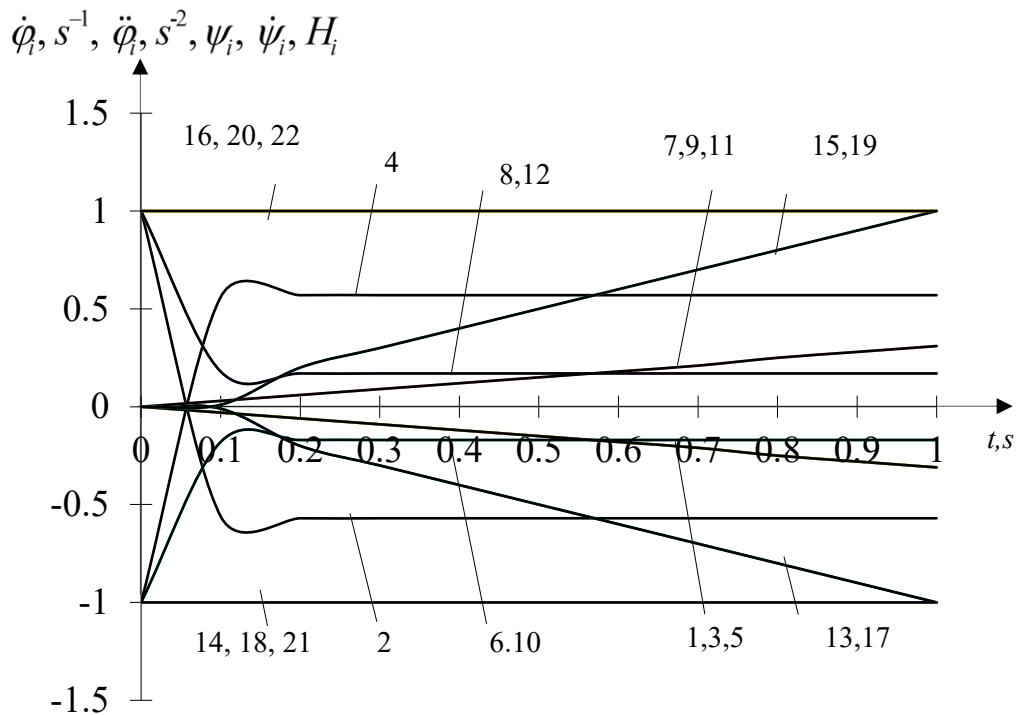


Figure 2. Graph of transient processes: 1, 3, 5, 7, 9, 11 – angular velocities ($\dot{\phi}_1, \dot{\phi}_2, \dot{\phi}_3$); 2, 4, 6, 8, 10, 12 – angular accelerations ($\ddot{\phi}_1, \ddot{\phi}_2, \ddot{\phi}_3$); 13, 15 – auxiliary functions $-\dot{\phi}_i, s^{-1}, -\ddot{\phi}_i, s^{-2}, \psi_i, \dot{\psi}_i, H_i$, 17, 19 – ψ_2 , 14, 16 – $\dot{\psi}_1$, 18, 20 – $\dot{\psi}_2$, 21, 22 – H auxiliary function of the pneumatic system drive. Here 1, 2, 3, 5, 6, 10, 13, 14, 17, 18, 21 – in the case $u(t) = +1$; 4, 7, 8, 11, 12, 15, 16, 19, 20, 22 – in the case $u(t) = -1$

Table 3

Values of the operating parameters in modeling the motion of the fan drive mechanisms of the cotton-picking machine

T, s	$\dot{\phi}_1, s^{-1}$	$\ddot{\phi}_1, s^{-2}$	$M_1, N \cdot m$	$\dot{\phi}_2, s^{-1}$	$\ddot{\phi}_2, s^{-2}$	$M_2, N \cdot m$	$\dot{\phi}_3, s^{-1}$	$\ddot{\phi}_3, s^{-2}$	$M_3, N \cdot m$	$n_1, n_2, n_3, \text{min}^{-1}$	$V_1, V_2, V_3, m/s$	p_1, kVt	p_2, kVt
0	0	442.	152	0	-	-	0	-	-	0	0	0	0
0.1	15.	96.4	33.	15.	180.7	59.	15.	180.7	59.6	145	1.82	0.5	0.9
0.2	30.	93.6	32.	30.	182.1	60.	30.	182.1	60.1	290	3.64	0.98	1.82
0.3	45.	93.6	32.	45.	182.2	60.	45.	182.2	60.1	435	5.46	1.47	2.74
0.4	60.	93.5	32.	60.	182.2	60.	60.	182.2	60.1	580.1	7.3	1.96	3.65
0.5	75.	93.5	32.	75.	182.2	60.	75.	182.2	60.1	725.1	9.1	2.45	4.56
0.6	91.	93.6	32.	91.	182.2	60.	91.	182.2	60.1	870.2	10.93	2.94	5.47
0.7	106	93.4	32.	106	182.3	60.	106	182.3	60.1	1015.	12.75	3.43	6.4
0.8	121	93.9	32.	121	182.0	60.	121	182.0	60.0	1160.	14.57	3.94	7.3
0.9	136	93.5	32.	136	182.2	60.	136	182.2	60.1	1305.	16.4	4.41	8.2
1	151	93.9	32.	151	182.0	60.	151	182.0	60.0	1450	18.21	4.92	9.1

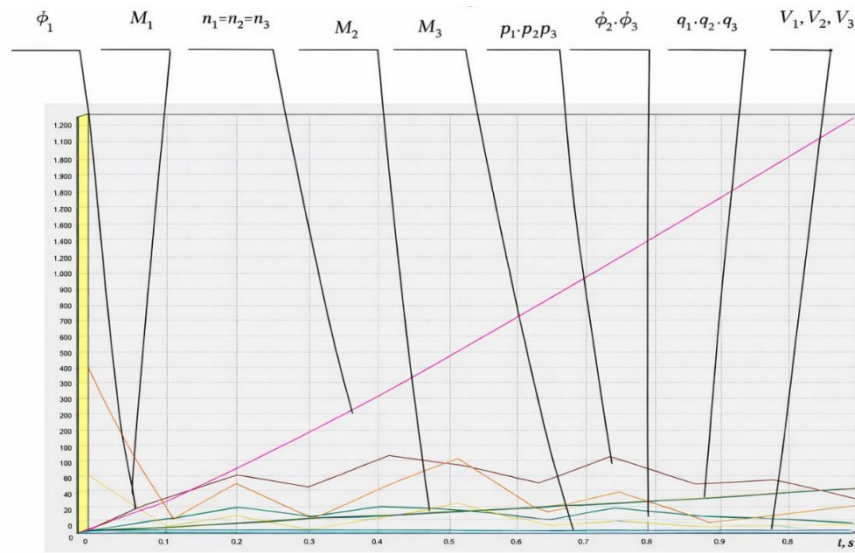


Figure 3. Graph of the variation characteristics of the motion parameters in modeling the motion of the fan drive mechanisms of the cotton-picking machine

Here $\dot{\phi}_1$ - is the angular velocity of the counter-drive of the pneumatic system, rad/s ; $\dot{\phi}_2$ and $\dot{\phi}_3$ are the angular velocities of the first and second fans (simultaneously), rad/s ; $\ddot{\phi}_1$ is the angular acceleration of the counter-drive, rad/s^2 ; $\ddot{\phi}_2$ and $\ddot{\phi}_3$ are the angular accelerations of the first and second fans (simultaneously), rad/s^2 ; M_1 is the driving torque, $\text{N}\cdot\text{m}$; M_2 and M_3 are the resistance torques in the first and second fans, $\text{N}\cdot\text{m}$; n_1 is the rotational speed of the counter-drive, rev/min ; n_2 and n_3 are the rotational speeds of the first and second fans (simultaneously), rev/min ; V_1 is the rotational speed of the counter-drive, m/s ; V_2 and V_3 are the linear velocities of the first and second fans (simultaneously), m/s ; p_1 is the power of the counter-drive, kW ; p_2 and p_3 are the powers of the first and second fans (simultaneously), kW [15].

Based on the values presented in the Results section, the fluid flow rate, working volume, angular velocity, and theoretical losses of the hydraulic motor were calculated. The obtained values represent the characteristics of the hydraulic motor [16].

Conclusion

By formulating the Hamilton-Pontryagin function, an adjoint system was developed. The developed adjoint system made it possible to obtain a solution for the control algorithm $u(t)$, to formulate L.S. Pontryagin's boundary-value problem, and to determine, by numerical solution, the values of the coefficients j_i, b_i, c_i within the interval +1 and -1 of the transient process. Substituting the determined coefficients j_i, b_i, c_i into the main equations (1) made it possible to obtain results characterizing the automated test bench of the hydraulic-motor-driven fan of the cotton-picking machine and the process of testing its drives.

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