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RESEARCH OF ELECTROMECHATRONIC SYSTEMS WITH VARIABLE PARAMETERS USING THE EXAMPLE OF A TRANSPORT MECHANISM

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ДОСЛІДЖЕННЯ ЕЛЕКТРОМЕХАТРОННИХ СИСТЕМ ЗІ ЗМІННИМИ ПАРАМЕТРАМИ НА ПРИКЛАДІ ТРАНСПОРТУЮЧОГО МЕХАНІЗМУ

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In the article an analysis of the influence of the variability of the system's mass on its dynamics in electromechatronic systems is presented.

It is shown that electromechatronic systems with variable parameters are particularly relevant, as their operation is accompanied by dynamic changes in mass, inertial, force, and kinematic characteristics during operation. These changes are caused by load variations, uneven material feed, changes in speed modes, and the influence of external factors, significantly complicating control processes. This necessitates the use of modern methods of mathematical modeling and analysis to ensure the effective operation of such systems. It is shown that transport mechanisms, particularly conveyors, are typical examples of electromechatronic systems with variable parameters. It is established that, in general, three types of dynamic forces (torques) arise in a mechanical system: the first arises from changes in the system's speed, the second from changes in the mass (moment of inertia), and the third from changes in the gear ratio. Therefore, a very large number of possible system behaviors are possible.

Given the complexity of the process, mathematical modeling has been established as the only method for studying processes in mechanical systems with variable parameters. The MATLAB/Simulink software package is used in the research. A short conveyor loader operating in reversible mode to dispense bulk material into passing containers is considered as a system for studying the effect of mass variability on the system's dynamics. The kinematic and structural diagrams of the loader are presented and analyzed in detail, taking into account the relationships between its main components, allowing us to reflect the features of motion transmission and the formation of operating modes. The operating principle of individual components and their impact on the overall system dynamics are described. Furthermore, the

mechanical characteristics of the loader's electric drive are studied, their main parameters and patterns of change depending on the load and operating modes are determined, which is important for further analysis and synthesis of control systems.

A digital model of this mechanical system is presented in the MATLAB/Simulink environment. The conveyor acceleration process is simulated with no material on the belt, a fully loaded belt, and gradual loading. This results in transient processes during conveyor start-up at various throughput values. It is established that the influence of variable mass on the dynamics is significant when its value at maximum load is comparable to or greater than the constant mass.

Key words: *electromechatronic systems, variable parameters, transport mechanism, dynamic characteristics, performance, transient processes, control system.*

Introduction. In today's industrial and process automation environment, electromechatronic systems play a key role in ensuring the efficiency, flexibility, and reliability of equipment. Of particular relevance are systems with variable parameters, whose operation is accompanied by dynamic changes in mass, inertial, force, and kinematic characteristics during operation. Such changes can be caused by load variations, uneven material feed, changes in speed conditions, or the influence of external factors, complicating control processes and requiring the use of modern modeling and analysis methods [1, 2].

A typical example of electromechatronic systems with variable parameters are transport

mechanisms, particularly conveyors, which are widely used in the mining, metallurgy, food, and logistics industries. A characteristic feature of such systems is the presence of a variable load, which directly impacts drive dynamics, energy consumption, and the accuracy of maintaining specified operating modes. This necessitates considering nonlinear effects, changes in stiffness and damping, as well as the interaction of electrical and mechanical subsystems during the study [3].

A conveyor loader is an integral part of continuous handling systems and is designed to move, feed, and evenly distribute bulk or individual materials within a technological process. Its widespread use is due to its high productivity, automation capabilities, and integration into complex production lines across various industries.

Structurally, a conveyor loader consists of a traction element (belt, chain, or roller system), a drive mechanism, support elements, loading and unloading units, and a control system. The primary functional element is the electric drive, which provides movement of the traction element and determines the dynamic characteristics of the entire system. The loader's operating mode is characterized by a variable load, depending on the material feed rate, its physical and mechanical properties, and operating conditions [4, 5].

A characteristic of conveyor loader operation is the uneven flow of material, which leads to changes in the torque on the motor shaft, fluctuations in travel speed, and additional dynamic loads on structural elements. This, in turn, impacts the energy efficiency, reliability, and durability of the equipment. Considering these factors is essential for constructing adequate mathematical models and developing effective control systems [6].

Thus, the study of the operating characteristics of a conveyor loader as an electromechatronic system with variable parameters allows for a deeper understanding of the processes occurring within it and the creation of preconditions for increasing the efficiency of its operation in real production conditions.

The objective to study an electromechatronic system with variable parameters using a conveyor as an example, develop an appropriate mathematical model, and analyze the influence of variable parameters on the dynamic characteristics of the system.

Research results. Mechanisms that exhibit both real and fictitious changes in mass (moment of inertia) include loading/unloading conveyors, thin sheet coilers in rolling mills, and mine hoists with variable rope winding radii. Additionally, in some

cases, transmission devices with a variable gear ratio between the mechanism and the motor are used – slip clutches (electromagnetic, hydraulic, powder), speed variators, crank-connecting rod pairs, cams, etc.

Let us consider the equation of motion for $m \neq const$ and $i \neq const$, neglecting for simplicity the flexibility of the kinematic constraints. The equation can be obtained from the equality of the impulse of force and the momentum in differential form. For translational motion, this equation has the form [1]:

$$(F_M - F_{CM})dt = d[m_M(V_M - U_M)] \quad (1)$$

where F_M, F_{CM}, m_M – the driving force, resistance force and mass reduced to the movement of the mechanism, N, kg;

U_M – projection of the velocity of the changing mass ($m_M = var$), which coincides with the direction of movement of the main mass, m/s.

When $U_M = const$ ($dU_M/dt = 0$) we have:

$$m_M \frac{dV_M}{dt} + (V_M - U_M) \frac{dm_M}{dt} = F_M - F_{CM} \quad (2)$$

This equation does not explicitly take into account changes in the gear ratio i . Therefore, we write (2) in terms of the electric drive coordinates, reduced to the motor shaft:

$$F_M = F \cdot i; F_{CM} = F_C \cdot i; V_M = V / i; m_M = m \cdot i^2,$$

where m – the fictitious mass reduced to the generator on the engine rotor, kg;

F, F_C, V – real forces and speed on the rotor generator, N, m/s.

Then

$$i^2 md \left(\frac{V}{i} \right) + \frac{V-U}{i} d(i^2 m) = i(F - F_C) dt.$$

Differentiating and dividing both sides by i and dt , we obtain:

$$m \frac{dV}{dt} + (V-U) \frac{dm}{dt} + \frac{m}{i} (V-2U) \frac{di}{dt} = F - F_C \quad (3)$$

For rotating motion ($\omega = V/R; \omega_U = U/R; M = FR; J = mR^2$)

$$J \frac{d\omega}{dt} + (\omega - \omega_U) \frac{dJ}{dt} + \frac{J}{i} (\omega - 2\omega_U) \frac{di}{dt} = M - M_C \quad (4)$$

where ω_U – the component of the angular velocity of the engine corresponding to the component U_M , 1/s.

If J and i are expressed through the angle of rotation α of the motor shaft, then the last equation will have the form:

$$J(\alpha) \frac{d\omega}{dt} + \omega(\omega - \omega_U) \frac{dJ(\alpha)}{d\alpha} + \frac{J(\alpha)}{i(\alpha)} \omega(\omega - 2\omega_U) \frac{di(\alpha)}{d\alpha} = M - M_c \quad (5)$$

As can be seen from the last three equations, in general, three types of dynamic forces (moments) arise in a mechanical system: the first of these arise when the speed of the system changes, the second – when the mass (moment of inertia) changes, and the third – when the gear ratio changes.

Therefore, a very large number of possible system behaviors are possible. For example, even in the absence of external forces acting on the system, that is, at $F - F_c = 0$ ($M - M_c = 0$), it can accelerate, decelerate, or move at a constant speed (stand still). In this case, the mass (moment of inertia) and gear ratio can decrease or remain constant.

Given the complexity of the flow, mathematical modeling is the only method for studying processes in mechanical systems with variable parameters. The MATLAB/Simulink software package is used in this research.

To study the effect of mass variability on the dynamics of a system, we will consider a short conveyor loader operating in reverse mode to dispense bulk material into passing containers. Bulk material falls vertically from the loader onto the conveyor belt. Belt loading begins when the motor is started. The kinematic diagram of the loader is shown in Figure 1.

The initial data for calculations and research are [1]:

- dispenser capacity – Q , t/h;
- maximum conveyor belt speed – V_{\max} , m/s;
- conveyor length – L_T , m;
- linear mass of rollers and tape – q_p , kg/m.

Since the speed of the additional mass falling onto the belt is perpendicular to the speed of the main mass of the system, and the gear ratio $j = \text{const}$ is, the equation of motion (3) has the form

$$m \frac{dV}{dt} + V \frac{dm}{dt} = F_p - F_c, \quad (6)$$

where F_p – the driving force of the engine, reduced to the belt ($F_p = M_p j$), N;

M – torque on the engine shaft, Nm;

F_c – static resistance force caused by dry friction in bearings under pressure from the belt with the transported material H,

$$F_c = F_c(t) = K_c g (m_c + m_v) = K_c L_T q_p g + K_c Q_m(t) g,$$

where K_c – the coefficient of friction ($K_c = 0.06 \div 0.1$);

m_c – constant mass, kg.

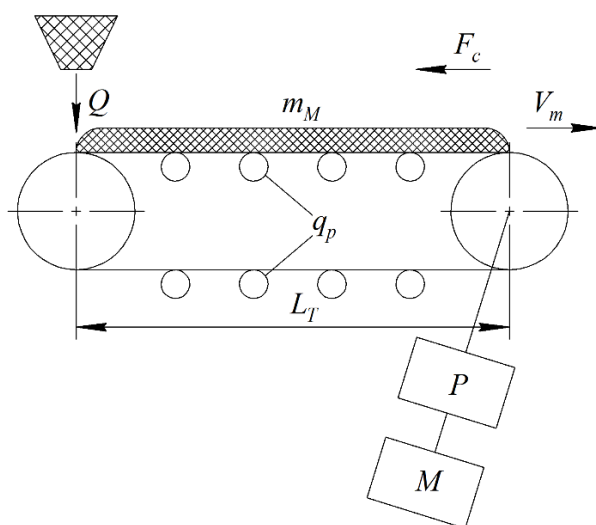


Fig. 1. Kinematic diagram of the loader

The mass of the rollers and tape,

$$m_c = q_p L_T;$$

m_v , $Q_m(t)$ – variable value of mass on the tape, kg.

$$m_v = Q_m(t) = Q_{(t/y)} \frac{1000}{3600} \cdot t = Q_{(kg/s)} \cdot t;$$

m – the total mass of the conveyor reduced to linear motion, taking into account the inertia of the engine,

$$m = m_d + m_c + m_v = 1.1 J_d \cdot j^2 + q_p L_T + Q_m(t),$$

where J_d – the moment of inertia of the engine rotor, kgm^2 .

The structural diagram of the mechanical system of the loader (Fig. 2) is obtained as the structure of the solution of equation (6) relative to V

$$V = \int \frac{1}{m} \left[M_p j - K_c g (m_c + Q \cdot t) - V \frac{dm}{dt} \right] dt.$$

The inertial force caused by the change of mass will be denoted by $F_{dm} = V \frac{dm}{dt}$.

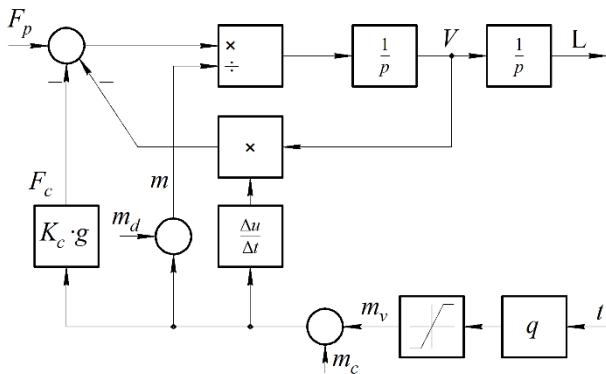


Fig. 2. Structural diagram of the mechanical system of the loader

Moment M_P engine is determined by its mechanical characteristic (Fig. 3, a), which can be generated by any electric drive system (TC-M, FC-AM, AVC) using a torque controller. It can be determined by equations [1, 2]:

section a-b – $M(\omega) = M_{max} = \lambda_M M_H$,

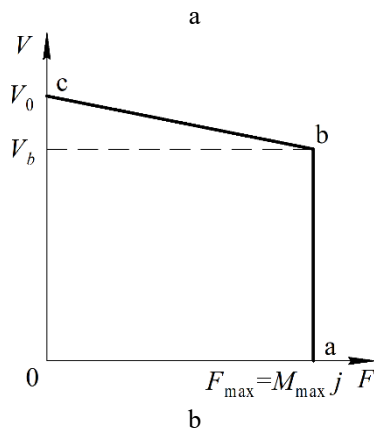
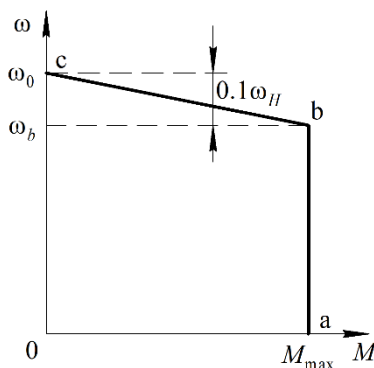


Fig. 3. Mechanical characteristics of the loader electric drive: a – speed-torque characteristic; b – speed-force characteristic

section b-c –

$$M(\omega) = M_{max} - K_M(\omega - \omega_b) = K_M(\omega_0 - \omega), \quad (7)$$

where λ_M – the engine overload capacity by torque ($\lambda_M = 1.8 \div 2.4$);

K_M – coefficient of rigidity of mechanical characteristics,

$$K_M = M_{max} / (\omega_0 - \omega_b) \cong M_{max} / 0.1\omega_H,$$

if we accept

$$\omega_b = \omega_0 - 0.1\omega_H.$$

At the first stage of loading (t_1) increases $Q_m(t)$ and upon completion of the stage is equal to

$$Q_{ml} = Q \cdot t_1,$$

where t_1 – the duration of the tape loading, which is determined by the time it takes the tape to travel the path L_T , i.e.

$$L_T = L_T = \int_0^{t_1} V(t) dt.$$

At the second stage (unloading) $Q_m(t)$ it begins to decrease until it reaches the value

$$Q_{mc} = Q t_T = Q L_T / V_{max} = q_m L_T,$$

where q_m – the linear mass of bulk material on the belt at a steady belt speed V_{max} ;

t_T – the time it takes to travel a distance along the belt L_T at a speed of V_{max} .

That is, the mass will become stable Q_{mc} after the tape has passed L_T from the moment t_1 .

Thus, the second stage ends when the belt has traveled a distance equal to $2L_T$. After this, the amount of material flowing onto the belt will be equal to that flowing off the conveyor. Without significant loss of accuracy, this process can be replaced with a simpler one: once $Q_m(t)$ it reaches Q_{mc} , it can be limited to this level, i.e.,

$$Q_m(t) = Qt \text{ at } Q_m(t) < Q_{mc},$$

$$Q_m(t) = Q_{mc} = const \text{ in the future.}$$

In this case, the change in driving force corresponds to the characteristic of the electric drive (Fig. 3). For ease of consideration, we will convert

the value of the torque on the motor shaft to linear motion (Fig. 3, b):

$$F(V) = M_{\max} j = F_{\max} = \text{const} \text{ at } V \leq V_b = \omega_b / j ,$$

$$F(V) = M_{\max} j - K_M j (\omega - \omega_b) = F_{\max} - K_M j^2 (V - V_b) \text{ at } V > V_b .$$

The digital model of this mechanical system in the Simulink environment of the MATLAB package is shown in Fig. 4. The mechanical characteristic of the engine is formed by the Constant, Sum 1, Gain, Gain 1 blocks according to equation (7) [6, 7]. The Saturation block limits the value of the torque at the level $\pm M_{\max}$ implementing the "a b" section of the mechanical characteristic. The structure of the mechanical part repeats the structural diagram (Fig. 2). The value of the variable mass is obtained at the output of Integrator 3 by integrating the productivity q (kg/s). At the output of the comparison block (Relational Operator), a logical signal "1" is formed when $L < L_T$, otherwise ($L \geq L_T$) the output will be "0". Consequently, the increase in mass will occur until the belt passes the distance L_T , after which the input of integrator 3 will be 0, and the output will be a constant value of the mass of bulk material Q_{mc} , which corresponds to the maximum load. The described structure implements the formation of m_v with simplification of the unloading processes. In general, for the precise (two-stage) formation of variable mass, the described structure must be complicated.

Fig. 5 shows the results of modeling the conveyor acceleration process with no material on the belt, fully loaded and gradual loading.

The system was modeled with the following parameters:

$$V_{\max} = 2.5 \text{ m/s}; L_T = 6 \text{ m}; q_p = 25 \text{ kg/m.}$$

(constant mass of conveyor elements, $m_c = 150 \text{ kg}$)

Engine parameters:

$$P_H = 1.2 \text{ kW}; \omega_0 = 104.7 \text{ s}^{-1}; \omega_H = 92.6 \text{ s}^{-1};$$

$$\lambda_M = 2; J_d = 0.0575 \text{ кгм}^2.$$

$$(M_{\max} = 25.8 \text{ Нм}, K_M = 2.47).$$

$$\text{Gear ratio } j = \omega_H / V_m = 37 \text{ m}^{-1};$$

$$\text{Coefficient of friction } K_c = 0.1;$$

With two performance values:

– $Q_1 = 75 \text{ t/h} = 20.83 \text{ kg/s}$, (mass of material at full conveyor load $Q_{mc} = q_1 L_T / V_{\max} = 50 \text{ kg}$);

– $Q_2 = Q_1 \cdot 5 = 375 \text{ т/год} = 104.1 \text{ kg/s}$, ($Q_{mc} = 250 \text{ kg}$).

As can be seen from Fig. 5, at a performance level of Q_1 , the change in dynamic torque during start-up is insignificant and the nature of the speed change is practically linear. However, when operating at a performance level of Q_2 , the influence of the sliding static torque on the acceleration dynamics is significant, which is reflected in an increase in the acceleration time and a curvature of the $\omega(t)$ curve.

We see that the influence of the variable mass (Q_i) on the dynamics is significant when its value at maximum load (Q_{mc}) is commensurate with the constant mass (m_c) and greater than it.

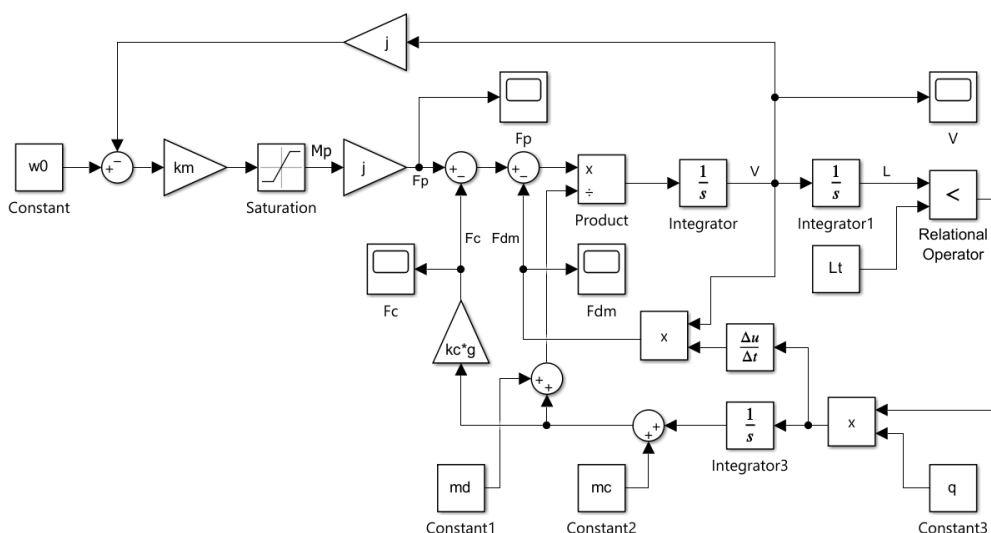


Fig. 4. Digital mathematical model of an electromechatronic system (conveyor) in the MATLAB / Simulink environment

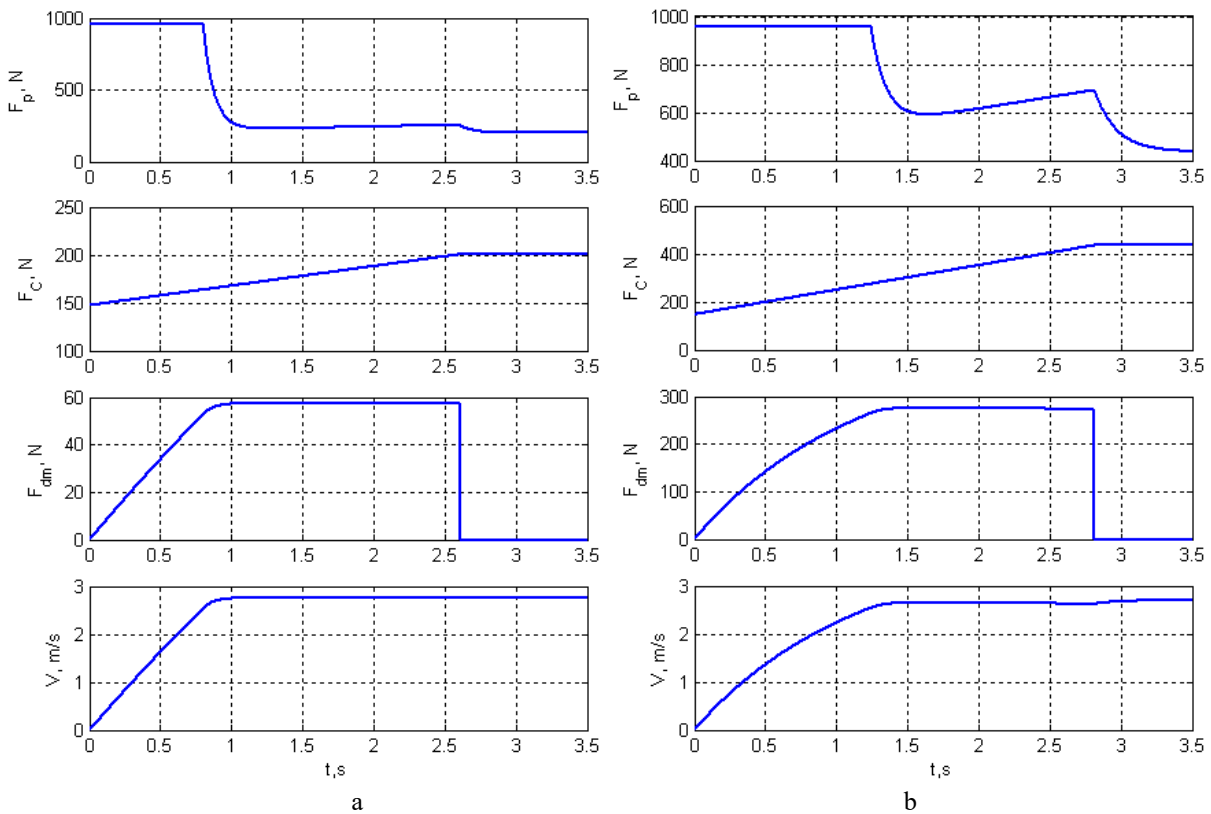


Fig. 5. Transient processes of conveyor start-up at:
 a – $Q = 75 \text{ t/h}$; b – $Q = 375 \text{ t/h}$

The results obtained during the modeling of the electromechatronic system of the conveyor loader are of significant practical significance and can be used in several key areas [8]. First of all, they form the basis for improving electric drive control systems, in particular for the development of adaptive and robust algorithms capable of effectively compensating for the influence of variable parameters and ensuring stable operation under uneven loads [9, 10].

Furthermore, the simulation results can be used to optimize conveyor equipment operating modes to reduce energy consumption and improve overall system efficiency. Dynamic process analysis allows for the determination of optimal speed modes, reduction of peak loads, and avoidance of electric drive overloads.

An important area of application is improving the reliability and durability of equipment. Modeling allows us to identify critical operating modes that cause excessive mechanical and electrical loads and develop measures to minimize them. This helps reduce wear on structural components and decrease the likelihood of emergency situations.

Furthermore, the research results can be used during the design phase of new transport systems,

such as conveyors and roller tables, to support the informed selection of equipment parameters, including electric motor power, transmission mechanism characteristics, and control systems. They are also useful for creating digital twins of conveyor systems, enabling the prediction of their performance under various operating conditions.

Thus, the simulation results have both theoretical and practical value, helping to improve the efficiency, reliability and adaptability of electromechatronic systems with variable parameters.

Conclusions. This article examines an electromechatronic system with variable parameters and conducts simulations using a conveyor mechanism as an example. The analysis revealed that conveyor systems are characterized by significant parameter variations, particularly load, moment of resistance, and inertial characteristics, which leads to nonlinear dynamics and complicates control processes. Given the complexity of the processes, mathematical modeling is the only method for studying processes in mechanical systems with variable parameters.

A short conveyor loader operating in reversible mode to dispense bulk material into passing

containers was considered as a system for studying the influence of mass variability on its dynamics.

A mathematical model of the conveyor loader's electromechatronic system was developed. This model accounts for parameter changes over time and allows for the study of real dynamic processes within the system. Based on the simulation, the influence of variable load on key operating modes was analyzed, specifically, the conveyor acceleration process with no material on the belt, with a fully loaded belt, and with gradual loading.

The study was conducted at two performance levels: $Q_1 = 75$ t/h and $Q_2 = 75$ t/h. It was found that at a performance level of Q_1 , the change in dynamic torque during start-up is insignificant, and the speed change is virtually linear. However, when operating at a performance level of Q_2 , the influence of the sliding static torque on acceleration dynamics is significant, resulting in an increase in acceleration time and a curve curvature $\omega(t)$. The simulation results showed that the influence of variable mass on dynamics is significant when its value at maximum load is comparable to or greater than the constant mass. The simulations allowed us to establish patterns in the influence of parameter changes on the stability, accuracy, and quality of the system's transient processes.

The obtained results have practical significance and can be used in the design and modernization of control systems, particularly for selecting controller structures, adjusting their parameters, and developing adaptive and robust control algorithms. Application of the proposed approaches will contribute to increased efficiency of transport mechanisms, improving their energy performance and reliability under conditions of uncertainty and variable loads.

Using the simulation results will improve the efficiency of the transport mechanism's electric drive control by adapting to changing operating conditions, reducing energy consumption, and lowering the level of dynamic loads on system components. This, in turn, will contribute to increased reliability and durability of the equipment.

The feasibility of applying the obtained results to the design and modernization of transport mechanisms, as well as the development of modern automated control systems, is substantiated. A promising direction for further research is the

implementation of intelligent control methods and the creation of digital models capable of operating in real time.

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Руднєв Є.С., Романченко Ю.А. Дослідження електромехатронних систем зі змінними параметрами на прикладі транспортуючого механізму.

В статті представлений аналіз впливу змінності маси системи на її динаміку в електромехатронних системах.

Показано, що особливої актуальності набувають електромехатронні системи зі змінними параметрами, функціонування яких супроводжується динамічною зміною масових, інерційних, силових і кінематичних характеристик у процесі роботи. Зазначені зміни зумовлюються варіацією навантаження, нерівномірністю подачі матеріалу, зміною швидкісних режимів та впливом зовнішніх факторів, що істотно ускладнює процеси керування. Це обумовлює необхідність застосування сучасних методів математичного моделювання та аналізу для забезпечення ефективного функціонування таких систем. Показано, що одним із типових представників електромехатронних систем зі змінними параметрами є транспортуючі механізми, зокрема конвеєри. Встановлено, що у загальному випадку в механічній системі виникає три види динамічних сил (моментів): перші з них виникають при змінній швидкості системи, другі – маси (моменту інерції), треті – передатного числа. Тому можлива дуже велика кількість варіантів поведінки системи.

Враховуючи складність перебігу, встановлено, що єдиним методом дослідження процесів в механічних системах зі змінними параметрами може бути математичне моделювання. У дослідженнях використовується пакет прикладних програм – MATLAB / Simulink. В якості системи для дослідження впливу змінності маси системи на її динаміку, розглянуто короткий конвеєрний завантажувач, що працює у реверсивному режимі для дозування сипучого матеріалу в ємності, які рухаються повз нього. Наведено та детально проаналізовано кінематичну та структурну схеми завантажувача з урахуванням взаємозв'язків між

його основними елементами, що дозволило відобразити особливості передачі руху та формування робочих режимів. Описано принцип функціонування окремих вузлів і їх вплив на загальну динаміку системи. Крім того, досліджено механічну характеристику електроприводу завантажувача, визначено її основні параметри та закономірності зміни залежно від навантаження і режимів роботи, що є важливим для подальшого аналізу та синтезу систем керування.

Подано цифрову модель цієї механічної системи в середовищі Simulink пакета MATLAB. Змодельовано процес розгону конвеєра при відсутності матеріалу на стрічці, повністю завантаженого та при поступовому завантаженні. В результаті цього отримано перехідні процеси пуску конвеєра при різних значеннях продуктивності. Встановлено, що вплив змінної маси на динаміку завантаження сумірне з незмінною масою і більше її.

Ключові слова: електромехатронні системи, змінні параметри, транспортуючий механізм, динамічні характеристики, продуктивність, перехідні процеси, система керування.

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