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STUDY OF OSCILLATORY PROCESSES IN ELECTROMECHATRONIC SYSTEMS

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ДОСЛІДЖЕННЯ КОЛИВАЛЬНИХ ПРОЦЕСІВ В ЕЛЕКТРОМЕХАТРОННИХ СИСТЕМАХ

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In the article an analysis of oscillatory processes occurring in electromechanical and electromechatronic systems is presented.
It has been shown that oscillations reflect the exchange of energy between accumulators via an active transmission channel. The oscillations reflect the exchange of energy between the storage devices via the active transmission channel. In mechanical systems, such accumulators are masses (moments of inertia), and the transmission channels are shaft lines. An electric motor is a universal converter of electromagnetic energy into mechanical energy and vice versa. It also contains two energy accumulators between which exchange is possible: the armature (rotor) winding, which contains electromagnetic energy, and the inertia on the shaft (the accumulation of mechanical energy). In the transmission channel, energy is converted from one form to another due to the presence of an excitation flow.
The authors note that in electromechanical and electromechatronic systems, electromechanical vibrations are also possible, in addition to mechanical ones. Both internal viscous friction in the shafting and losses in the machine's anchor circle damp these vibrations.
This article examines an electromechanical system that exhibits both types of oscillations. A unified structural diagram for any type of electromechanical electric drive system, as well as its mathematical model, is presented.
A differential equation for the motor rotor motion with a stepwise increase in the control input signal was obtained. The values of the first derivatives at the initial instant were found. The damping coefficients and oscillation frequencies were determined.
An electromechanical system was modeled in MATLAB/Simulink using a structural diagram with a constant electromagnetic motor torque and specified parameters. The logarithmic damping decrement was determined in the absence of mechanical damping and in the presence of shaft line losses.
The reaction of the electromechanical system to the sudden appearance of a control action at the input is presented, as well as the reaction in the absence of mechanical damping and when the anchor is powered from a current source, from which it is evident that in the absence of internal viscous friction in the shaft line, mechanical vibrations are still damped due to internal viscous friction in the engine itself.
Key words: *electric drive, engine, oscillatory processes, electromechanical system, internal viscous friction, mechanical damping.*

Introduction. Modern developments in science and technology are characterized by the rapid integration of electrical, mechanical, and information technologies, leading to the emergence of a new class of technical objects – electromechanical and electromechatronic systems. These systems form the basis of most modern technological processes, vehicles, robotic systems, precision mechanics devices, and automated production lines [1].

Electromechanical systems combine electrical and mechanical elements whose interaction enables the conversion of electrical energy into mechanical energy or vice versa. Such systems include electric drives, generators, electrically controlled transmissions, and industrial robot drives. Their effectiveness is determined by the coordination of the electrical and mechanical subsystems, their dynamic characteristics, and their ability to operate reliably under external disturbances and load changes [2].

Along with the development of sensor technology, microprocessor technology, and digital control systems, a new level of technical integration has emerged: electromechatronic systems [3]. They integrate electromechanical, electronic, computer, and information components into a single structure, creating intelligent, controlled systems. Such systems are capable of not only performing specified functions but also adapting to changing external conditions, analyzing the state of their own subsystems, and performing self-diagnostics.

Oscillatory processes play a key role in shaping the dynamic characteristics of both electromechanical and electromechatronic systems, determining their stability, reliability, and energy efficiency. In modern electric drives, automatic control systems, robotic and power plants, as well as electromechatronic complexes and systems, oscillations arise from the interaction of electrical, magnetic, and mechanical subsystems. Their occurrence is determined by both the design features of the system and external influences, changes in load, or operating modes [4].

Oscillatory processes can arise due to:

– disturbance of the system balance (sudden change in load, supply voltage, resistance moment, etc.);

– elastic deformations of shafts or couplings;

– feedback electromechanical connection between the armature current and the rotation speed;

– resonance phenomena, when the natural frequency of the mechanical part of the system coincides with or is close to the disturbance frequency.

Types of oscillations:

1. Natural oscillations occur when a system deviates briefly from its equilibrium state without external disturbance. They are characterized by a natural frequency ω_0 and attenuation coefficient ξ.

2. Forced oscillations – caused by periodic external forces or torques (e.g., power supply pulsations). They can be amplified if the excitation frequency is close to the system's natural frequency (resonance).

In an electromechanical system, electrical and mechanical oscillations are interconnected. In such a system, a change in current causes a change in the electromagnetic torque, which, in turn, changes the rotational speed [5]. The change in speed affects the rotational EMF, which again changes the current, thus creating a closed cycle of energy exchange. This leads to electromechanical oscillations, which can be [6]:

– damped if the system has sufficient internal friction (energy losses);

– persistent harmonics, if the losses are compensated by external disturbance;

– divergent (unstable) if the feedback is positive (for example, if the regulator is incorrectly configured).

Studying the nature of oscillatory processes is a pressing issue in modern electromechanics and electromechatronics, as excessive or uncontrolled oscillations can lead to reduced system efficiency, increased energy losses, noise, vibration, and premature wear of components. At the same time, the rational use of controlled oscillations can form the basis for the development of highly sensitive sensor systems, resonant converters, and intelligent electric drives [7, 8].

The relevance of the study is due to the need to develop new methods for modeling, analysis and damping of oscillatory processes to improve the dynamic stability and control accuracy of electromechanical and electromechatronic systems.

The objective to study the patterns of occurrence and development of oscillatory processes in electromechatronic systems, identify the main factors influencing their dynamics, and analyze approaches to reducing the amplitude and intensity of unwanted oscillations.

Research results.

Oscillations represent the exchange of energy between accumulators through an active transmission channel. In mechanical systems, these accumulators are masses (moments of inertia), and through the channels, shaft lines. An electric motor is a universal converter of electromagnetic energy into mechanical (kinetic) energy and vice versa. It also has two energy accumulators between which exchange is possible: the armature (rotor) winding, which contains electromagnetic energy, and the inertia on the shaft (the accumulation of mechanical energy). In the transmission channel, energy is converted from one form to another due to the presence of an excitation flux. The forward channel is the conversion "current – electromagnetic torque", while the reverse channel is the conversion "speed – back EMF."

An increase in speed (kinetic energy) is accompanied by an increase in EMF, which reduces the machine current (electromagnetic energy) – electromagnetic energy flows from the armature winding into the kinetic energy of the armature (rotor). The presence of active resistance in the winding makes the transmission channel less than ideal (dissipation). With high resistance, the energy lost during this transfer makes it impossible to return the kinetic energy of mechanical vibrations (as speed decreases) back to the armature winding.

Thus, in an electromechanical system, in addition to the mechanical oscillations mentioned above, electromechanical oscillations are also possible. Both internal viscous friction in the shafting and losses in the machine's armature chain dampen these oscillations. Furthermore, the negative internal coupling of the armature winding's EMF (speed) affects the mechanical oscillations in the shafting in the same way as the internal viscous friction, reducing their amplitude and frequency.

Let's consider an electromechanical system in which both types of oscillations are observed. Its structural diagram for any type of electric drive system can be represented as shown in Figure 1.

The following notations are used in it:

ω_0 – ideal idle speed of the engine, s^{-1};

K – control action transmission coefficient,

for the thyristor converter-motor system: $K = K_G / C$F;

for a frequency-controlled electric drive – $K = 2\pi K_{Tf} / p_n$;

for cascade asynchronous electric drives and double-feed machines –

$$K = K_G \omega_{0N} / K_{ce} E_{RN},$$

where K_G – gain factor of the valve converter (rectifier – inverter);

K_{Tf} – frequency converter transmission coefficient ($K_{Tf} = \Delta f / \Delta U_d$);

p_n – number of pole pairs of an asynchronous motor;

K_{ce} – gain coefficient for the EMF of the bridge rectification circuit of the rotary converter ($K_{ce} = 1{,}28 \div 1{,}35$);

γ – coefficient of rigidity of the mechanical characteristics of the engine, Nms, $\gamma = M_N / \Delta\omega_{(N)}$;

E_{RN} – nominal value of rotor EMF, V;

T_e – the value of the electromagnetic time constant of the main circuit of the engine, s;

$T_e = L_e / R_e$ – for the thyristor converter-motor system;

$T_e = 1/\left(\omega_{0N} s_{(c)}\right)$ – for frequency-controlled asynchronous electric drive;

$T_e = L_d / R_{d\,cr}$ – for cascade asynchronous electric drive;

L_e, R_e – equivalent value of inductance and active resistance of the armature circuit of the thyristor converter-motor;

L_d, $R_{d\,cr}$ – equivalent value of inductance and active resistance of the rectified current circuit of the rotor of the asynchronous valve cascade, H, Ohm;

ω_{0N} – synchronous speed of the motor at the rated voltage frequency ($\omega_{0N} = 2\pi f_N / p_n$), s^{-1};

$s_{(c)}$ – the value of the critical slip of the rotor at the nominal voltage frequency, taking into account the inductance and active resistance of the frequency converter;

C_{12}, β_{12} – coefficients of shaft rigidity and viscous internal friction in it, respectively, Nms.

The mathematical model of EMS has the following form [1]:

$$\left.\begin{aligned} & M - C_{12}\int(\omega_1 - \omega_2)dt - \beta_{12}(\omega_1 - \omega_2) = J_1 \frac{d\omega_1}{dt}; \\ & C_{12}\int(\omega_1 - \omega_2)dt - M_{C2} = J_2 \frac{d\omega_2}{dt}; \\ & T_e \frac{dM}{dt} + M = \gamma(KU_c - \omega_1). \end{aligned}\right\}, \quad (1)$$

After substitutions and transformations, we have the differential equation of motion of the motor rotor (ω_1) with a stepwise increase in the control signal U_c at the input and $M_{C2} = const$:

$$\frac{T_M T_e}{\Omega_{12}^2}\frac{d^4\omega_1}{dt^4} + \left(\frac{T_M}{\Omega_{12}^2} + \frac{2\alpha_{BT} T_e T_{M2}}{\Omega_{12}^2}\right)\frac{d^3\omega_1}{dt^3} + \left(\frac{K_j}{\Omega_{12}^2} + \frac{2\alpha_{BT} T_{M2}}{\Omega_{12}^2} + T_e T_M\right)\frac{d^2\omega_1}{dt^2} + T_M\frac{d\omega_2}{dt} + \omega_1 =$$
$$= K\left[\frac{K_j}{\Omega_{12}^2}\frac{d}{dt}U_y + U_y\right] -$$
$$-\frac{1}{\gamma}\left[\frac{2\alpha_{BT} T_e}{\Omega_{12}^2}\frac{d^2 M_{C2}}{dt^2} + \left(\frac{2\alpha_{BT}}{\Omega_{12}^2} + T_e\right)\frac{dM_{C2}}{dt} + M_{C2}\right]$$

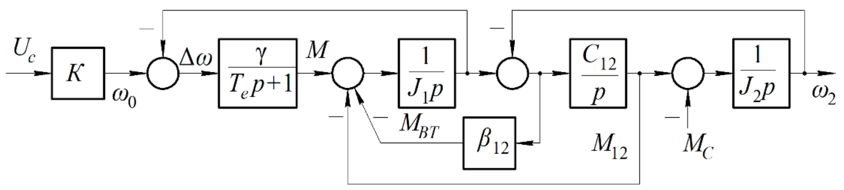

Fig. 1. Unified structural diagram of a two-mass electromechanical system

Similarly, the differential equation for the second mass is obtained:

$$\frac{T_M T_e}{\Omega_{12}^2}\frac{d^4\omega_2}{dt^4}+\left(\frac{T_M}{\Omega_{12}^2}+\frac{2\alpha_{BT}T_eT_{M2}}{\Omega_{12}^2}\right)\frac{d^3\omega_2}{dt^3}+$$
$$+\left(\frac{K_j}{\Omega_{12}^2}+\frac{2\alpha_{BT}T_{M2}}{\Omega_{12}^2}+T_eT_M\right)\frac{d^2\omega_2}{dt^2}+$$
$$+T_M\frac{d\omega_2}{dt}+\omega_2=KU_y-\frac{1}{\gamma}\left[\frac{T_MT_e}{\Omega_{12}^2T_{M2}}\frac{d^3M_{C2}}{dt^3}+\right. \qquad (2)$$
$$\left(\frac{2\alpha_{BT}T_e}{\Omega_{12}^2}+\frac{T_M}{\Omega_{12}^2T_{M2}}\right)\frac{d^2M_{C2}}{dt^2}+$$
$$\left.+\left(\frac{K_j}{\Omega_{12}^2T_{M2}}+\frac{2\alpha_{BT}}{\Omega_{12}^2}+T_e\right)\frac{dM_{C2}}{dt}+M_{C2}\right]$$

where T_M, T_{M2} – electromechanical time constants of the electric drive, s;
$T_M=(J_1+J_2)\Delta\omega_{(N)}/M_N$, $T_{M2}=J_2\Delta\omega_{(N)}/M_N$;

Ω_{12} – natural frequency of oscillations of a two-mass mechanical system;

K_j – coefficient of mass ratio in a two-mass mechanical system $K_j=(J_1+J_2)/J_1=1+J_2/J_1$;

M_{C2} – load moment on the shaft of the second mass, Nm.

Let's assume that both types of oscillations – mechanical and electromechanical – are observed in an electromechanical system. In this case, the solution to differential equation (2) is:

$$\omega_1(t)=e^{\alpha_1 t}(C_{1\omega}\cos\nu t+C_{2\omega}\sin\nu t)+$$
$$+e^{\alpha_3 t}(C_{3\omega}\cos\Omega_p t+C_{4\omega}\sin\Omega_p t)+KU_c-M_C/\gamma, \qquad (3)$$

where α_1, α_3 – the attenuation coefficients of electromechanical and mechanical oscillations, respectively, 1/s;

ν, Ω_p, – circular frequencies of the specified oscillations, rad/s;

$C_{j\omega}$ – constants of integration, defined as the solution of a system of linear equations for the initial conditions of the process (a jump-like increase in the control action U_c at the input with a constant load M_{C2}):

$$\begin{aligned}
&C_{1\omega}+C_{3\omega}=\omega_1(0);\\
&\alpha_1C_{1\omega}+\nu C_{2\omega}+\alpha_3c_{3\omega}+\Omega_pC_{4\omega}=\omega_1'(0);\\
&C_{1\omega}(\alpha_1^2-\nu^2)+C_{3\omega}(\alpha_3^2-\Omega_p^2)+2C_{2\omega}\alpha_1\nu+\\
&+2C_{4\omega}\alpha_3\Omega_p=\omega_1''(0);\\
&C_{1\omega}\alpha_1(\alpha_1^2-3\nu^2)-C_{2\omega}\nu(\nu^2-3\alpha_1^2)+\\
&+C_{3\omega}\alpha_3(\alpha_3^2-3\Omega_p^2)-C_{4\omega}\Omega_p(\Omega_p^2-3\alpha_3^2)=\omega_1'''(0),
\end{aligned} \qquad (4)$$

where $\omega_1(0)$, $\omega_1'(0)$, $\omega_1''(0)$, $\omega_1'''(0)$ are the initial values of the rotor speed and its derivatives.

Knowing the initial values of the coordinates of the state of the system (1): $\omega_1(0)=\omega_2(0)=0$; $M(0)=0$, we find the value of the derivatives of these coordinates at $t = 0$. We write the system of equations (1) in Cauchy form (in operator form)

$$\begin{cases}
p\omega_1=\dfrac{M}{J_1}-\dfrac{C_{12}}{J_1}\dfrac{1}{p}(\omega_1-\omega_2)-\dfrac{\beta_{12}}{J_1}(\omega_1-\omega_2)\\
p\omega_2=-\dfrac{M_{C2}}{J_2}+\dfrac{C_{12}}{J_2}\dfrac{1}{p}(\omega_1-\omega_2)\\
pM=\dfrac{\gamma KU_c-\gamma\omega_1}{T_e}-\dfrac{1}{T_e}M
\end{cases} \qquad (5)$$

Substituting the values $\omega_1(0)$, $\omega_2(0)$, $M(0)$, into (5), we find the value of the first derivatives at the initial moment of time. Differentiating the equation of system (5), we obtain expressions for the second and third derivatives of the state coordinates. As a result, we will have

$$\omega_1'(0)=0;\ \omega_2'(0)=-\frac{M_{C2}}{J_2};\ M'(0)=\frac{KU_c\gamma}{T_e};$$
$$\omega_1''(0)=\frac{KU_c\gamma}{T_eJ_1}-\frac{\beta_{12}M_C}{J_1J_2};\ \omega_2''(0)=0;\ M''(0)=-\frac{KU_c\gamma}{T_e^2}$$
$$\omega_1'''(0)=-\frac{KU_c\gamma}{J_1T_e}\left(\frac{\beta_{12}}{J_1}+\frac{1}{T_e}\right)-\frac{M_{C2}}{J_1J_2}\left(C_{12}+\frac{\beta_{12}^2}{J_1}\right); \qquad (6)$$
$$\omega_2'''(0)=\frac{C_{12}M_{C2}}{J_2^2};$$
$$M'''(0)=\frac{KU_c\gamma}{T_e^2}\left(\frac{1}{T_e}-\frac{\gamma}{J_1}\right)+\frac{\gamma\beta_{12}M_{C2}}{T_eJ_1J_2}.$$

By substituting the initial values of the velocity and its derivatives (6) into (4) with known α_1, α_2, ν, Ω_p, we can determine $C_{j\omega}$.

The attenuation coefficients and oscillation frequencies are determined by their characteristic equations according to the differential equation

$$p^4+\left(\frac{1}{T_e}+2\alpha_{BT}\frac{T_{M2}}{T_M}\right)p^3+\left(\frac{K_j}{T_eT_M}+\frac{\beta_{12}K_j}{\gamma T_eT_M}+\Omega_{12}^2\right)\times$$
$$\times p^2+\frac{\Omega_{12}^2}{T_e}p+\frac{\Omega_{12}^2}{T_eT_M}=0, \qquad (7)$$

taking its roots as complex conjugates $p_1=\alpha_1+j\nu$, $p_2=\alpha_1-j\nu$, $p_3=\alpha_3+j\Omega_p$, $p_4=\alpha_3-j\Omega_p$:

$$(p-p_1)(p-p_2)(p-p_3)(p-p_4)=0;$$

$$p^4 - 2(\alpha_1+\alpha_3)p^3 + \left[(\alpha_1^2+\nu^2)+(\alpha_3^2+\Omega_p^2)+ 4\alpha_1\alpha_3\right]p^2 - 2\left[\alpha_3(\alpha_1^2+\nu^2)+\alpha_1(\alpha_3^2+\Omega_p^2)\right]p + (\alpha_1^2+\nu^2)(\alpha_3^2+\Omega_p^2)=0, \qquad (8)$$

Equating the coefficients of the same powers of p equations (7) and (8) yield a system of equations, solving which we determine the roots. The resulting system will be quite complex; an approximate solution will be as follows:

$$\alpha_1 \cong -\frac{1}{2T_e}\ ;\ \alpha_3 \cong -\alpha_{BT}\frac{T_{M2}}{T_M}\ ;\ \nu \cong \frac{1}{2T_e}\sqrt{\frac{4T_e - T_M}{T_M}}\ ;$$

$$\Omega_p \cong \sqrt{\Omega_{12}^2 - \alpha_{BT}\frac{T_{M2}}{T_M^2}(\alpha_{BT}T_{M2}-2)}\ . \qquad (9)$$

Figure 2 shows the response of the electromechanical system to the sudden appearance of the control input U_c. In the absence of internal viscous friction in the shaft line ($\beta_{12}=0$), mechanical vibrations are still damped due to the internal viscous friction in the motor itself ($\gamma \neq 0$) – Fig. 3. Only in its absence, that is, at $\gamma = 0$, or when the motor is powered from a current source (and not voltage), is there no damping of mechanical vibrations (Fig. 4).

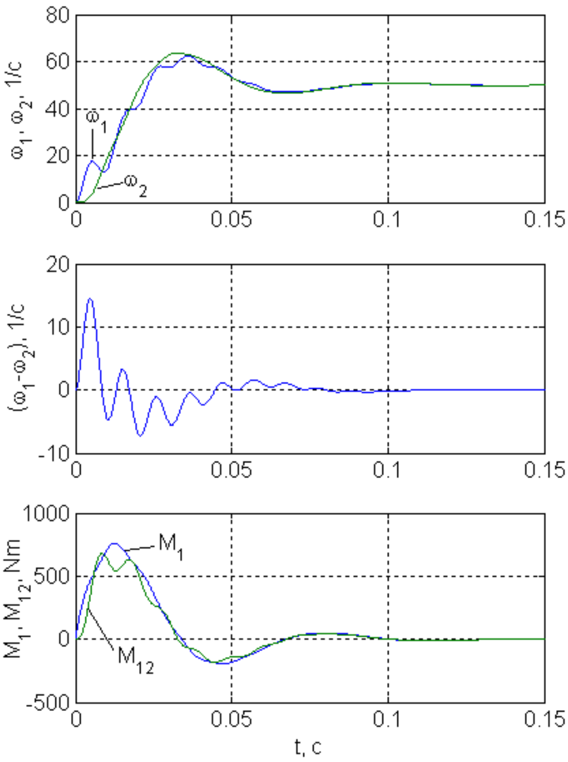

Fig. 2. Response of an electromechanical system to a sudden appearance of a control action [1]

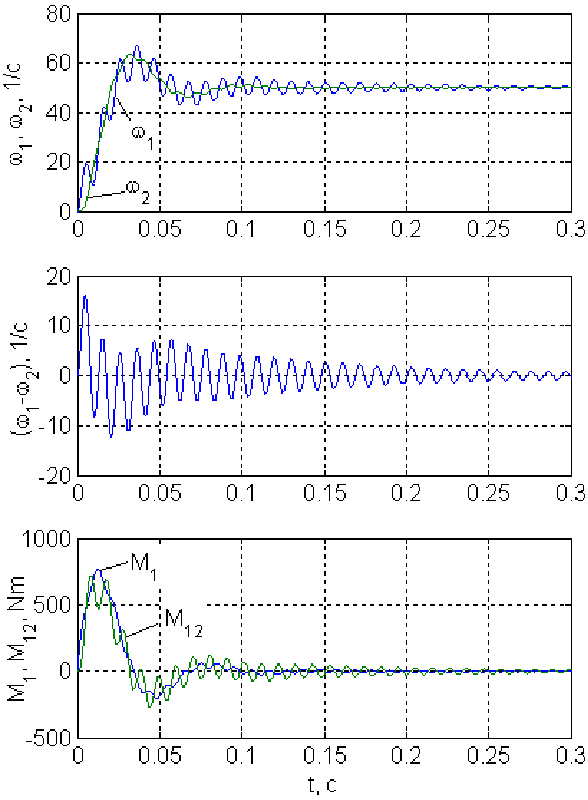

Fig. 3. Response of an electromechanical system in the absence of mechanical damping [1]

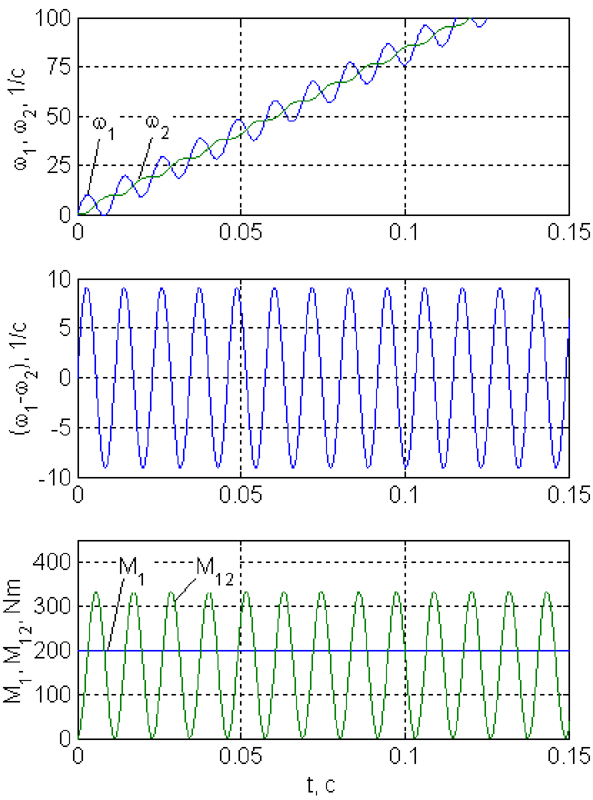

Fig. 4. Response of an electromechanical system in the absence of mechanical damping [1]

An electromechanical system with the following parameters was simulated in the MATLAB/Simulink environment:

$C_{12} = 10 \cdot 10^3$ Nm; $J_1 = 0.04$ kgm^2; $\omega_0 = 50$ s^{-1};
$\beta_{12} = 3.2$ Nms; $J_2 = 0.2$ kgm^2; $T_e = 0.01$ s.
$\gamma = 30$ Nms;

The model was formed in accordance with the structural diagram in Fig. 1. When simulating the power supply mode from a current source, the electromagnetic torque of the motor (M_1) was set constant and equal to 200 Nm.

In the absence of mechanical damping ($\beta_{12} = 0$), the oscillations are damped with a logarithmic decrement of 0.093. In the presence of losses in the shaft line, the logarithmic decrement approaches 0.5.

Conclusions. Thus, two types of oscillations are possible in an electromechanical system: mechanical and electromechanical. Both the internal viscous friction in the shafting and the losses in the machine's armature circuit damp these oscillations. Furthermore, the negative internal coupling of the armature winding's EMF affects the mechanical oscillations in the shafting in the same way as the internal viscous friction, reducing their amplitude and frequency.

Based on the results of modeling the electromechanical system in MATLAB/Simulink, it was found that even without internal viscous friction in the shaft line, mechanical vibrations are still damped due to the internal viscous friction in the motor itself. Only in its absence, or when the motor is powered by a current source (rather than a voltage source), is there no damping of mechanical vibrations.

In the absence of mechanical damping, oscillations are damped with a logarithmic decrement of 0.093. In the presence of losses in the shaft line, the logarithmic decrement approaches 0.5.

Oscillatory processes have a significant impact on the stability, precision, and efficiency of both electromechanical and electromechatronic systems. In automatic control systems, oscillatory processes can cause overshoot, self-oscillation, or even instability, leading to deterioration in speed or position control. In electric drives, oscillations cause mechanical vibrations, noise, and shaft and coupling overload, reducing equipment lifespan. In generators, oscillatory phenomena lead to voltage and current pulsation, which reduces power quality and can place additional strain on electrical networks.

Electromechatronic systems combine electrical, mechanical, and information subsystems interacting through sensors, microprocessor controllers, and actuators. Oscillatory processes in such systems are complex and affect multiple levels simultaneously. At the sensor level, they can cause measurement noise, feedback errors, and positioning inaccuracies. At the control level, signal fluctuations or data transmission delays lead to digital self-oscillations or oscillatory modes due to sampling. At the actuator level, vibrations caused by electromagnetic forces are transmitted to mechanical elements, reducing the precision of actions (for example, in robotic manipulators or mechatronic platforms). At the integrated system level, the interaction of electrical, mechanical, and software components can lead to electromechatronic resonances, complicating control and requiring active damping or adaptive control.

The importance of the analysis of oscillatory processes.

To ensure reliable and safe operation of electromechanical and electromechatronic systems, it is necessary:

– analyze frequency properties and natural frequencies of mechanical structures;

– correctly select damping parameters and feedback controls;

– apply digital filters, active damping and adaptive control algorithms capable of compensating for the effects of vibrations in real time;

– use sensor diagnostics to detect hazardous vibrations and predict vibration loads.

Thus, research and control of oscillatory processes in electromechanical and electromechatronic systems are key to increasing the accuracy of positioning and speed control, ensuring the stability of automatic control systems, reducing mechanical wear of components, and improving the energy efficiency and reliability of modern technological systems.

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Руднєв Є. С., Романченко Ю. А. Дослідження коливальних процесів в електромехатронних системах.

В статті представлений аналіз коливальних процесів, що відбуваються в електромеханічних та електромехатронних системах.

Показано, що коливальні процеси відіграють ключову роль у формуванні динамічних характеристик як електромеханічних так й електромехатронних систем і визначають їхню стабільність, надійність та енергоефективність. Коливання відображають обмін енергіями між накопичувачами через активний канал передачі. У механічних системах такими накопичувачами є маси (моменти інерції), а каналами – валопроводи. Електричний двигун є універсальним перетворювачем електромагнітної енергії в механічну і навпаки. У ньому також є два накопичувачі енергії, між якими можливий обмін – обмотка якоря (ротора), в якій міститься електромагнітна енергія, і інерційність на валу (накопичення механічної енергії). В каналі передачі відбувається перетворення енергій з одного виду в інший завдяки наявності потоку збудження.

Авторами зазначено, що в електромеханічних та електромехатронних системах, окрім механічних коливань, можливі також і електромеханічні. Як внутрішнє в'язке тертя у валопроводах, так і втрати у якірному колі машини роблять ці коливання загасаючими.

В статті розглянуто електромеханічну систему, в якій спостерігаються обидва види коливань. Подано уніфіковану структурну схему для будь-якого типу електромеханічної системи електропривода, а також її математичну модель.

Отримано диференціальне рівняння руху ротора двигуна при стрибкоподібному збільшенні керуючого сигналу на вході. Знайдено значення перших похідних в початковий момент часу. Визначено коефіцієнти загасання та частоти коливань.

Виконано моделювання електромеханічної системи в середовищі MATLAB/Simulink відповідно до структурної схеми з постійним значенням електромагнітного моменту двигуна та заданими параметрами. Визначений логарифмічний декремент затухання коливань при відсутності механічного демпфування та при наявності втрат в валопроводі.

Наведено реакцію електромеханічної системи на стрибкоподібну появу на вході керуючого впливу, а також реакції при відсутності механічного демпфування і живленні якоря від джерела струму., з яких видно, що при відсутності внутрішнього в'язкого тертя у валопроводі механічні коливання все одно загасають завдяки внутрішньому в'язкому тертю у самому двигуні.

Ключові слова: *електропривод, двигун, коливальні процеси, електромеханічна система, внутрішнє в'язке тертя, механічне демпфування.*

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