Fast response of mechatronics module for robotic

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Abstract. The synthesis technique, the mathematical model and results of experimental investigation of the control system of the robotic complex mechatronic module are presented in the article. It is shown that in most cases the dynamic system can be approximated by the serial connection of two first-order aperiodic links, while the speed in the torque control loop can reach 200-300 rad/s. The specified speed of the system was achieved due to improved specific weight and dimensions parameters of the electric drive (element of the mechatronic system) made on the basis of a contactless motor. The obtained results indicate the possibility of successful application of the proposed mechatronic module for objects of robotized systems in which the reference signal changes at a frequency not exceeding 50 Hz.

1. Introduction

Mechatronic systems, which include an electric drive, a mechanical transmission and a working body, can be successfully applied to solve positioning problems in robotic complexes [1]. This task can be successfully solved only with the system approach to the design of the electrotechnical complex. When implementing high-precision positioning, the elements of the system being designed should provide high speed. As a rule, the implemented objects have a significant spread of parameters, and for the adjustment of the system, analytical methods of synthesis must be supplemented by reliable methods of identifying the object [2].

2. Statement of the problem

The introduced control objects have a high-precision execution of the mechanics and electric drive and do not allow significant mechanical shocks and vibrations [3]. Therefore, the developed methodology for the synthesis and analysis of a system with improved dynamic indicators must meet the following requirements:

- assurance of reliable identification of the object, while the level of external influences should not exceed the allowed level in the conditions of accuracy preservation of the object’s mechanical parts;
- a sufficient degree of reliability to restore the mathematical description of the object of regulation;
- experimental evaluation of the dynamic indicators of the developed system.

3. Research methods

In the experimental determination of the logarithmic frequency response (LFR) of links, the following variants of schemes can occur: a single link, links connected in series, links forming a closed single-loop system, links forming a closed system with cross links (see Figure 1).
Direct determination of the LFR of any link (see Figure 1) is possible when, firstly, this link is stable and, secondly, the power of input signal $U_{in}$ is provided by the device for the experimental determination of the frequency characteristics (i.e., with regulation amplitude from 0.01 to 5 V and permissible load value up to 50 mA).

With the successive connection of several links (see Figure 1, b), it is possible to experimentally determine the LFR of links having large input signal powers (for example, generators, motors). In addition, the experiment takes into account the change in the static and dynamic properties of the links, due to the effect of the real load [4]. This scheme can be used when there are no unstable or integrating links among the links included in series. The links having a high gain factor also make it difficult to conduct an experiment in this scheme [5].

\[ L_{out} = L_1 - L_2, \quad \phi_{out} = \phi_1 - \phi_2 \] (1)

If several links A, B and C form a stable closed system (see Figure 1, c), then it is possible to experimentally determine the LFR of the entire system and any of its links.

To determine the LFR of the entire cascade of links A, B, C (see Figure 1, b), it is enough to remove the sinusoidal test signal $U_{inx}$ from the input of link A, to remove one set of characteristics (amplitude $L_1$ and phase $\phi_1$) by output signal $U_{out}$.

If it is necessary to determine the LFR ($L_{out}$ and $\phi_{out}$) of link C, then, in addition to previous characteristics $L_1$ and $\phi_1$, (with the same amplitude of signal $U_{in}$), let us remove characteristics $L_2$ and $\phi_2$ from output signal $U_{out}$. Then:

\[ L_{out} = L_1 - L_2, \quad \phi_{out} = \phi_1 - \phi_2 \] (1)

If it is necessary to determine the characteristics by output signal $U_{out}$, the determination of the characteristics of link B is carried out in the same way as in the previous case [6]. It is more time-consuming to determine the LFR of link A, which has an adder at the input. In this case, signal $U_A$ is obtained by direct experiment, and the error signal of closed control system $\Delta U$ is calculated in accordance with expression:

\[ \Delta U = U_{in} - U_{out} \] (2)

As experience of development and experimental research of control systems of industrial mechatronics modules has shown [7, 8], it is better to perform the experimental determination of the LFR of an mechatronics module in closed systems. In this case, firstly, the actual influence of the elements on each other is preserved, which can differ substantially from the calculated one. Thus, the presence of only interference, circulating through closed control loops can change the characteristics 2 ... 10 times [9, 10]. Secondly, the presence of the main (external) feedback, even in the course of the experiment and far from the optimal tuning, guarantees the existence of the mechatronics module mode near the working (or calculated) point, and this not only preserves the real nature of the links effect on each other, but also is important from the point of view of the safe conduct of the experiment.

Figure 1. Variants of connection of links in the experimental determination of LFR
(for example, the appearance of large voltages and currents on the stator winding is excluded).

A general algorithm for synthesizing a control system using experimental LFR can be represented by successively performing the following steps [11]:

- determination of the LFR of the unchanged part of the control system (in this case, the converter-motor complex);
- construction of the model of the immutable part of the system. A successful choice of the model predetermines the rational course of further stages of synthesis. Having experimental LFR systems with outputs in different coordinates, even a complex system can be represented as a successive connection of simpler links from the point of view of the dynamic properties, even of an arbitrary structure. It is very important that all intermediate coordinates are observable and, therefore, it is technically possible to perform feedback on them. The effect of all cross-links is automatically taken into account when determining the LFR. If one uses analytical methods, then, in order to simplify the recording of differential equations and preserve their clarity, one must introduce unobserved coordinates into the circuit, which complicates the structural schemes [12]. Thus, the representation of the model of the immutable part of the system in the form of a serial connection of simpler dynamic links, which LFR are identical to the LFR of a real system, greatly simplifies the subsequent synthesis;
- experimental verification of the selected corrective links based on the experimental LFR of closed control loops. Synthesis of regulators for state variables should be carried out sequentially, starting with the internal, the fastest-acting control loop.

4. Mathematical model of mechatronics module

In the experimental study of the mechatronics module with SRMIE, its direct channel was represented by a series connection of two links in which the first link was the contour of indirect regulation of the electromagnetic torque (CRT), the second link took into account the dynamic properties of the mechanical part of the motor [13].

The identification of the mechatronics module (CRT) using experimental frequency characteristics was carried out in two stages. First, the phase currents were identified. At the second stage, the voltage $U_{sr}$ was taken in the channel "frequency converter-motor" [14], and for the output - the electromagnetic torque of the motor, which was estimated by the acceleration of the electric machine. At the same time, the phase current control circuits were tuned in the current source mode.

Consideration of the dynamic characteristics of the current loop, which affects not only the transient but also the steady-state operating modes of the mechatronics module, is of fundamental importance [15], since with the rotation of the motor shaft the commutation of the stator current (which is carried out by the signals of the rotor position sensor) can significantly worsen the characteristics of the circuit for possible over-regulation of the current at the time of its commutation.

Since it is difficult to single out the component of the armature current in the SRMIE, the dynamic indices were determined for the real phase current in the sequential excitation circuit. The trial harmonic signal was applied to the summation input of the current regulator [16], the output signal from the current sensor was measured by the "Vector 2M" device. An estimation of the current loop dynamics was carried out for the characteristic operating modes of the mechatronics module: the operating mode at the stop, at full speed (idling and under load).

The experiment showed that the LFR of the current control loop [17] has a uniform transmission band of 200 rad/s, which does not depend on the rotational speed of the motor. Approximation of the experimental frequency characteristics in the frequency band up to 1000 rad/s resulted in a structural circuit of the current control loop equivalent to the series connection of inertial links with a transfer function:

$$W_{ce} = \frac{k}{(1+T_1p) \cdot (1+T_2p)}, \quad (3)$$

On the laboratory sample of the mechatronics module, $k = 1 / k_{out} = 0.32; T_1 = 5 \text{ ms}; T_2 = \tau = 2.5 \text{ ms}$. 


Here \( T_3 = T_{cr} = T_3 \cdot r / (k_{oc} \cdot k_{tc}); \) \( r \) - resistance of the armature winding; \( k_{oc} \) is the transmission coefficient of the current sensor; \( k_{tc} \) is the gain of the thyristor converter; \( T_4 \) - the time constant of the current regulator chosen equal to the electromagnetic time constant of the armature circuit of the \( T_{ac} \) (see Figure 2).

The rotating masses of the mechatronics module (in general, it is the motor shaft and an operating member) with the moment of inertia \( J \) can be taken into account by a transfer function of the form:

\[
W(p) = \frac{1}{J \cdot p}
\]  

(4)

The final influence of various factors on the dynamic properties of the mechatronics module is illustrated by the experimental frequency response of the open loop of speed control [18].

The LFR analysis of the converter-motor complex shows that in the frequency range of 10 … 100 rad/s, the system exhibits the properties of an integrating link with a constant phase shift of 90°. At frequencies less than 10 rad/s, this characteristic deviates from the characteristic corresponding to an ideal integrating unit, which is explained by the presence of losses in the system. The decrease in the phase characteristic in the frequency range above 100 rad/s is due to the fact that the inertial links begin to appear here: pure delay and aperiodic [19].

The calculation of the dynamic properties of the converter and the elements of the motor itself (electromagnetic and mechanical inertia) in the detailed structural scheme of the SRMIE [20] makes it possible to construct the structure of the converter-motor complex (see Figure 2, a).

![Figure 2. The transient process of the electromagnetic torque.](image)

The block diagram (see Figure 2, b) is the result of approximation of the dynamic characteristics of the converter-motor system in the frequency band up to 120 rad/s, and takes into account the dynamic properties of both the electric converter [21] and the dynamic properties of the motor itself, which is not typical of traditional electric machines, which can be described independently of the converter [22].

5. Experimental results

The purpose of this item is to give a real assessment of the developed system of the mechatronics module. The final, indisputable answer can give an experiment that takes into account all the features of the mechatronics module. The considered mechatronics module has many competitors, which are universally recognized and have high dynamic parameters [23]. In this regard, the analysis of the dynamic characteristics of the mechatronics module with SRNIV was carried out in comparison with the best samples of foreign analogues Unidrive [24].

The modern adjustable AC mechatronics module is realized according to the schemes with
different methods of forming the electromagnetic torque (in the polar coordinate system or in the Cartesian coordinate system). The generalized block diagram of the frequency-controlled asynchronous mechatronics module [25] includes the SR, the contour of indirect regulation of the electromagnetic torque of the CRT motor, the link M, which takes into account the mechanical inertia of the mechatronics module. At the CRT link, indirect torque control is performed with allocation of virtual stator current components: \( I_w \) - active and \( I_\mu \) - reactive. Current control circuits \( I_w \) and \( I_\mu \) are connected in parallel [26]. Current control loop \( I_w \) operates as a function of the output of the PC controller. Current control loop \( I_\mu \) is more often switched on autonomously [27]. Adjustment of these circuits is performed by regulators PTw and PTT. The unchangeable part of each of the control loops includes a control circuit for the autonomous inverter, inverter, asynchronous motor and its model, by which the values of signals \( I_w \) and \( I_\mu \) are determined.

The tested mechatronics module contained an asynchronous electric motor of type MTF111-6 (3.5 kW, 380 V, 895 rpm), whose stator circuits were connected to frequency converter SIMOVERT MASTERDRIVES 6SE7021-3EB61 (8.7 kVA, 380 V, 13.2 A) or to the UNIDRIVE UNI1405 frequency converter (4 kW, 380 V, 9.5 A).

The test sinusoidal signal was applied to the free SR input via the analog-to-digital converter of the ADC [28]. The output signals of the SR controller, the current reference signals \( I_w t \), \( I_\mu t \), the virtual currents \( I_w \), \( I_\mu \) were measured by the device through a digital-to-analog converter of the DAC. The speed was measured by a digital speed sensor - an encoder.

The LFR of closed current control loop \( I_w \) (\( I_w \) channel) has a band of uniform transmission of frequencies (see Figure 3, curve 1), reaching up to \( \omega \approx 500 \) rad/s. In the second case, the LFR of the closed loop (see Figure 3, curve 2) is limited to the right by smaller values of frequencies \( \omega \approx 120 \) rad/s, but this only indicates that the model of the asynchronous motor is more correctly compiled in this case.

![Figure 3. LFR of closed loop control of the active component of current \( I_w \):](image)

The presence of the effect of pure delay on the LFR of links and control loops should be explained by the discrete character of the signal conversion inherent in modern frequency converter control systems [29]. Moreover, it seems that today manufacturers of switch frequency converters for AC mechatronics modules often spend a large amount of computing resources of programmable microcontrollers on the solution (sometimes redundant) of service tasks, and the dynamics issues are not considered enough.
6. Conclusion

It is shown that in most cases the dynamic system can be approximated by the serial connection of two first-order aperiodic links, while the speed in the torque control loop can reach 200-300 rad/s.

The specified speed of the system was achieved due to improved specific weight and dimensions parameters of the electric drive (element of the mechatronic system) made on the basis of a contactless motor. The obtained results indicate the possibility of successful application of the proposed mechatronic module for objects of robotized systems in which the reference signal changes at a frequency not exceeding 50 Hz.

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