Engineering Method for Adjusting Electric Drive Regulators of Manipulator Motion Units With Significant Nonlinearities

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Abstract

The article develops an engineering method for tuning (or reconfiguring during operation) the regulators of electric drives of manipulator mobility units, which takes into account the presence of significant nonlinearities. This method prevents the appearance of "primary self-oscillations" in the automatic control system of electric drives of the manipulator's mobility units, which stimulate the emergence of resonant elastic vibrations and self-oscillations (the effect of autoelasticity). The proposed method allows not only to eliminate the cause of the autoelasticity effect, but also to do so at the engineering level of mastery of the mathematical apparatus, computer mathematics systems, and programming skills. The manifestation of the self-elasticity effect is associated with the presence of such factors as: dynamic properties of the drive of mobility units; elastic flexibility of manipulators; significant nonlinearities of a structural and technological nature or those that arise during operation in mechanical and electrical devices. The engineering simplicity and convenience of the method is expressed in the fact that the adjustment of the regulators of electric drives of the mobility units during the manufacture of the manipulator or their reconfiguration during operation does not require specialized scientific research, but can be performed by a specialist with an engineering level of mathematical training in an interactive mode in a short time.

Keywords

Automatic control system, PID controller, significant nonlinearity, numerical optimization methods, computer mathematical model, directional antenna, manipulator

1. Introduction

In the aerospace industry, multi-link manipulators are used to ensure smooth and insensitive movement of inertial objects with significant "windage" in three-dimensional space [1]. Aerospace manipulators must usually be lightweight, have at least three degrees of mobility (i.e., mobility nodes), and cover a large working area [2,3]. At the same time, the electric drive regulators of the manipulator's motion units must provide the ability to perform rapid reorientation and precise tracking of the input control action [4-7]. The elasticity of the manipulator, together with the dynamic properties of the actuators, the buoyancy of the objects moved by the manipulator, and the objective presence of significant nonlinearities in the mechanical design of the manipulator such as hysteresis, insensitivity zone, and saturation, lead to the emergence of the so-called "autoelasticity" effect (AEE) during operation. drives of mobility units and then develops even to resonant modes associated with the elasticity of the manipulator structure [8-10]. It is clear that an urgent problem arises regarding the adjustment (or reconfiguration during operation) of the electric drive regulators of the manipulator's mobility units, which takes into account the presence of significant nonlinearities and suppresses the cause of the AEE, i.e., suppresses the "primary self-oscillations".

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The AEE begins with "primary self-oscillations" (SO), which are associated with the failure to take into account the effect of significant nonlinearities when setting up the controllers of electric

Once again, we emphasize that, in terms of physical content, a significant nonlinearity is either inherent in the design and technological execution of the manipulator, or arises during normal operation as a result of wear and runout in the bearings of the electric drive, or is caused by external mechanical (physical) shocks, or is specifically set by the control algorithm of the manipulator's mobility unit [11-12].

2. Problem Statement

At present, there are well-developed methods for analyzing and synthesizing the operating modes of nonlinear automatic control systems (ACS) in general and, in particular, significantly nonlinear ACS, which are aimed at: first, finding out the conditions for the occurrence of self-oscillations or instability; second, finding ways to stabilize and (or) eliminate self-oscillations: frequency methods (Popov frequency method of stability analysis; Goldfarb-Popov harmonic linearization method); phase plane method (phase trajectories); fitting method (Andronov point transformation method); statistical linearization method; methods of catastrophe theory; method of Lyapunov functions [4-7]. Existing methods for the analysis and synthesis of nonlinear ACS are based on the fundamental theoretical mathematical works of A.M. Lyapunov, which outlines the necessary and sufficient conditions for the stability of nonlinear systems. These methods are aimed at mathematicians and scientists, not at operational engineers. In aerospace engineering, manipulators are manufactured and used en masse. The problem of AEE is of a massive nature. Controllers need to be adjusted and reconfigured in the course of operation on a massive scale. This means that a method is needed that is accessible at the theoretical level to operating engineers and is focused on the use of modern and advanced computer mathematics systems with advanced specialized software aimed at solving static and dynamic optimization problems. In other words, we need an engineering method (EM) for engineering practice. In the MATLAB computer mathematics system, there is a so-called Nonlinear Control Design (NCD Blockset) package that implements a method of dynamic optimization with user-defined time constraints [4-7]. This method can be considered semi-engineering for the reason that the heuristic method of setting time constraints (the desired model of change in the output coordinates of the ACS) is more of an art than an engineering method. The scientific and technical task is to develop an engineering method available for mass use in engineering practice for tuning (or reconfiguring during operation) of electric drive regulators of manipulator mobility units, which takes into account the presence of significant nonlinearities. The paper proposes an engineering method for tuning electric drive regulators of manipulator mobility units with significant nonlinearities based on the use of numerical optimization methods for an algorithmically specified criterion.

3. Engineering method of adjusting the regulators of electric drives of manipulator motion units with significant nonlinearities

Since engineering method refers to "tuning", it is actually a method of parametric synthesis of automatic control system controllers with a given structure. The structure of the ACS of electric drives for manipulator mobility units is well established in engineering practice and in most cases it is a two-circuit structure [11-14]. Engineering method is based on:

- on the use of numerical methods for optimizing a criterion that depends on the vector of controller parameters and, at the same time, it is either impossible or very difficult to obtain this dependence in an explicit analytical form;
- using computer mathematical models (modeling algorithms) of dynamic links of automatic control systems (ACS) and static characteristics of nonlinear elements with both significant

and smooth (insignificant) nonlinearities, which allow to calculate the quantitative value of the criterion (i.e., the numerical value of the criterion is found by applying modeling algorithms: hence the name - algorithmically defined criterion).

The engineering method allows: algorithmically calculating the quantitative values of the criterion for the given values of the controller parameter vector in order to obtain a quantitative integrated assessment of the efficiency of the ACS functioning; visually observing the change in time of the variables characterizing the quality of the ACS functioning and interactively analyzing and synthesizing the controller algorithm. When using the engineering method, a nonlinear element (NE), which is a nonlinear link of directed action, is modeled as a static link with a static characteristic that corresponds to the physical content of the action of the nonlinear element in the ACS. The engineering method can be used for parametric synthesis of the controller (PSC) and for controller tuning (CT) during operation. The initial data for the use of engineering method PSC is a mathematical model of a prototype ACS, i.e., a structural diagram of a prototype ACS with known mathematical models of all links of directed action, as well as circuits that include nonlinear elements. The initial data for the application of the engineering method CT is a real ACS.

3.1. Stages of engineering method of the PSC

Building the structure of the modernized ACS. The type of controller with a known structure of control laws is selected and the controller is connected to the structural diagram of the computer mathematical model of the ACS prototype. The parameters of the controller are to be determined by numerical optimization of an algorithmically specified criterion.

Search for the first approximation to the optimal values of the controller parameters, which will be further calculated by numerical optimization of an algorithmically specified criterion.
Selection of a reference mathematical model for modeling the desired change in time of those variables that are selected for tuning in the mathematical model of the ACS. Selection of the criterion for evaluating the difference (tuning criterion) in time between the corresponding output variables (coordinates) of the reference mathematical model (desired change in time) and the mathematical model of the ACS (change in time of variables at the given values of the controller parameters). Selection of the method of numerical optimization of the controller parameters. Connecting the reference model and the algorithm for calculating the quantitative value of the criterion for assessing the discrepancy (tuning criterion) to the structural scheme of the modernized ACS. Application of the numerical method for parametric synthesis (tuning), i.e., search for optimal values of the controller parameters. The stages of EM CT consist of 3 - 8 stages of EM PCS, where mathematical models of the ACS elements - the prototype and the modernized ACS - are replaced by full-scale models (i.e., real equipment and devices). Let us consider the use of EM PCS to adjust the control of the ACS of the electric drive of the link mobility unit, on which the actuating element with a fixed directional antenna is located. This antenna is designed to transmit sensing signals in the mode of identifying a “swarm” of small-sized objects (i.e., scanning a selected area when searching for actively maneuvering group objects and their group tracking (capturing the movement of a group object)). The input signal u(t) sets the angular velocity of the actuating element of the manipulator x(t), which is the output signal [14-19]. The initial data are presented in Fig. 1 in the form of a block diagram of the computer mathematical model of the ACS - a prototype of the electric drive of the link mobility unit, on which the actuating element with a fixed directional antenna is located. All variables are presented in a dimensionless form (relative values calculated in relation to nominal values).

The mathematical model of the ACS prototype consists of mathematical models: 1 - angular velocity sensor of the actuating element; 2, 3, Relay, 4 - electronic converter (EC) and electrical part of the electric drive; 5 - mechanical part of the electric drive with the actuating element; 6 - force sensor.

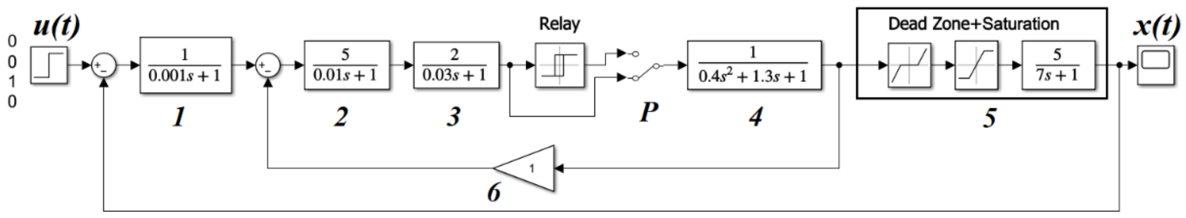


Figure 1: Block diagram of the computer mathematical model of the prototype ACS: Prototype L (switch P in the lower position); Prototype R (switch P in the upper position)

The block diagram of the computer mathematical model of the prototype L ACS allows modeling the prototype ACS with a linear mathematical model of the ES (switch P in the lower position), and the prototype R ACS models the ES with a power amplifier with a relay characteristic ([-10;10], switch P in the upper position). It should be emphasized that in both computer mathematical models of the prototype L and R, a significant nonlinearity of the mechanical part of the electric drive with the link on which the actuating element is located is modeled in the form of a zone of insensitivity [-1;1] and saturation [-5;5]. Let's proceed to the implementation of the stages of the EM PID.

Stage 1. As controllers for the internal and external circuits, we choose proportional, integral, and differentiating controllers (PID controllers) (Fig. 2). The mathematical models of the regulators take into account the physical realization of these regulators (a real differentiating link and the limitation of the type of saturation zone ([-10;10]) for the output signal of PID regulators) [4-7].

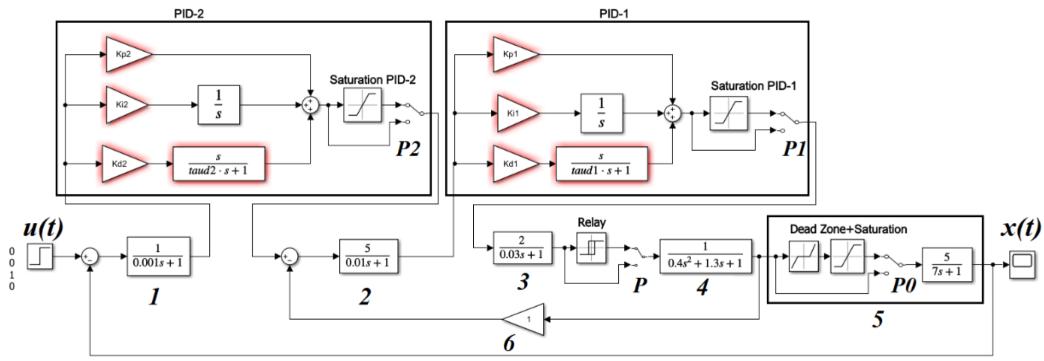


Figure 2: Schematic diagram of the computer mathematical model of the modernized ACS L (switch P in the lower position) and the modernized ACS R (switch P in the upper position) of the electric drive of the link mobility unit, on which the actuating element with a fixed directional antenna is located: PID-1 and PID-2 controllers are connected to the internal and external circuits, respectively; the position of switches P0, P1, and P2 is set at the stages of the method

Stage 2. The parameters (Kp1, Ki1, Kd1) and (Kp2, Ki2, Kd2) f the PID-1 and PID-2 controllers, respectively, are subject to parametric synthesis (tuning). According to the recommendations [4] of [Project ACS], we assume that $taudj = 0.15 \cdot \frac{Kdj}{Kpj}$ $(j = 1, 2)$. We will search for the first approximation (initial tuning) to the optimal values of the parameters of the PID-1 and PID-2 controllers of both schemes of the modernized ACS (L and R, Fig. 2) using the Ziegler-Nichols oscillation method [4, 17, 19] [Designing ACS, ACS Manual] without taking into account all significant nonlinearities (i.e., all switches in Fig. 2 are in the lower position). As a result, we get this: PID-1 (Kp1 =1.2, Ki1 = 3, Kd1 = 0.12, taud1 = 0.015) and PID-2 (Kp2 = 2.1, Ki2 = 3.5, Kd2 = 0.315, taud2 = 0.0225). The transition function of the computer mathematical model of the modernized SCS L and R (Fig. 2), which was constructed for the values of the controller parameters calculated without taking into account the effect of significant nonlinearities, is shown in Fig. 3.

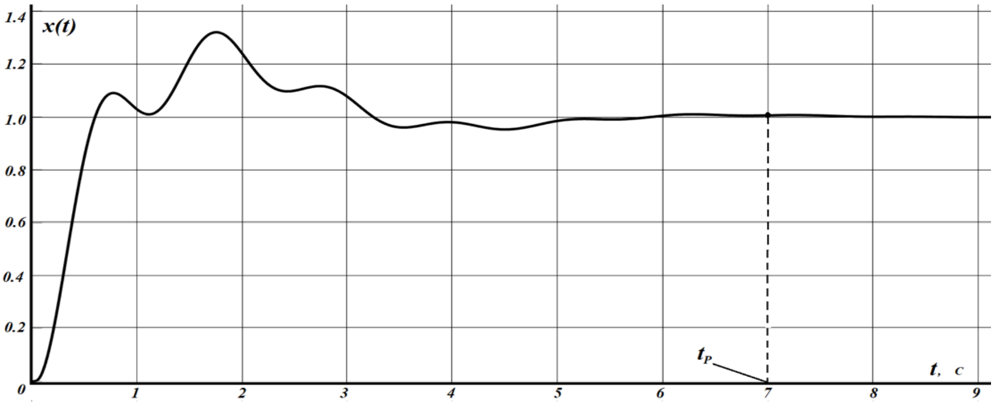


Figure 3: Transient function SISO LTI of the mathematical model of the modernized ACS L and R (all switches in Fig. 2 are in the lower position): transient duration time t_p=7 s; overshoot 35%

Stage 3. For tuning, we select the output coordinate of the modernized ACS L and ACS R, i.e., the angular velocity of the manipulator's actuating element x(t). We assume that the duration of the transient process should be reduced to 2 s, and the overshoot should be approximately halved. Taking into account the form of the transient function (Fig. 3) and analyzing the physical content of the processes occurring in the modernized ACS L and ACS R, we choose the standard 5th-order Butterworth form as a reference model for changing the output coordinate of the modernized ACS L and ACS R over time [17-19]. The continuous transfer function of the system, which allows generating a continuous transient process that corresponds to the standard Butterworth form, is as

$$W(s) = \frac{v_0^k}{P_k(s)}, \tag{1}$$

where $P_k(s)$ - is the k-th order characteristic polynomial. The 5th-order characteristic polynomial of the standard Butterworth form is:

$$P_k(s) = s^5 + 3.24 \cdot s^4 \cdot v_o + 5.24 \cdot s^3 \cdot v_0^2 + 5.24 \cdot s^2 \cdot v_0^3 + 3.24 \cdot s \cdot v_0^4 + v_0^5 \tag{2}$$

Using the transfer function of the reference mode [17-19]:

$$W(s) = \frac{v_0^5}{s^5 + 3.24 \cdot s^4 \cdot v_o + 5.24 \cdot s^3 \cdot v_0^2 + 5.24 \cdot s^2 \cdot v_0^3 + 3.24 \cdot s \cdot v_0^4 + v_0^5} \tag{3}$$

build a normalized reference transfer function at $v_o = 1$ (see Fig. 4) and find [FEA Manual] the value of the parameter v_o at which the duration of the desired reference transient t_{PE} does not exceed 2 s:

$v_o = \frac{t_{PN}}{t_{PE}} = \frac{14}{2} = 7$, where t_{PN} is the duration of the normalized reference transient.

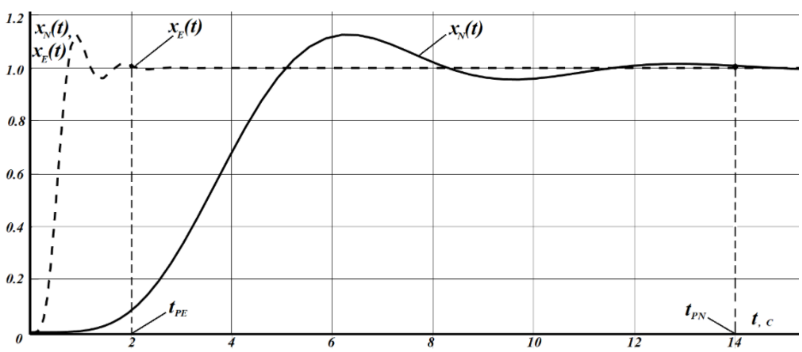


Figure 4: Transient functions at the output of the normalized $x_N(t)$ ($v_o = 1$) and desired $x_E(t)$ ($v_o = 7$) reference models: t_{PN}, t_{PE} - the time of the transient process duration in the normalized and desired reference models, respectively

Stage 4. As a criterion for assessing the time difference between the corresponding output variables (coordinates) of the reference mathematical model (desired change in time) and the mathematical model of the ACS (change in time of variables at the given values of the parameters of the PID-1 and PID-2 controllers), that is, the tuning criterion, we choose the weighted square error integral:

$$I = \int_{t_0}^{t_f} \alpha(t) \cdot (x_E(t) - x(t))^2 dt \ , \tag{4}$$

where we assume that the weighting factor $\alpha(t) = 1, t_0 = 0, t_f = 10\ s$.

The quantitative value of the criterion is shown in the display D (see Fig. 5).

Stage 5. As a method of numerical optimization of the parameters of the PID-1 and PID-2 controllers, it is proposed to choose a numerical method among the methods described in [17, 19].

As an example, in step 7 we will consider the use of the Gauss-Seidel numerical method.

Stage 6. Fig. 5 shows the connection of the reference model 7 and the algorithm for calculating the quantitative value of criterion I (integral of the weighted square of the error, the value of which is displayed on the display D) to the computer mathematical model of the modernized ACS.

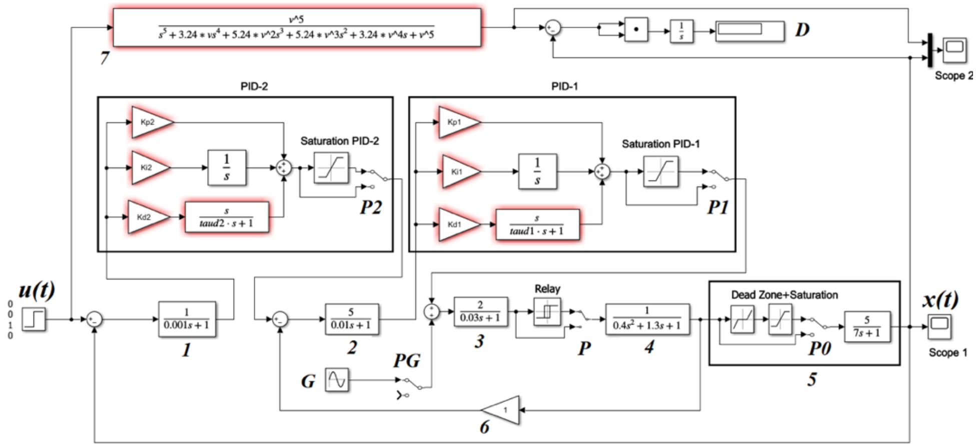


Figure 5: Block diagram of the computer mathematical model of the modernized ACS with the connected reference model 7 and the algorithm for calculating the quantitative value of the tuning criterion displayed on the display D: G - vibration (oscillation) generator for vibration linearization

The block diagram shown in Fig. 5 allows modeling the types of modernized ACS depending on the position of the switches. If all switches are in the position indicated in the diagram (Fig. 5), except for switches P and PG, which are moved to the lower position, then the modernized ACS L is modeled. If all switches are in the position indicated in the diagram, except for switch PG, which is moved to the lower position, then the modernized ACS R1 is modeled. If all the switches are in the up position (as shown in the diagram in Fig. 5), then the modernized ACS R2 is modeled.

The peculiarity of the modernized ACS R1 and R2 compared to the modernized ACS L is the presence of a significantly nonlinear relay-type element in their composition. Significant nonlinearity of the relay type is inherent in some types of electronic converters used in electric drives of manipulator mobility units.

The feasibility of using such converters is determined by the relevant design and technological features of the electric drive and manipulator. The peculiarity of the modernized ACS R2 compared to R1 is the use of vibration linearization to reduce the influence of a nonlinear relay-type element on the effective functioning of the ACS.

The physical meaning of the effect of vibration linearization on improving the static characteristics of an electronic converter is as follows. In the presence of a smooth useful signal at the input of a link with a significant nonlinearity of the relay type (the useful signal and the signal from the vibration generator G are added), a smooth dependence of the average value of the output signal of this link during the period of operation of the vibration generator G on the average value of the input signal will be ensured.

Stage 7. Let us apply the Gauss-Seidel numerical method to optimize (tune) the parameters of the PID-1 and PID-2 controllers. We will use a computer mathematical model (Fig. 5), taking into account a different set of significant nonlinearities for each option of the ACS modernization. The option of modernization of the ACS is denoted by the letters L or R1 or R2.

The position of the switches (Fig. 5) for the variant of the modernized ACS: variant L corresponds to the upper position of the switches P0, P1, P2 and the lower position of the switches P and PG; variant R1 corresponds to the upper position of the switches P, P0, P1, P2 and the lower position of the switch PG (i.e., vibration linearization is not applied); variant R2 corresponds to the upper position of all switches, i.e., vibration linearization is applied).

The tuning (optimization) criterion depends on the six parameters of the PID-1 and PID-2 controllers:

$$I(r) \rightarrow \min_{r \in DFD}, \tag{5}$$

where $r = [r_1, r_2, r_3, r_4, r_5, r_6]$ is a vector composed of the parameters of the PID-1 and PID-2 controllers;

$$r_1 = k_{p1}, r_2 = k_{i1}, r_3 = k_{d1}, r_4 = k_{p2}, r_5 = k_{i2}, r_6 = k_{d1} \tag{6}$$

The DFD is the domain of admissible solutions for finding the optimal values of the parameters of the PID-1 and PID-2 controllers, which is set by the physical content of the problem (in particular, the features of the implementation of the PID-1 and PID-2 controllers in a particular problem). We will denote the tuning criterion for the corresponding variant of the ACS modernization by the letters L or R1, or R2, i.e.: $IL(r), IR1(r), IR2(r)$.

We consider the parameters of the controllers taud1 and taud2 to be constant parameters. These parameters are equal to the values that were obtained in step 2 of the method, i.e., during the initial tuning of the PID-1 and PID-2 controllers: taud1 = 0.0150 and taud2 = 0.0225.

We emphasize once again that to begin applying the numerical Gauss-Seidel method, the first approximation to the optimal values of the parameters of the PID-1 and PID-2 controllers, obtained at stage 2 by the Ziegler-Nichols oscillation method for the SISO LTI mathematical model of the modernized ACS L and R1, R2 (all switches in Fig. 2 are in the lower position), is used.

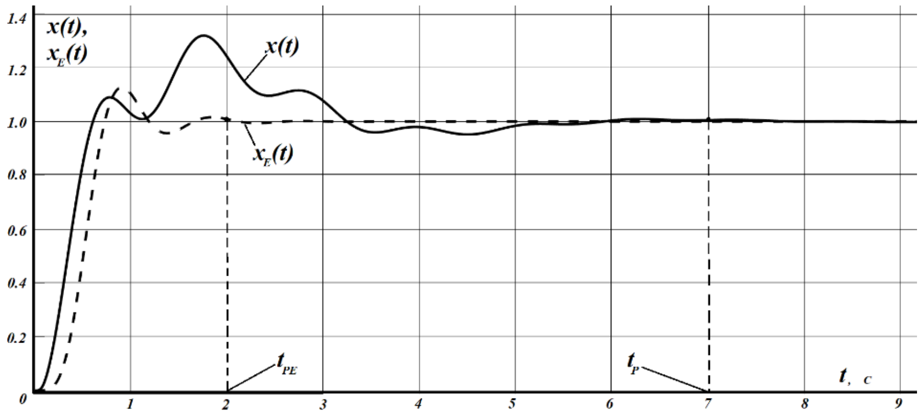
4. Results and discussions

4.1. The result of the first approximation to the optimal values of the parameters of the PID-1 and PID-2 controllers

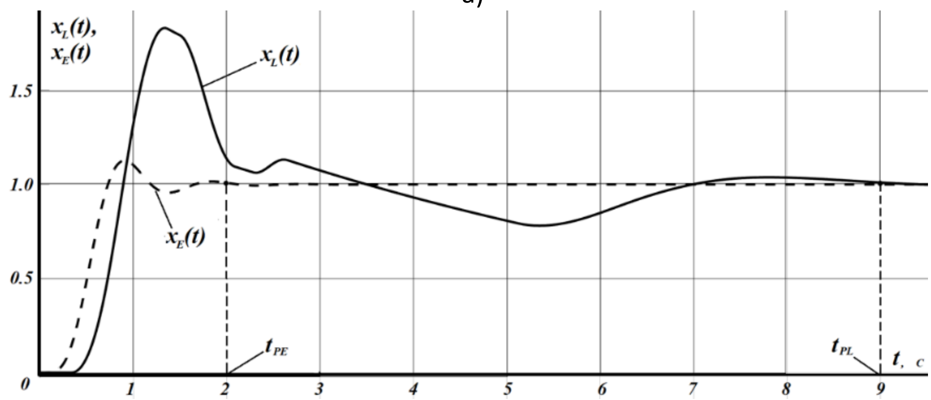
Comparative modeling of the transient functions of the reference model 7 and the mathematical model of the modernized ACS L, R1, and R2 (Fig. 5) for the first approximation

$$r1 = [Kp1 = 1.2, Ki1 = 3, Kd1 = 0.12, Kp2 = 2.1, Ki2 = 3.5, Kd2 = 0.315] \tag{7}$$

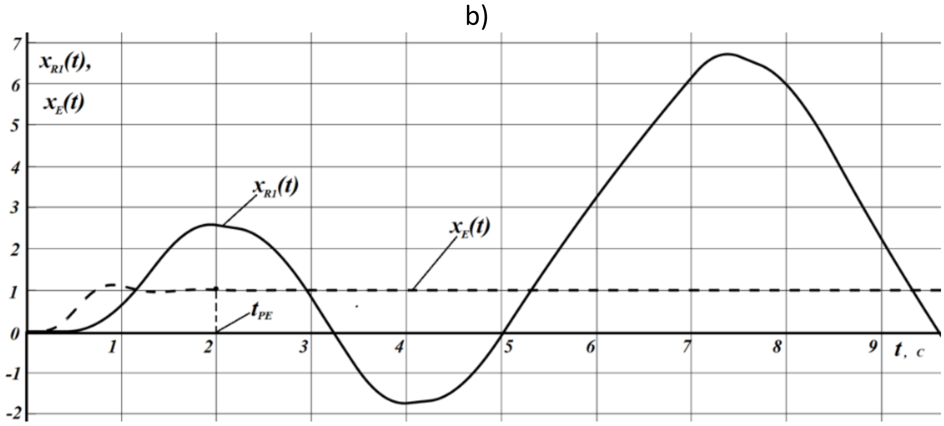
to the optimal values of the parameters of the PID-1 and PID-2 controllers obtained at stage 2 is shown in Fig. 6 (a, b, c, d).



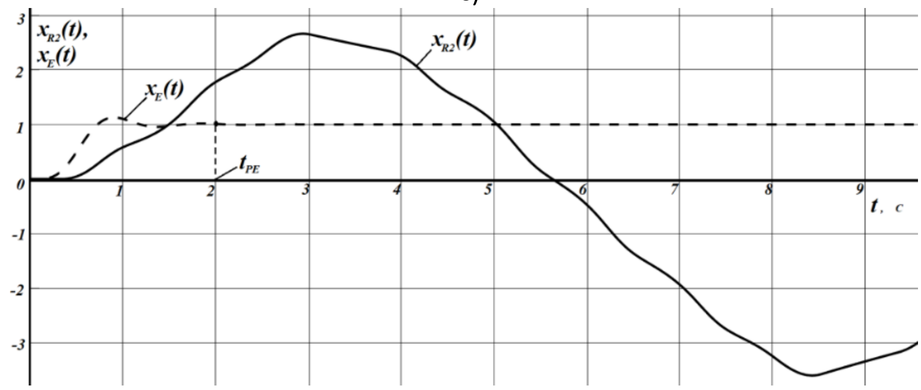
a)



b)



c)



d)

Figure 6: Transition functions of the reference model 7 ($x_E(t)$) and and the mathematical model of the modernized ACS L ($x_L(t)$) or R1($x_{R1}(t)$), or R2 ($x_{R2}(t)$) for the first approximation to the optimal values of the parameters of the PID-1 and PID-2 controllers obtained at stage 2: a) - all switches

(Fig. 5) are in the lower position (the influence of significant nonlinearities is not taken into account); b) - switches (Fig. 5) P0, P1, P2 - in the upper position, and switches P and PG - in the lower position; c) - switches (Fig. 5) P, P0, P1, P2 - in the upper position, and switch PG - in the lower position; d) - all switches (Fig. 5) in the upper position

When using the first approximation r1 to the optimal values of the parameters of the PID-1 and PID-2 controllers, which were obtained in step 2, the following values of the tuning criterion are displayed on the display D:

$$IL(r1) = 0.5871, IR1(r1) = 61.21, IR2(r1) = 60.51 \quad (8)$$

in accordance with the computer mathematical models of the modernized ACS L or R1 or R2 (Fig. 5).

4.2. The result of tuning (optimizing) the parameters of the controllers PID-1 and PID-2

Using the Gauss-Seidel method, six parameters of the PID-1 and PID-2 controllers were tuned for each of the modernized ACSs L, R1, R2. The result of parameter tuning is denoted by rCL, rCR1, rCR2, respectively.

The Gauss-Seidel method uses a "coordinate descent" [17, 19]. In the process of optimization for each coordinate (parameter of the PID-1 and PID-2 controllers), a direct interactive method of coordinate descent was used (i.e., the optimization was performed almost "manually"). One complete cycle consists of passing through six coordinates, i.e., from $r_1 = k_{p1}$ to $r_6 = k_{d2}$ inclusive (see Step 7). After optimization for a particular coordinate, the minimum point at that coordinate was memorized. The optimization process did not aim to achieve a global minimum.

Since we are talking about an engineering tuning method, the goal was to show that even without "automation" (the use of special software to find the minimum of an algorithmically specified criterion), and even in manual mode, it is possible to achieve the desired result of tuning a significantly nonlinear ACS. It should be emphasized that during the optimization process, a visual comparison of the quality of the transient of the modernized ACS with the quality of the transient of the reference model was performed using a Scope 2 oscilloscope (Fig. 5).

As a result of performing one complete cycle in the interactive mode of coordinate descent (the time of one complete cycle was less than 30 minutes), the following quantitative values of the parameters of the PID-1, PID-2 controllers and the tuning criterion for the modernized ACS were obtained:

$$L: rCL = [\mathrm{Kp1} = 2.5; \mathrm{Ki1} = 3.2; \mathrm{Kd1} = 0.14; \mathrm{Kp2} = 2.1; \mathrm{Ki2} = 2; \mathrm{Kd2} = 0],$$

$$IL(rCL) = 0.06487;$$

$$R1: rCR1 = [Kp1 = 10; Ki1 = 4; Kd1 = 0.4; Kp2 = 2.1; Ki2 = 1.5; Kd2 = 0],$$

$$IR1(rCR1) = 0.2387;$$

$$R2: rCR2 = [Kp1 = 5, Ki1 = 4.5, Kd1 = 0, Kp2 = 2.1, Ki2 = 1, Kd2 = 0],$$

$$IR2(rCR2) = 0.2895.$$

Transition functions for the computer mathematical models of modernized ACS L, R1, and R2 for the vector of parameters of PID-1 and PID-2 controllers equal to the corresponding rCL, rCR1,rCR2, and rCR2 are shown in Figs. 7, 8, 9.

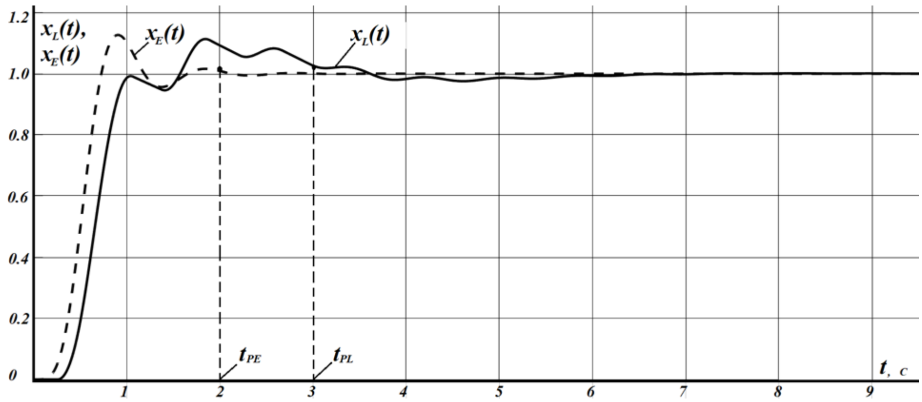


Figure 7: Transition functions of the reference model 7 ($x_E(t)$) and the mathematical model of the modernized ACS L ($x_L(t)$) (Fig. 5) for one complete cycle of approaching the optimal values of the parameters of the PID-1 and PID-2 controllers: $t_{PL} = 3\ s$ is the duration of the transition process in the modernized ACS L

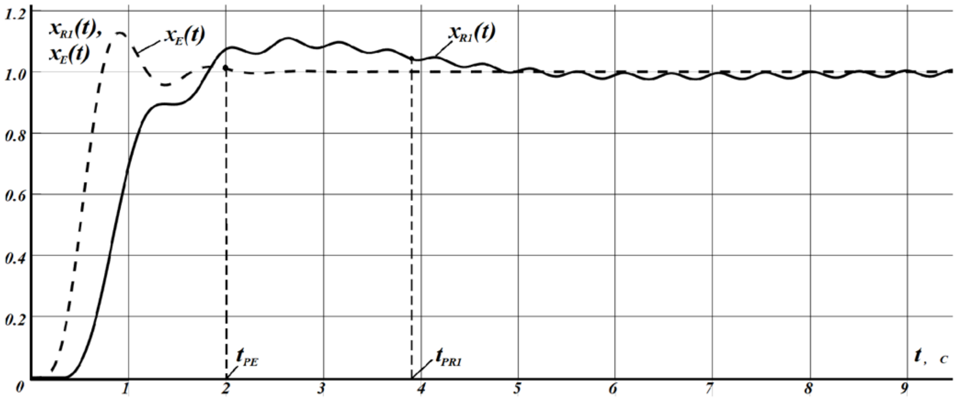


Figure 8: Transition functions of the reference model 7 ($x_E(t)$) and the mathematical model of the modernized ACS R1 ($x_{R1}(t)$) (Fig. 5) for one complete cycle of approaching the optimal values of the parameters of the PID-1 and PID-2 controllers: $t_{R1} = 3.8\ s$ is the duration of the transient process in the modernized ACS R1

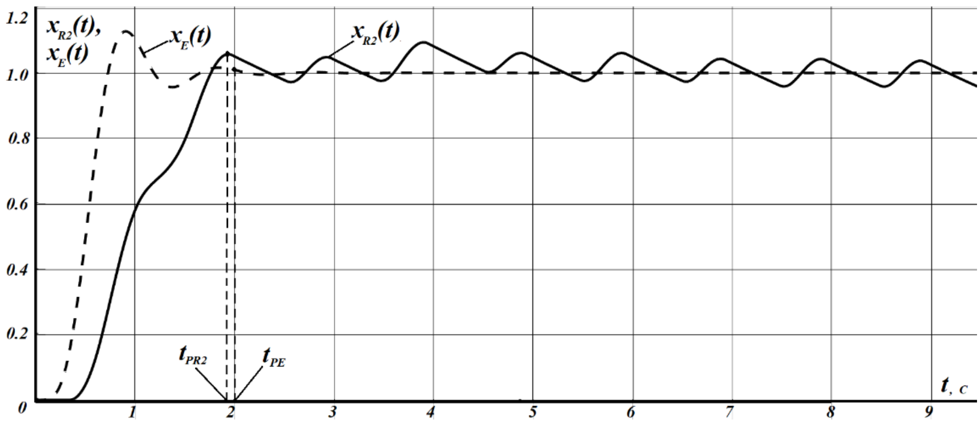


Figure 9: Transition functions of the reference model 7 ($x_E(t)$) and the mathematical model of the modernized ACS R2 ($x_{R2}(t)$) (Fig. 5) for one complete cycle of approaching the optimal values of the parameters of the PID-1 and PID-2 controllers: $t_{R2} = 1.9\ s$ is the duration of the transient process in the modernized ACS R2; the vibration amplitude of the vibration generator G (Fig. 5) was 20 relative units, and the angular frequency was 6.28 rad/s

5. Conclusions

1. The paper develops an engineering method for tuning (or reconfiguring during operation) the electric drive regulators of manipulator mobility units, which takes into account the presence of significant nonlinearities. This method allows to eliminate the cause of the effect of autoelasticity (the occurrence of resonant elastic vibrations and self-oscillations caused by the dynamic properties of the drive of the units of mobility of elastic flexible manipulators and significant nonlinearities of a constructive and technological nature or those that arise during operation), that is, suppresses the "primary self-oscillations".
2. The engineering simplicity and convenience of the method is expressed in the fact that the adjustment of the electric drive regulators of the mobility units during the manufacture of the manipulator or their reconfiguration during operation does not require specialized scientific research, but can be performed by a specialist with an engineering level of mathematical training in an interactive mode in a short time.
3. The positive difference between the proposed method and the method implemented by the Nonlinear Control Design (NCD Blockset) package of the MATLAB computer mathematics system is that it significantly simplifies the method of setting the desired change in time of the variables characterizing the state of the automatic control system (time constraints). In the developed method, these constraints are set by a choice of standard forms of SISO LTI models (reference models), which are well known in engineering practice. At the same time, quadratic integral criteria for approximating the transient process at the ACS output to the transient process of the reference model are used, which are also widely used in engineering practice.
4. In the computer mathematical models discussed in this paper, we modeled typical significant nonlinearities caused by the design and technological features of the mechanical part of aerospace manipulators and their electric drives: the zone of insensitivity, saturation, and relativity.
5. In just one optimization cycle, the developed engineering method allowed us to achieve, compared to the first approximation to the desired (reference) transient: to improve the quantitative value of the tuning criterion by about two orders of magnitude; to reduce the duration of the transient from virtually infinity (if the automatic control system was unstable during the first approximation) to about 3 to 4 s (without using vibration linearization); to achieve a value of the overshoot that ranges from 25% to 75% of the reference overshoot.
6. The use of the well-known engineering method of vibration linearization as part of the proposed engineering method allowed to further reduce the time of the transient process duration (time to reach the steady state of vibration linearization) from 3 - 4 s to 1.9 s with the desired time of the transient process duration of 2 s.
7. Further research will consider:

- application of nonlinear controllers (nonlinear corrective devices) of electric drives of manipulator mobility units with significant nonlinearities;
- expanding the vector of adjustable parameters from six ($r = [r_1, r_2, r_3, r_4, r_5, r_6]$, where $r_1 = k_{p1}, r_2 = k_{i1}, r_3 = k_{d1}, r_4 = k_{p2}, r_5 = k_{i2}, r_6 = k_{d1}$ (see step 7)) to ten components due to the inclusion of the parameters of the mathematical model of the real differentiating link taud1, taud2 and the parameters of the vibration generator (Fig. 5), which are the amplitude and angular frequency of vibrations.

8. The engineering method proposed in this paper for tuning the electric drive regulators of manipulator mobility units with significant nonlinearities allows us to:

- to obtain quantitative values of the controller parameters for a ACS with a given structure and a known type of significant nonlinearities based on the use of known, practically tested, and available software tools of modern computer mathematics systems;
- to be fully programmed using any numerical optimization method, which will allow full automation of parametric optimization of the ACS with significant nonlinearities.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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