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STABILIZATION OF POSITIONING POINTS IN THE CONTROL SYSTEM OF INDUSTRIAL ROBOTS-MANIPULATORS

Abstract: To stabilize the position of the grip of the manipulator at the working point of positioning, a modal procedure for optimal adjustment of the parameters of the proportional and differential parts of the multidimensional PID controller based on the original method of uncertain coefficients is proposed. To eliminate the static error, it is suggested to use the Davison method of adjusting the integral part of the PID controller. The proposed approach is universal and can be used to stabilize the modes of operation of other technical objects and technological processes.

*Keywords***:** manipulator robot, multidimensional PID controller, two-loop control system, modal adjustment of PID controller parameters, method of uncertain coefficients

Introduction

In recent years, industrial robots have become widespread all over the world. They allow you to improve the quality of work, minimize the production time of parts and save on industrial costs. Industrial robotics also used in hazardous industries and hazardous areas. The positive effect of the introduction of industrial robots is usually noticeable simultaneously from several sides: labor productivity increases, the quality of the final product improves, production costs decrease, working conditions for people improve, and finally, the transition of an enterprise from one type of product to another is significantly facilitated [1-3].

Control methods for industrial robots are associated with the development of algorithms for controlling their specified (software) spatial movement. These control algorithms considered as nonlinear algorithms for dividing the program movement of manipulators by their degrees of mobility. The difficulty of their implementation related to the problem of solving nonlinear equations that characterize the configuration of an industrial robot at a given position of their working bodies. One of the traditional ways to solve this problem is to linearize the equations describing the behavior of the manipulation system with small changes in the coordinates of the elements of an industrial robot. Methods of nonlinear compensation using regulators and feedback are also often used [4-6, 9, 18].

One of the most well-known methods of controlling industrial robots is the speed vector control method [7]. The essence of this method consists of specifying a speed of movement of the working bodies of the manipulators of the robot in the form of a six-dimensional vector representing the projection of the vectors of angular velocity of the

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working body and speed of a point in any coordinate system. Thus, we can fully determine the speed of the working body at the current point of the trajectory. The practical use of this method is limited to the occurrence of degenerate mechanism configurations in the control process, which much take into account by the control algorithm. As a result, this control method has a sufficient complexity of implementation, so it usually combined with the method of sequential adjustments to the position of the manipulator in the digital implementation of control systems. In this case, the speed vector’s control algorithm formed as an increment of the manipulator's coordinates for one cycle of algorithm calculation. The disadvantage of this approach is the frequent selection of nodal points of a complex trajectory, so that transitions from one point to another when planning the trajectory do not change the fundamentally necessary picture of movement [7].

The limitation of setting the coordinates of the manipulator position in the synthesis of the control system often makes it possible to use approximate solutions. In this case, the inverse Jacobi matrix calculated by interpolating the nodal, characteristic points of the trajectory. If there is feedback on the position, this is quite enough to achieve the final goal of management. In the absence of position feedback, interpolation can produce large errors, especially when using the force vector’s control method [7], which simulates the idea of control in a given direction.

One of the most important tasks when implementing industrial robot control systems is to configure parameters of multidimensional controllers, in particular, PID controllers. The PID controller is the most common type of controller. About 90-95% of the regulators currently in operation use the PID algorithm. The reason for such high popularity is the simplicity of construction and industrial use, clarity of operation, suitability for solving most practical problems, and low cost [8-11].

Analysis of the problem of configuring PID controllers

Despite a large number of publications, there are still many problems in configuring parameters of PID controllers [8]. Problems complicated by the fact that in modern control systems, dynamics are often unknown, regulated processes cannot considered independent, measurements are highly noisy, the load is unstable, and technological processes are continuous [4-7,13, 17]. Some of the problems arise due to the complexity of operation. In many PID controllers, the differential component disabled only because it is difficult to configure it correctly. Users neglect the calibration procedure. Lack of deep knowledge of the dynamics of the regulated process does not allow you to choose the correct parameters of the regulator. As a result, 30% of the regulators used in the industry configured incorrectly [9]. Therefore, the main efforts of researchers are currently focused on finding reliable methods for configuring both built–in PID controllers and those that function on a separate computer [8].

As a rule, the construction of accurate models for technological processes and the determination of parameters in them is often not required, but rather the problem lies in the definition of the process controller. In the one-dimensional case, this problem is quite simple. In particular, it can be partially solved using the Ziegler-Nichols method [7,13]. A typical PID controller completely solves the problem of stabilization of nonlinear objects of the first order [8-11,13,14]. For practical convenience, such controls also used for objects higher than the first order. However, the requirements for the system in terms of both dynamic properties and suppression of perturbations are forcibly relaxed, especially in the presence of non-linearities in the system. Currently, not many technical objects can be represented by first-order controls, while second-order equations describe the dynamics of most industrial objects well [1,5,17].

The scope of application of traditional PID controllers is significantly expanded due to the introduction of additional channels. Based on the PID controller, various controllers are offered that have certain properties: a fractional order controller, a controller with error weights, and so on. First of all, modifications involve converting the regulator so that it becomes stable [5,6,12,15]. In the article [5], a modal method for constructing a robust controller for second-order systems proposed, which ensures the quality of control processes, given in the form of estimates of transition time, overregulation, and permissible error in statics. However, configuring a multidimensional PID controller has not received enough attention. In the works of Davison [15,16], a method for configuring only the PI part of the PID controller when using step perturbations and input reference signals is proposed.

Thus, the multidimensional configuration of the PID controllers is still very topical at this time.

Problem statement

On fig.1 the General device of a typical manipulate industrial robot with one hand-manipulator is given.

Simple and well-known representatives of this type of industrial robots are the robot PUMA560 (Fig. 2) and the robot ABB (Fig.3) and their numerous modifications.

In General, for the specified type of industrial robot (Fig.1) with k kinematic pairs, which does not have excessive degrees of mobility. Under this k-dimensional vector of moments $\boldsymbol{j}(t)$ in kinematic pairs is associated with the k-dimensional vector $\boldsymbol{\theta}(t)$ of rotation angles in hinges. Thus, the nonlinear dynamic equation of the manipulator movement is an equation of the Euler-Lagrange form:

$$\boldsymbol{M}(\boldsymbol{\theta})\frac{d^2\boldsymbol{\theta}(t)}{dt^2}+\boldsymbol{N}(\boldsymbol{\theta})\frac{d\boldsymbol{\theta}(t)}{dt}+\boldsymbol{G}(\boldsymbol{\theta})\boldsymbol{\theta}(t)=\boldsymbol{j}(t), \quad (1)$$

where $\boldsymbol{M}(\boldsymbol{\theta})$ – a symmetric positive-definite inertia matrix of dimension k x k; $\boldsymbol{N}(\boldsymbol{\theta})$ – a k-dimensional vector-column of moments due to Coriolis forces and centrifugal forces; $\boldsymbol{G}(\boldsymbol{\theta})$ – a k-dimensional vector of gravitational load.

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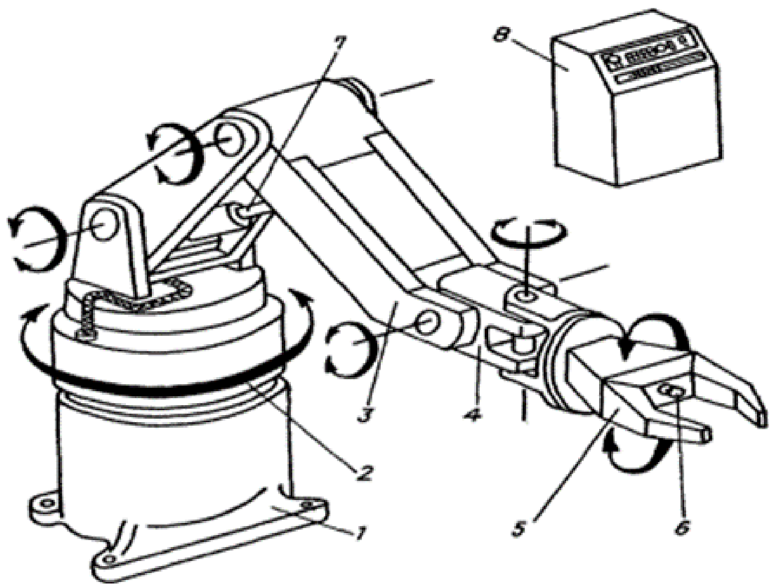

Figure 1. The General structure of industrial robot:
1 – the base (supporting structure) of the robot, 2 – column,
3 – hand manipulator, 4 – brush of the manipulator,
5 – working on (capture), 6 – feedback sensor,
7 – drive arms 8 – unit control unit

Figure 2. Robot PUMA560

Figure 3. Robot ABB

In General, the motion control system of an industrial robot manipulator is a two-circuit control system, the block diagram of which shown in Fig.4. As follows from this diagram, the motion control of the industrial robot manipulator consists of three components: the software control U_{DC}, the stabilizing control U_{FC}, and an additional U_{WP} signal corresponding to the working point WP.

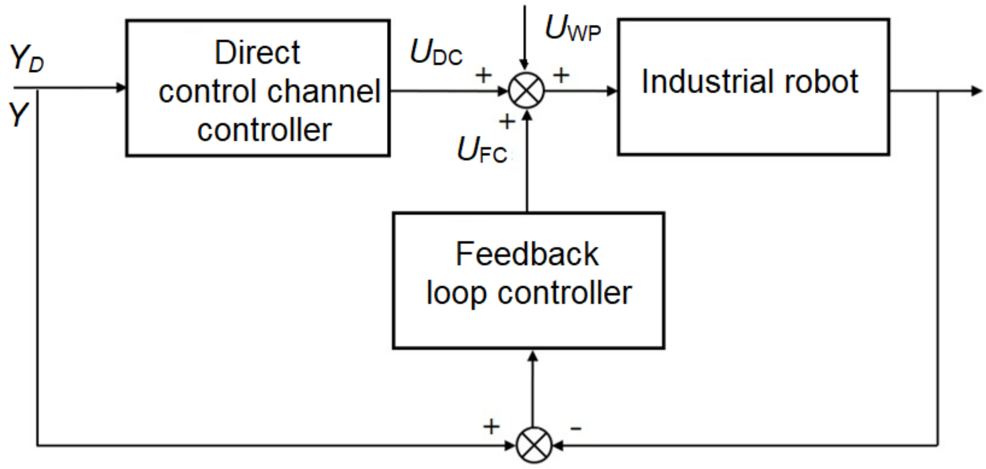

Figure 4. Block diagram of the control system

The additional signal helps to improve the quality of control, providing faster adaptation to changes in the parameters of the industrial robot, and increases the flexibility of the control system. The control system provides tracking by the vector of rotation angles in the hinges $\boldsymbol{\theta}(t)$ of any given (reference) trajectory $\boldsymbol{\theta}_r(t)$, where $\boldsymbol{\theta}_r(t)$ is a k - dimensional vector-column of arbitrary time functions. It is reasonable to assume that these functions have derivatives of the first and second orders, i.e. the required angular velocity $\frac{d\boldsymbol{\theta}_r(t)}{dt}$ and angular acceleration $\frac{d^2\boldsymbol{\theta}_r(t)}{dt^2}$ exist and are available directly, without the need for differentiation operation $\boldsymbol{\theta}_r(t)$. It is also desirable that the manipulator control system provides trajectory tracking regardless of the permissible weight of the load $\boldsymbol{m}$, i.e. that the dynamic characteristics of the manipulator are insensitive to the value of the payload and provide the specified quality indicators of transients.

This article discusses the problem of stabilizing the positioning points of the working body on the optimal settings of a multidimensional PID controller in the feedback loop of the control system for industrial robot manipulators described above.

Configuring parameters of a multidimensional PID controller

Let’s approximate a nonlinear mathematical model of a dynamic system (1) by the decomposition in a number of Taylor in the vicinity of the current working point of the RT program trajectory of an industrial robot manipulator with a linear time-invariant multidimensional model [19,23]

$$\boldsymbol{L}\frac{d^2\boldsymbol{\theta}(t)}{dt^2} + \boldsymbol{K}\frac{d\boldsymbol{\theta}(t)}{dt} + \boldsymbol{R}(t)\boldsymbol{\theta}(t) = \boldsymbol{j}(t), \quad (2)$$

where $\boldsymbol{\theta}(t)$ and $\boldsymbol{j}(t)$ are deviations of vectors of rotation angles and moments in hinges from their program values

$$\boldsymbol{\theta}(t) = \boldsymbol{\theta}_{given}(t) - \boldsymbol{\theta}_{current}(t); \; \boldsymbol{j}(t) = \boldsymbol{j}_{given}(t) - \boldsymbol{j}_{current}(t).$$

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Three matrices $\boldsymbol{L}$, $\boldsymbol{K}$, $\boldsymbol{R}$ with dimension k x k, included in the linearized model (2), depend on the position of the current working point WP and can obtained from the expressions [19]:

$$\boldsymbol{L} = [\boldsymbol{M}^*]_{\mathrm{WP}}\ , \boldsymbol{K} = \left[\frac{\partial(\boldsymbol{N}+\boldsymbol{H})}{\partial\boldsymbol{\theta}}\right],\ \boldsymbol{R} = \left[\frac{\partial(\boldsymbol{N}+\boldsymbol{G})}{\partial\boldsymbol{\theta}}\right], \tag{3}$$

where $[\boldsymbol{M}^*]_{\mathrm{WP}}$ – reduced to the working poin symmetric positive definite inertia matrix with dimension k x k; $\boldsymbol{N}$, $\boldsymbol{H}$, $\boldsymbol{G}$ – reduced to the working point the centrifugal forces, Coriolis forces and gravity forces respectively.

It follows from (1) and (3) that the matrix $\boldsymbol{L}$ is always symmetric, positive definite, and therefore not degenerate.

Equation (2) is a system of related linear differential equations describing the dynamics of the robot in deviations in the presence of perturbations in the vicinity of the current working point of the WP.

To obtain a linearized differential equation, introduce the following designation of generalized coordinates:

$$v_i = \theta_i;\ w_{k+i+1} = \frac{d\theta_i}{dt}\ , i = 1, \dots k.$$

At the same time, considering that

$$\boldsymbol{x} = (\boldsymbol{v}, \boldsymbol{w})^T;\ \boldsymbol{j}(t) = \boldsymbol{u}(t), \qquad \frac{d\boldsymbol{v}}{dt} = \boldsymbol{w}(t)$$

equation (2) can be written as

$$\frac{d\boldsymbol{w}(t)}{dt} + \boldsymbol{L}^{-1}\boldsymbol{K}\boldsymbol{w}(t) + \boldsymbol{L}^{-1}\boldsymbol{R}\boldsymbol{v}(t) = \boldsymbol{L}^{-1}\boldsymbol{j}(t). \tag{4}$$

or in the standard form of the Cauchy:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t), \tag{5}$$

$$\boldsymbol{y}(t) = \boldsymbol{C}\,\boldsymbol{x}(t), \tag{6}$$

where $\boldsymbol{x} \in R^n, \boldsymbol{y} \in R^n, \boldsymbol{u} \in R^k, \boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}$ – constant matrices of the corresponding dimension, and the matrix $\boldsymbol{A}$ is block, i.e. $\boldsymbol{A} = \{\boldsymbol{A}_{jr}\}, (j, r = 1{,}2)$, де $\boldsymbol{A}_{11} = \boldsymbol{E}, \boldsymbol{A}_{12} = \boldsymbol{0},\ \boldsymbol{A}_{21} = = \boldsymbol{L}^{-1}\boldsymbol{K},\ \boldsymbol{A}_{22} = \boldsymbol{L}^{-1}\boldsymbol{R}.$

Also assume that $\boldsymbol{C}$=$\boldsymbol{I}$, i.e. the object is completely observable. This assumption is not fundamental and is used for greater clarity of the results obtained below.

Known that the control law of a multidimensional PID controller has the following form [9.10]:

$$\boldsymbol{u}(t) = \boldsymbol{P}\boldsymbol{v}(t) + K_I \int \boldsymbol{v}(t) + \boldsymbol{P}_D\boldsymbol{w}(t), \tag{7}$$

where the matrices $\boldsymbol{P}$, K_I, $\boldsymbol{P}_D$ are constant, have the corresponding dimension, and are the gain coefficients of the proportional, integral, and differentiating parts of the PID controller.

Also introduce for the system (5), (6) a quadratic quality functional of the form

$$F(\boldsymbol{x}, \boldsymbol{u}) = \int \boldsymbol{x}^T\boldsymbol{G}\boldsymbol{x} + \boldsymbol{u}^T\boldsymbol{Q}\boldsymbol{u})dt, \tag{8}$$

where $\boldsymbol{G}$, $\boldsymbol{Q}$ – diagonal matrices of constant coefficients of the corresponding dimension.

In addition, given the observance of the superposition principle for linear systems, let's first consider the configuration of the proportional and differentiating parts of the PID controller, i.e.

$$\boldsymbol{u}(t) = \boldsymbol{P}\boldsymbol{x}(t) + \boldsymbol{P}_D\dot{\boldsymbol{x}}(t), \tag{9}$$

With these assumptions and designations the previously formulated task of stabilizing the positioning points of an industrial robot manipulator can defined as follows.

It necessary to synthesize a robust multidimensional PID controller for stabilizing the positioning points of the programmed motion of the industrial robot manipulator, which implements the control law (9) and minimizes the functional (8).

In this staging, this task is the task of ACOR (Analytical Construction of Optimal Regulators). The main drawback of the ACOR method is the absence of a direct relationship between the coefficients of the functional (8) and the dynamic indicators of transient processes in the stabilization mode. To eliminate this disadvantage, it is proposed to use a modal synthesis of the stabilization law (9) based on the method of undefined coefficients proposed by the authors in the article [20, 21, 24], which in this article is generalized to the vector control case using the superposition principle.

Method of undefined coefficients. Without losing the generality of the results obtained further, we assume in the system (5), (6) $\boldsymbol{x} = (x_1, x_2, \dots, x_n)^T$ – the state vector; $\boldsymbol{y} = (y_1, y_2, \dots, y_n)^T$ – the measured output vector – $\boldsymbol{u} = (u_1, u_2, \dots, u_k)^T$ the control vector; ***A***,***B***,***C*** – the coefficient matrices with the dimension *n* x *n*, *n* x *k*, *n* x *n*, and *n=2k*.

Stage 1. Accept that $\boldsymbol{u}=(u_1, 0,\dots, 0)^T$, u_1=u. It is known [13] that for fully observable (***C***= ***E***) systems of the form (5), (6) in the case of a quadratic quality criterion (8), the extreme control **u** is a linear function of the state moreover, the vector of feedback coefficients can be selected in such a way that the poles of the closed system (5), (6) will be located at arbitrary points specified in advance, providing the required dynamic properties:

$$\boldsymbol{u} = \boldsymbol{P}^T\boldsymbol{x}.$$

Thus, the problem reduced to choosing the spectrum of optimal poles and determining feedback coefficients based on it.

Assuming at first that the poles are pre-selected, we show a method for determining such coefficients $\boldsymbol{P}(p_1, p_2, \dots, p_n), i = \overline{1,n}),$ that are linearly included in the expression for the coefficients of the characteristic polynomial of a closed system:

$$\det(\lambda) = |A + BP^T - E\lambda| = \left\| \begin{bmatrix} a_{11} + b_1p_1 - \lambda & \cdots & a_{1n} + b_1p_n \\ \vdots & \ddots & \vdots \\ a_{n1} + b_np_1 & \cdots & a_{nn} + b_np_n - \lambda \end{bmatrix} \right\| \tag{10}$$

Indeed, let's assume that $\frac{b_j}{b_s} \neq 0$ $(j, s = 1, n)$. Then, subtracting the *j*-th line from the *s*-th line $(j \neq s)$, which multiplied by $\frac{b_j}{b_s}$,, we get a determinant equal to the original (10), in which the feedback coefficients $\boldsymbol{P}(p_1, p_2, \dots, p_n), i = \overline{1,n})$ are included in the *s*-th line. By

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opening it on this line and grouping the terms at the appropriate degrees, we finally come to the following expression:

$$H(\lambda) = \lambda^n + \left(\sum_{i=1}^{n} c_{\text{n-1,i}} p_i + d_{\text{n-1}}\right)\lambda^{n-1} + \ldots + \left(\sum_{i=1}^{n} c_{0,\text{i}} p_i + d_0\right)$$

or

$$H(\lambda) = \lambda^n + \left(\overline{c}_{n-1}^T \overline{p} + d_{\text{n-1}}\right)\lambda^{n-1} + \ldots + \left(\overline{c}_0^T \overline{p} + d_0\right). \quad (11)$$

Unknown parameters c_{ji}, $d_j (j = \overline{0, n-1}; i = \overline{1, n})$, we determine by n+1 steps by the method of undefined coefficients. To do this, at the first step, assuming in the determinant (10) and revealing it by one of the known methods [22], we find that the coefficients found for various degrees λ determine the unknown coefficients $d_i (i = \overline{0, n-1})$ of the expression (11) for the corresponding degrees. In the next n steps, assuming one of the coefficients $p_i (i = \overline{1, n})$ in turn to be equal to unity and the other coefficients equal to zero and revealing the determinant (10), we get expressions for the unknown parameter at the appropriate degree in the form

$$c_{ji} = f_i - d_j, \quad (12)$$

where f_i –coefficient for the i-th characteristic determinant disclosed.

The characteristic polynomial of a closed system (10) with desired roots $(\lambda_1, \lambda_2, \ldots, \lambda_n)$ has the form

$$F(\lambda) = \prod_{\text{i=1}}^{n} (\lambda - \lambda_i) = \sum_{\text{j=0}}^{\text{n-1}} \gamma_j \lambda^j + \lambda^n. \quad (13)$$

As a result, adding the difference in (11) to (13) with the same degrees of $\lambda^j (j = \overline{0, n-1})$ and taking into account (12), we obtain a system of linear algebraic equations to determine the feedback coefficients:

$$\text{Col}(\boldsymbol{c}^T)\boldsymbol{P} = \boldsymbol{\gamma} - \boldsymbol{d}, \quad (14)$$

where $\boldsymbol{\gamma} = (\gamma_{n\text{-1}}, \gamma_{n\text{-2}}, \ldots, \gamma_0), \boldsymbol{d} = (d_{n\text{-1}}, d_{n\text{-2}}, \ldots, d_0)$.

Thus, solving system (14) for the first component of the control vector **u**, we obtain

$$u_1 = p_{11}x_1 + \cdots p_{1n}x_n.$$

Stage 2. Further considerate closed system (10) with the found control u1. We accept $\boldsymbol{u}=(0, u_2, 0, \ldots, 0)^T$, u_2=u. With this in mind, formed a new determinant (10). Repeating the procedure of the first stage we get

$$u_2 = p_{21}x_1 + \cdots p_{2n}x_n.$$

Continue in the same way to form the following components of the vector u up to the k-th component.

Stage n. Further considerate closed system (10) with the found control u_{k-1}. We accept $\boldsymbol{u}=(0, 0, \ldots, u_k)$, $u_k=u$. Repeating the procedure of the first and subsequent stages we get

$$u_k = p_{k1}x_1 + \cdots p_{kn}x_n.$$

Next, for the obtained values of the vector P, taking into account (5) and (9), we form the equations of the optimal closed system in the form of:

$$\dot{\boldsymbol{x}}(t) = (\boldsymbol{A}^* + \boldsymbol{B}\boldsymbol{P}_D\boldsymbol{A}^*)\boldsymbol{x}(t), \qquad (15)$$

where $\boldsymbol{A}^* = (\boldsymbol{A} + \boldsymbol{B}\boldsymbol{P})$.

As a result, on the principle of superposition, we obtain the matrix of coefficients of proportional and differential parts of a PID regulator in equation (14). Algorithm select the desired spectrum of the roots providing the predetermined dynamic performance of transient processes of stabilization proposed by the authors in [21]. This choice of two matrices of coefficients $\boldsymbol{P}$ and $\boldsymbol{P}_D$ allows us to obtain an almost ideal control curve that meets the specified dynamic parameters of transients in the stabilization mode of k kinematic pairs of the industrial robot manipulator. However, a so-called "static error" may occur. This error removed using the integratial part of the PID controller. In addition, using the integratial part of the PID controller, you can reduce the degree of oscillation of stabilization processes. According to Davison [15,16], the integral coefficient KI can be defined as

$$K_I = \varepsilon(\boldsymbol{C}\boldsymbol{A}^{-1}\boldsymbol{B})^{\uparrow}, \qquad (16)$$

where ε – scalar control parameter. This integral controller decomposes the system (5), (6) by stable states. In fact, this a fundamental matrix $(\boldsymbol{C}\boldsymbol{A}^{-1}\boldsymbol{B})^{\uparrow}$that is exactly transmitted at zero frequency. The sign ↑ in formula (16) means a pseudo-inversion that for some rectangular matrix $\boldsymbol{G}$ has the form $\boldsymbol{G}\uparrow = \boldsymbol{G}^T(\boldsymbol{G}\boldsymbol{G}^{\boldsymbol{T}})^{-1}$.

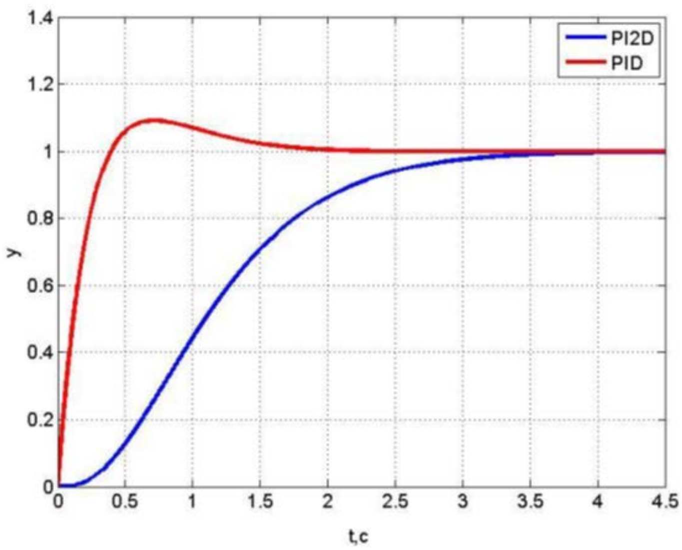

Figure 5. Transient characteristics of PID and PI2D controllers

In our case, for $\boldsymbol{C}$=$\boldsymbol{E}$, $\boldsymbol{B}$= $\boldsymbol{E}$, $\boldsymbol{A}^{-1}\boldsymbol{A}$= $\boldsymbol{E}$, the integral coefficient of the PID controller $\boldsymbol{K}_I$= ε$\boldsymbol{E}$ is a unity diagonal matrix multiplied by the scalar value ε. the Scalar control parameter ε can be easily selected when modeling the program movement of an industrial robot manipulator. Denoting the PI2D controller configured in the above way, we can notice

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(Fig.5) that for the i-th kinematic pair of the manipulator, in comparison with the Ziegler-Nichols transition characteristic setting (PID controller), the PI2D controller transition process is aperiodic without over-regulation.

Conclusion

The efficiency of using manipulative industrial robots largely determined by the quality and speed of their performance of the specified (program) modes of operation. The quality, in turn, depends on the accuracy of stabilization of the positionary points of the program movement of the manipulator. In this regard, this article proposes a procedure for configuring parameters of multidimensional PID controllers based on the modal synthesis of the stabilization law using the proposed method of undefined coefficients. This approach is universal and can used to stabilize the operation of other technical objects and technological processes.

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