Складено математичну модель підводного комплексу, яка містить нелінійні елементи гідродинамічної природи. Показано неможливість застосування методу оберненої динаміки для синтезу високоточних систем автоматичного керування такими об'єктами. Розроблено принцип декомпозиції для формування еталонної моделі, який дає змогу синтезувати системи керування підводними комплексами методом оберненої динаміки. Працездатність принципу декомпозиції перевірено синтезом системи керування підводним апаратом як складовою підводного комплексу

Ключові слова: еталонна модель, метод оберненої динаміки, автоматичне керування, підводний комплекс

Составлена математическая модель подводного комплекса, которая содержит нелинейные элементы гидродинамической природы. Показана невозможность применения метода обратной динамики для синтеза высокоточных систем автоматического управления такими объектами. Разработан принцип декомпозиции для формирования эталонной модели, который дает возможность синтезировать системы управления подводными комплексами методом обратной динамики. Работоспособность принципа декомпозиции проверена синтезом системы управления подводным аппаратом как составляющей подводного комплекса

Ключевые слова: эталонная модель, метод обратной динамики, автоматическое управление, подводный комплекс

UDC 681.5

DOI: 10.15587/1729-4061.2016.74875

FORMATION OF A REFERENCE MODEL FOR THE METHOD OF INVERSE DYNAMICS IN THE TASKS OF CONTROL OF UNDERWATER COMPLEXES

O. Blintsov
PhD, Associate Professor
Department of Information Security
Lviv Polytechnic National University
Bandera str., 12, Lviv, Ukraine, 79000
E-mail: energybox@mail.ru

1. Introduction

A wide range of underwater work is performed with the use of underwater complexes (UC), which usually consist of underwater vehicles (UV) and surface support vessels [1]. For rapid information exchange and power supply to underwater component of the complex, flexible connections are used that connect UV with support vessels [2]. The main type of flexible connection between the elements of UC is a tether cable (TC).

Solving modern underwater tasks is impossible without efficient systems of automatic control (SAC) of UC. Such SAC must provide coordinated control of several non-linear multidimensional objects, which include surface ships, UV and TC. The tasks of managing UC are formed as a set of tasks of control of its constituents and require synthesis of SAC:

– high dynamic accuracy for the processing of tasks, in the form of functions of time;

– by one dimensional and multidimensional systems;

– with robust properties;

– capable to work and maintain stability under conditions of parametric uncertainty.

The presence of mechanical connection via TC between the components of UC significantly complicates the problem of synthesis of SAC. In addition, mathematical models of the elements of UC contain nonlinearities that are set in arbitrary form.

One of the powerful methods, which enables to synthesize high-precision SAC by complex non-linear objects, is the method of inverse dynamics (ID) [3]. Inverse problem of dynamics is known from theoretical mechanics as the problem of determining forces acting on a body if the trajectory of its motion is known. In the theory of automatic control, the method of ID implements the concept of inverse control. Its essence consists in the following. Based on the requirements to control quality, a reference model of SAC is synthesized. It is a differential equation with desired dynamic characteristics of control system. The order of the differential equation of a reference model cannot be less than the order of the object of control. Next, a senior derivative is expressed from the reference model. The resulting expression is substituted into the equation of the object instead of a senior derivative and a law of control is expressed from it.

In the theory of automatic control, the method of ID was launched as a method of structural synthesis of nonlinear SAC [4]. The papers [5, 6] contributed to the wide spread of the method of ID, in which high-precision SAC are synthesized by nonlinear objects with low sensitivity to parametric and coordinate perturbations. These particular problems occur at the synthesis of UC SAC because substantial nonlinearities and parametric uncertainties of the control object are characteristic for them, predetermined by the operation under real sea conditions. Therefore, development of the method of inverse dynamics for the automation of UC control is an actual scientific task.

2. Analysis of scientific literature and the problem statement

In the implementation of underwater technologies, high dynamic accuracy of control is crucial. However, the method of ID contains a drawback that makes its application for the control of UC impossible without considerable simplifications of their mathematical models (MM).

The essence of the drawback is in the following. A reference model for a one-dimensional object is chosen in the form of differential equation of the n-th order, which corresponds to the order of the object. However, the structure of the UC MM as the object of control contains nonlinear elements that are set in arbitrary form [7]. For example, a MM of propellers and UV hulls contain non-linear coefficients of hydrodynamic nature, which are set in tabular or graphic form [8]. Bringing MM of such objects to the structure of a reference model is impossible. And simplification of UC MM greatly reduces accuracy of control. In this regard, it is impossible to obtain a high-precision UC SAC by the classic method of ID.

The choice of the structure of a reference model is also limited in the method. It must be set in the form of a differential equation. The possibility to set a reference model in the form of arbitrary function of time, for example, in the form of analytical solution of the selected differential equation, is not provided. This limits the type of transitional processes of SAC.

The paper [9] proposed to modify the method of ID for the realization of control system of a manoeuvring aircraft. The system settings that cannot be measured by sensors are calculated by way of solving nonlinear differential equation. But the synthesis of SAC is performed according to the classical procedure. The peculiarities of application of the method of ID to control an object with lower number of controlling influences than the number of degrees of freedom are outlined in [10]. However, the synthesis of a regulator is also performed by the classical procedure. The method of ID for synthesis of the system of stabilization of UV pitch [11] proved efficient. However, a mathematical model (MM) of the object was significantly simplified for its application, which reduced the accuracy of control.

To manage the objects under conditions of uncertainty, the method of ID is used in conjunction with the tools of fuzzy logic. The paper [12] proposed a structure of control system of a manipulator, the main component of which is derived by the classical method of ID. The effect of uncertainty is eliminated by fuzzy elements in additional compensation circuits with direct or reverse connection.

The ideas of inverse dynamics are developed in the approach of "direct – inverse control", in particular, for the synthesis of regulators under conditions of parametric uncertainty. One of the elements of these SAC is an inverse model of the object in the form of artificial neural network, which recreates its inverse dynamics [13]. However, training neural network is necessary to perform under condition of the absence of external perturbations. The availability of flexible connections in the composition of UC makes the separation of perturbing effect impossible and reduces the accuracy of these regulators.

Based on neural networks, model-less control system of technical objects with forecasting inverse control are synthesized [14]. The disadvantage of such systems is significant dependence of the quality of control on the type of a reference transition process, as well as sensitivity to perturbing influences.

The concept of inverse dynamics is also used in the method of adaptive inverse control of nonlinear objects based on artificial neural networks [15]. Unlike the classical method of ID, neural network approximates inverse dynamics of the object and functions under conditions of structural uncertainty of the object. The use of this approach for the synthesis of UC SAC does not provide high dynamic accuracy of control.

A system of dynamic stabilization of a sea platform based on the control with forecasting models was proposed in [16]. It is based on linearization of the object's MM, which reduces the accuracy of control. The paper [17] designed a system of control of the motion of an autonomous underwater vehicle. But its application for the automation of UC motion will not provide high accuracy of control due to the presence of a flexible connection.

A system of automatic control of the course of UV of working class as part of UC based on a PD-regulator was developed in [18]. It provides smooth control of the course at low speed, characteristic for UV of working class, which restricts the application of resulting regulator. In addition, such a SAC is sensitive to parameter errors of the object's MM that does not provide high accuracy of control.

Therefore, the analysis of scientific and technical literature reveals that the method of ID is used for control of non-linear technical objects of different nature mostly in the classic form. The development of other approaches of the concept of inverse control is carried out in the direction of control under conditions of structural and parametric uncertainties of the object. The questions of high precision control of UC, in particular, by the concept of inverse control, are still at initial stage.

3. The purpose and objectives of the study

The aim of the work is improvement of the method of inverse dynamics by applying the principle of decomposition to form a reference model that enables to synthesize high precision automatic control system of underwater complexes, the non-linear elements of which are set in arbitrary form.

To achieve the set goal, the following problems are to be solved:

– development of a MM of one-dimensional motion of UV as part of UC;

– design of the principle of decomposition of a reference model for the method of ID;

– synthesis of SAC of one-dimensional motion of UV as part of UC;

– verifying a synthesized SAC by the method of computer simulation.

4. Materials and methods for the improvement of the method of inverse dynamics

4. 1. Mathematical model of one-dimensional motion of an underwater vehicle as an element of an underwater complex

Underwater complexes represent complex multidimensional objects. The main performer of an underwater task is UV. Spatial motion of UV as a solid body in the composition of UC can be presented by a set of elementary one-dimensional motions [19].

Let us consider a mathematical model (MM) of one-dimensional motion of a propelled UV as a component of UC, i. e. under conditions of perturbing effect of TC (Fig. 1).

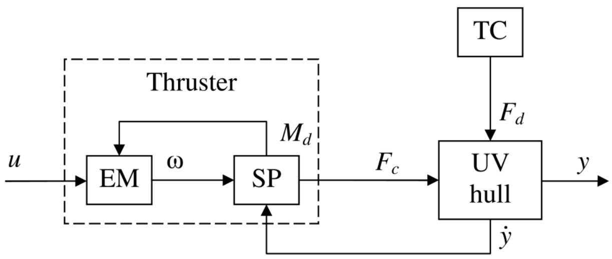

Fig. 1. Structure of MM of one-dimensional motion of UV as part of UC

Controlled motion of UV is provided by a thruster, which is an electric motor (EM) of direct current with a reducer, connected by a shafting with a screw propeller (SP). The inner space of electric motor is filled with liquid dielectric. A mathematical model of the thruster consists of EM MM and SP MM. Kinematical parameters of the UV motion are calculated in the MM of UV hull dynamics, which takes into account hydrodynamic force of resistance. The main influence of perturbation is the tension force of TC, which is calculated in the MM of the TC dynamics.

Such an object of control is classified as one-dimensional because it contains one control action u and one controlled magnitude y. In this case it consists of two one-dimensional objects, connected in series. Control input of MM of the thruster is the magnitude u, the output is the magnitude F_c, control input of MM of the UV hull is the magnitude F_c, the output is the magnitude y.

Electrical transient processes that occur in the electric motor are considerably faster than the mechanical ones, which allows accepting an assumption about instant change of current at the change of control action u, and presenting a MM of the thruster by a differential equation of the first order. One-dimensional motion of UV as part of UC, taking into account the adopted assumption, is described by a system of nonlinear differential equations:

$$\begin{cases} J\dot{\omega} = k_u u - k_\omega \omega - M_d(\omega, \dot{y}); \\ m\ddot{y} = F_c(\omega, \dot{y}) - F_s(\dot{y}) - F_d(y, \dot{y}), \end{cases} \quad (1)$$

where u is the control signal; ω is the speed of rotation of a screw propeller; y is the coordinate of UV (controlled magnitude); J is the inertia moment of the elements of the thruster brought to the screw propeller; k_u, k_ω are the coefficients that characterize electromechanical parameters of the thruster; M_d is the hydrodynamic brake moment of SP; m is the mass of UV with added masses of water; F_c is the SP thrust (control force); F_s is the resistance force of UV hull; F_d is the perturbing force of TC.

At any point in time the state of UV is characterized by three phase coordinates: y, $\dot{y}$ and ω. Detailed description of equations of MM of the motion of tethered UV is given in scientific and technical literature, such as in [19].

Perturbing effect F_d is modeled by using a MM of TC dynamics [20].

Dependencies $M_d(\omega, \dot{y})$ and $F_c(\omega, \dot{y})$ represent a MM of a screw propeller and are essentially non-linear. They have in their composition ω^2 and coefficients, which nonlinearly depend on ω and $\dot{y}$ and are defined from the curves of the action of propeller [21]. For the synthesis of SAC by the method of ID it is necessary to have an inverse model of SP in the form of dependency $\omega = f_{inv}(F_c, \dot{y})$. To build it analytically is impossible because the curves of SP action are derived experimentally and are presented in graphical (or tabular) form. However, an inverse model of SP can be set in a tabular form and, in combination with the means of approximation, may be used in the composition of SAC [22].

4. 2. Problems of the synthesis of automatic control systems of underwater complexes by the method of inverse dynamics

According to the classic method of ID, phase coordinates of one-dimensional object must be presented by the values of the object's output y and its (n–1) derivatives. A mathematical model of the object in this case should have the view of a differential equation of the n-th order:

$$f\left(y^{(i)}, u\right) = 0; \quad i = 0, 1, 2, \ldots, n,$$

where y is the control value, u is the control influence.

Phase coordinates of an object uniquely determine its state at any given time, but do not make it possible to forecast the motion of an object, i.e., its status in the next moment of time in the infinitely small time interval dt. To define the motion of an object, it is necessary to know phase coordinates and velocities of their changes. In this case only the speed of change of the phase coordinate $y^{(n-1)}$, which equals $y^{(n)}$, depends clearly on the control influence u, i. e. it can be changed in the required direction. The magnitude $y^{(n)}$ represents the highest derivative of the controlled magnitude of the object at any point in time.

Thus, for the motion of the object along required trajectory, the condition must be true in any moment of time:

$$y^{(n)}(t) = y_d^{(n)}(t),$$

where $y_d^{(n)}$ is the desired value of higher derivative of the controlled magnitude. This value is determined from the reference model that connects the controlled magnitude y and its set value $y_g(t)$ and presents a differential equation [4]:

$$y_d^{(n)} = \Phi\left(y^{(i)}, y_g^{(r)}\right); \quad i = 0, 1, 2, \ldots, n-1; \quad r = 0, 1, 2, \ldots, R.$$

The set value of the controlled magnitude y_g in a general case may be known (program SAC) or unknown (trailing SAC) function of time $y_g(t)$.

Next, from a MM of the object we receive its inverse model:

$$u = f\left(y^{(n)}, y^{(i)}\right); \quad i = 0, 1, 2, \ldots, n-1.$$

Desired value of the controlled influence is found by substituting $y_d^{(n)}$ instead of $y^{(n)}$ in the inverse model of the object:

$$u_d = f\left(y_d^{(n)}, y^{(i)}\right); \quad i = 0, 1, 2, \ldots, n-1.$$

The simplest implementation of UC is a control object of the 3rd order, the dynamics of which is described by a system with one equation of the first order and one equation of the second order (1). According to the classic method of ID, a reference model should represent a differential equation of the third order. As a reference model, let us take a linear differential equation with a single coefficient of amplification and the time constants T_0, T_1 , and T_2:

$$T_0T_1T_2\dddot{E}_y + T_0T_1\ddot{E}_y + T_0\dot{E}_y + E_y = 0; \quad E_y = y_g - y,$$

where E_y is the error of control.

Let us express higher derivative from the reference model:

$$\dddot{y}_d = \dddot{y}_g + \frac{\ddot{y}_g - \ddot{y}}{T_2} + \frac{\dot{y}_g - \dot{y}}{T_1T_2} + \frac{y_g - y}{T_0T_1T_2},$$

where $\dddot{y}_d$ is the desired value of higher derivative of the controlled magnitude.

The expression for $\dddot{y}_d$ must be substituted in a MM of the object of control. To do this, we apply the operation of differentiation to the second equation of a MM of the object:

$$m\dddot{y} = \dot{F}_c - \dot{F}_s - \dot{F}_d.$$

From the resulting expression we will find necessary value of the first derivative of the control force $\dot{F}_{cg}$, the action of which to the UV hull will provide a desired value of higher derivative of the controlled magnitude $\dddot{y}_d$:

$$\dot{F}_{cg} = m\dddot{y}_d + \dot{F}_s + \dot{F}_d.$$

A law of control is obtained from the system of equations:

$$\begin{cases} u_d = \dfrac{1}{k_u}\left(J\dot{\omega}_d + k_\omega \omega + M_d\right); \\ \dot{F}_{cg} = m\dddot{y}_d + \dot{F}_s + \dot{F}_d, \end{cases}$$

where $\dot{\omega}_d$ is the desired value of the first derivative of the magnitude ω. In this case $\dot{\omega}_d$ has to be determined based on $\dot{F}_{cg}$.

Under the condition of the problem of synthesis, an inverse dependency is considered known, which connects by the means of approximation the magnitudes ω and F_c, but not their derivatives. Therefore, the expression for the control influence cannot be obtained in analytical form, since to do this, it is necessary to have the relationship between the magnitudes $\dot{\omega}_d$ and $\dot{F}_{cg}$ in analytical form. The magnitude of control influence can be obtained through consistent calculation of $\dot{F}_{cg}$ and $\dot{\omega}_d$, which eliminates the need to receive the expression for u in analytical form. But it is necessary for it to complete differentiation of the inverse model of a screw propeller, presented by the means of approximation, which is a separate scientific task and is not always possible.

In addition, if one overcomes mentioned difficulties, the implementation of a regulator will contain additional variables: derivatives from the perturbing forces of TC and resistance of UV hull, as well as the magnitude $\ddot{y}$. The presence of additional derivatives increases the volume of computation and significantly reduces the accuracy of control.

4. 3. The principle of decomposition of a reference model

If the object of control is consistently connected one-dimensional objects, then its MM has the view of a system of differential equations, each of which has the order k_j:

$$\begin{cases} y_1^{(k_1)} = f\left(y_1^{(i_1)}, y_2\right); \quad i_1 = 0, 1, 2, \ldots, k_1 - 1; \\ y_2^{(k_2)} = f\left(y_2^{(i_1)}, y_3\right); \quad i_2 = 0, 1, 2, \ldots, k_2 - 1; \\ \ldots \\ y_j^{(k_j)} = f\left(y_j^{(i_j)}, y_{j+1}\right); \quad i_j = 0, 1, 2, \ldots, k_j - 1; \quad j = 1, 2, \ldots, m; \\ \ldots \\ y_{m-1}^{(k_{m-1})} = f\left(y_{m-1}^{(i_{m-1})}, y_m\right); \quad i_m = 0, 1, 2, \ldots, k_{m-1} - 1; \\ y_m^{(k_m)} = f\left(y_m^{(i_m)}, y_{m+1}\right); \quad i_{m-1} = 0, 1, 2, \ldots, k_m - 1; \\ y_{m+1} = u. \end{cases}$$

In the first equation, the controlled magnitude is y_1, the control influence is y_2, in the second equation, the controlled magnitude is y_2, the control influence is y_3, etc. A controlled magnitude of an object in general is the output of its first component – the magnitude y_1, a control influence of an object in general is the input of its last component – the magnitude u.

A general order of an object is defined as the sum of the orders of each equation in the system:

$$n = \sum_{j=1}^{m} k_j.$$

For the motion of an object along desired trajectory, the system of conditions must be fulfilled in any moment of time:

$$\begin{cases} y_1^{(k_1)} = y_{1d}^{(k_1)}(t); \\ y_2^{(k_2)} = y_{2d}^{(k_2)}(t); \\ \ldots \\ y_j^{(k_j)} = y_{jd}^{(k_j)}(t); \quad j = 1, 2, \ldots, m; \\ \ldots \\ y_{m-1}^{(k_{m-1})} = y_{(m-1)d}^{(k_{m-1})}(t); \\ y_m^{(k_m)} = y_{md}^{(k_m)}(t), \end{cases}$$

where $y_{jd}^{(k_j)}$ is the desired value of higher derivative of each component of the object. The magnitudes $y_{jd}^{(k_j)}$ set reference dynamics for every internal process that runs in the system. In accordance with the method of ID, their values must be determined from the reference model.

A reference model for the control of such an object is proposed to synthesize by the principle of decomposition. According to this principle, it is formed as a set of reference submodels based on the actual structure of the object:

$$\begin{cases} y_{1d}^{(k_1)}(t)=\Phi\left(y_1^{(i_1)},y_{1g}^{(r_1)}\right); \quad i_1=0,1,2,\ldots,k_1-1; \quad r_1=0,1,2,\ldots,R_1; \\ y_{2d}^{(k2)}(t)=\Phi\left(y_2^{(i_2)},y_{2g}^{(r_2)}\right); \quad i_2=0,1,2,\ldots,k_2-1; \quad r_2=0,1,2,\ldots,R_2; \\ \ldots \\ y_{jd}^{(k_j)}(t)=\Phi\left(y_j^{(i_j)},y_{jg}^{(r_j)}\right); \quad j=1,2,\ldots,m; \quad i_j=0,1,2,\ldots,k_j-1; \quad r_j=0,1,2,\ldots,R_j; \\ \ldots \\ y_{(m-1)d}^{(k_{m-1})}(t)=\Phi\left(y_{(m-1)}^{\left(i_{(m-1)}\right)},y_{(m-1)g}^{(r_{m-1})}\right); \quad i_{m-1}=0,1,2,\ldots,k_{m-1}-1; \quad r_{m-1}=0,1,2,\ldots,R_{m-1}; \\ y_{md}^{(k_m)}(t)=\Phi\left(y_m^{(i_m)},y_{mg}^{(r_m)}\right); \quad i_m=0,1,2,\ldots,k_m-1; \quad r_m=0,1,2,\ldots,R_m, \end{cases}$$

where y_{jg} is the necessary value of the output of the j-th component of the object.

Using a reference model, formed by the principle of decomposition, is possible with the presence of all values y_{jg} (as well as R_j of their derivatives). For the otput of the object of control y_1 (j=1), the magnitude $y_{1g}(t)$ is known as a controlling task.

The remaining values y_{jg} are defined by inverse models of the components of the object:

$$\begin{cases} y_{2g}=f\left(y_{1d}^{(k_1)},y_1^{(i_1)}\right); \quad i_1=0,1,2,\ldots,k_1-1; \\ y_{3g}=f\left(y_{2d}^{(k_2)},y_2^{(i_1)}\right); \quad i_2=0,1,2,\ldots,k_2-1; \\ \ldots \\ y_{(j+1)g}=f\left(y_{jd}^{(k_j)},y_j^{(i_j)}\right); \quad j=1,2,\ldots,m; \quad i_j=0,1,2,\ldots,k_j-1; \\ \ldots \\ y_{mg}=f\left(y_{(m-1)d}^{(k_{m-1})},y_{m-1}^{(i_{m-1})}\right); \quad i_m=0,1,2,\ldots,k_{m-1}-1; \\ y_{(m+1)g}=f\left(y_{md}^{(k_m)},y_m^{(i_m)}\right); \quad i_{m-1}=0,1,2,\ldots,k_m-1; \\ u_d=y_{(m+1)g}. \end{cases}$$

A law of control can be written down in the form of the system:

$$\begin{cases} y_{1g}=f(t); \\ y_{jd}^{(k_j)}(t)=\Phi\left(y_j^{(i_j)},y_{jg}^{(r_j)}\right); \quad j=1,2,\ldots,m; \quad i_j=0,1,2,\ldots,k_j-1; \quad r_j=0,1,2,\ldots,R_j; \\ y_{(j+1)g}=f\left(y_{jd}^{(k_j)},y_j^{(i_j)}\right); \\ u_d=y_{(m+1)g}. \end{cases}$$

The first equation of the system is the set value of the controlled magnitude. The second equation is reference submodels of internal transient processes of the system. The third equation is inverse models of the component of the object. The last equation specifies a desired control action of the object.

Decomposition of a reference model makes it possible to synthesize SAC without the need to bring a MM of the object to the view of differential equation of the n-th order. Instead of combining the equations of MM of the object, the formation of a reference model in the form of a system of reference submodels for each element of the object is fulfilled. Each submodel specifies desired dynamics of internal transient processes of the object of control.

4. 4. Synthesis of high-precision automatic control system of one-dimensional motion of an underwater vehicle as an element of an underwater complex

Let us form a reference model according to the principle of decomposition. With this purpose we will select the laws of elimination of errors for each equation of a MM of the object in the form of linear differential equations of the 1st and 2nd order with the time constants T_ω, T_{y0} and T_{y1}:

$$\begin{cases} T_\omega \dot{E}_\omega + E_\omega = 0; \quad E_\omega = \omega_g - \omega; \\ T_0 T_1 \ddot{E}_y + T_0 \dot{E}_y + E_y = 0; \quad E_y = y_g - y, \end{cases}$$

where ω_g is the necessary value of the magnitude ω, E_ω is the error of control of the magnitude ω, E_y is the error of control of the magnitude y.

Let us substitute expressions for errors in the equations and define higher derivatives $\dot{\omega}_d$ and $\ddot{y}_d$, which represent the desired values relative to the first derivative ω and the second derivative of the controlled magnitude y:

$$\begin{cases} \dot{\omega}_d = \dot{\omega}_g + \dfrac{\omega_g - \omega}{T_\omega}; \\ \ddot{y}_d = \ddot{y}_g + \dfrac{\dot{y}_g - \dot{y}}{T_1} + \dfrac{y_g - y}{T_1 T_0}. \end{cases}$$

A controlling influence is determined from a MM of the object, in which the desired values substitute higher derivatives:

$$\begin{cases} u = \dfrac{1}{k_u}\left(J\dot{\omega}_d + k_\omega \omega + M_d\right); \\ \omega_g = f_{inv}\left(F_g, \dot{y}\right); \\ F_g = m\ddot{y}_d + F_s + F_d. \end{cases}$$

Thus, the system of automatic control of one-dimensional motion of UV as a part of UC contains a regulator that implements the resulting law of control, and reverse connections by the phase coordinates of the object y, ẏ and ω. Information about current magnitudes of the forces F_d, F_s and the moment M_d (Fig. 2) must be supplied to the input of the regulator.

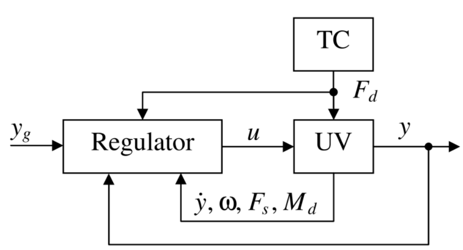

Fig. 2. SAC structure

In real UC, it is not always possible to measure the magnitudes F_d, F_s or M_d by instruments, but they can be calculated based on the corresponding MM of the UC elements. If their accuracy is insufficient, then corrections are made with the help of compensation circuits [23]. Thus a high dynamic accuracy of UC SAC is maintained.

The application of the principle of decomposition made it possible not to fulfill the transformations of MM of the object and receive a law of control that does not require computation of additional variables: derivatives from perturbing forces of TC and UV hull resistance, as well as the magnitude $\ddot{y}$.

4. 5. Control of phase coordinates

The principle of decomposition allows setting desired dynamics for each phase coordinate of the object. With this purpose, a reference model should contain submodels, each of which is responsible for managing a specific phase coordinate. Let us explain the essence of the proposal by the example. With this purpose we will present a MM of the object of control in the normal form of Cauchy:

$$\begin{cases} J\dot{\omega} = k_u u - k_\omega \omega - M_d; \\ m\dot{y}_1 = F_c - F_s - F_d; \\ \dot{y} = y_1. \end{cases}$$

Let us form reference submodels for each phase coordinate of the object in the form of the first-order differential equations with the time constants T_ω, T_{y0} and T_{y1}:

$$\begin{cases} T_\omega \dot{E}_\omega + E_\omega = 0; \quad E_\omega = \omega_g - \omega; \\ T_{y1}\dot{E}_{y1} + E_{y1} = 0; \quad E_{y1} = y_{1g} - y_1; \\ T_{y0}\dot{E}_y + E_y = 0; \quad E_y = y_g - y. \end{cases}$$

Let us express higher derivatives:

$$\begin{cases} \dot{\omega}_d = \dot{\omega}_g + \dfrac{\omega_g - \omega}{T_\omega}; \\ \dot{y}_{1d} = \dot{y}_{1g} + \dfrac{y_{1g} - y_1}{T_{y1}}; \\ \dot{y}_d = \dot{y}_g + \dfrac{y_g - y}{T_{y0}}. \end{cases}$$

Let us find control action by the substitution of higher derivatives in a MM of the object with the desired values:

$$\begin{cases} u = \dfrac{1}{k_u}\left(J\dot{\omega}_d + k_\omega \omega + M_d\right); \\ \omega_g = f_{inv}\left(F_g, \dot{y}\right); \\ F_g = m\dot{y}_{1d} + F_s + F_d; \\ y_{1g} = \dot{y}_d. \end{cases}$$

Thus, a reference submodel is selected separately for the task of desired dynamics of each phase coordinate of the object.

4. 5. Assignment of an arbitrary law of eliminating error

The principle of decomposition in conjunction with the method of ID opens up powerful capacities of formation of a reference model of SAC. Due to an independent choice of equations (submodels), which are part of the reference model, one can create a reference model as a system of arbitrary functions of time. Thus the restriction is removed that is in the choosing of the structure of a reference model or its submodels in the form of differential equations.

A law of eliminating error is proposed to form as a certain function of time for each phase coordinate of the object:

$$E = f\left(x_g, x, t\right),$$

where x_g is the set value of phase coordinate in the current moment of time t_c, x is the actual value of phase coordinate in the current moment of time t_c, $t \geq t_c$.

Then we find a desired trajectory of motion of phase coordinate:

$$x_d = x_g(t) - E(t).$$

After defining x_d, we find its derivatives of necessary order. Then the control action is determined by substituting of the desired values of the corresponding derivatives of phase coordinates in the inverse models of the object.

Thus, for example, in program SAC, where the dependency $y_g(t)$ is known in advance, instead of the reference submodels in the form of differential equations of the first order, one can apply their analytical solutions. Based on them, the desired values of higher derivatives of a MM of the object are numerically calculated:

$$\begin{cases} \dot{\omega}_d = \dot{\omega}_g(t_c) - \dot{E}_\omega; \quad E_\omega = \left(\omega_g(t_c) - \omega(t_c)\right)\exp\left(-\dfrac{t_h}{T_\omega}\right); \\ \dot{y}_{1d} = \dot{y}_{1g}(t_c) - \dot{E}_{y1}; \quad E_{y1} = \left(y_{1g}(t_c) - y_1(t_c)\right)\exp\left(-\dfrac{t_h}{T_{y1}}\right); \\ \dot{y}_d = \dot{y}_g(t_c) - \dot{E}_y; \quad E_y = \left(y_g(t_c) - y(t_c)\right)\exp\left(-\dfrac{t_h}{T_{y0}}\right), \end{cases}$$

where $t_h=\{0...t_{end}\}$ is the sequence of values of time, for which the errors are calculated; t_{end} is the horizon of error calculation.

A law of control in this case is defined, as before, from the inverse model of the object. Transient processes of SAC when choosing such a reference model correspond to transient processes of SAC with a reference model, set by a differential equation of the first order for each phase coordinate of the object. But their view can be changed by choosing another law of eliminating error in the function of time.

5. SAC simulation

To examine the laws of control received by an enhanced method of ID, in this work we performed a computer simulation of SAC of one-dimensional motion of UV as part of UC.

Simulation results of SAC at $T_\omega=T_{y0}=T_{y1}=0{,}5$ s with harmonic character $y_g(t)$ and zero initial values of phase coordinates of the object are presented in Fig. 3.

Initial values y_g and y differ, that is why in the first few seconds SAC eliminates the error of control, then the controlled magnitude coincides with its preset value. The charts of elimination of errors of the reference model E_e and the object E_y are almost equal. Minor deviations are caused by approximation of inverse model of a screw propeller, as well as by the assumption of the 1st order of MM of the thruster.

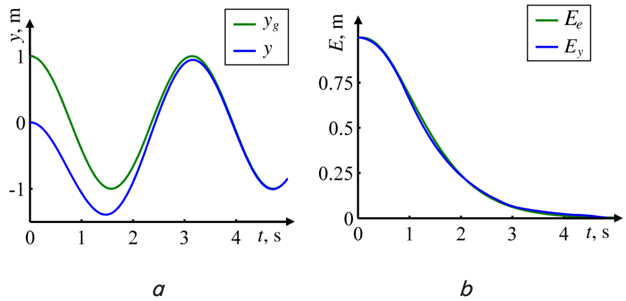

Fig. 3. Transition process at zero initial values of phase coordinates of the object: *a* is the set and the actual value of the controlled magnitude; *b* is the reference and the actual error of control

Fig. 4 displays the charts of the transition process of SAC at setting initial values of the object's phase coordinates ω_0 and $\dot{y}_0$ equal to their desired magnitudes.

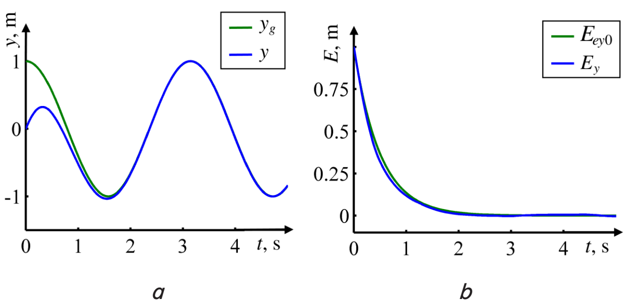

Fig. 4. Transition process at non-zero initial values of phase coordinates of the object: *a* is the set and the actual value of the controlled magnitude; *b* is the reference and the actual error of control

The chart of elimination of error E_y coincides with the chart of elimination of error of its reference submodel E_{ey0}. This occurs because the initial values of phase coordinates of the object coincide with their desired magnitudes, that is why a transition process of elimination of error of control matches the reference submodel for the controlled magnitude by a linear differential equation of the first order with the time constant T_{y0}=0,5 s.

The resulting SAC provides high precision control of UC. In this case, transition process of elimination of error almost completely coincides with the reference one, and after removing the error, the controlled magnitude strictly follows the set one without delay.

6. Discussion of the results of application of the principle of decomposition of a reference model

The method of ID is known in the theory of control as a method of synthesis of control systems of non-linear objects, including those of the highest order. Its main feature is to provide a high dynamic accuracy of control, which is the key requirement to the majority of modern underwater technologies.

In conjunction with the developed principle of decomposition, the method of ID provides powerful capacities for the synthesis of UC SAC. Formation a reference model by the principle of decomposition provides:

– a possibility of synthesis of high-precision SAC by the method of ID for UC, the nonlinearities of which are set in any form (graphically, tabulated, etc);

– a possibility to set a reference submodel to control each phase coordinate of UC;

– setting submodels in the form of arbitrary functions of time, including analytical, by the means of approximation or tabularly (with interpolation mechanism);

– combination of different laws of eliminating errors within the limits of single SAC, that is, in a general case, the choice of submodels is independent and is limited by the set requirements to stability and other criteria of SAC quality.

Defined properties extend capabilities of the method of ID and make it possible to select a reference model depending on the requirements to the set problem and the system of UC control.

Decomposition of the reference model does not guarantee strict following of the phase coordinates of the object of the transitional processes, set by their reference submodels. But the closer the value of the phase coordinates of higher orders to their desired values, the more precisely a controlled magnitude follows the transitional process, set by its reference submodel.

Application of the principle of decomposition to control UV as part of UC make it possible to synthesize SAC without loss of accuracy due to the simplification of a MM of the object, unlike the UV SAC obtained in [11]. In addition, the SAC obtained in this paper provides the following of the controlled magnitude by the set one without delay, unlike a PD regulator, designed to control UV as part of UC in [18].

It should be noted that real UC have limitations, in particular, by the control action. In this case, the work of SAC in the mode of saturation leads to the occurrence of over-regulation and oscillation, which manifest themselves on the objects of the second order. In this case it is necessary to adjust the parameters of the reference model or to apply optimization techniques by speed performance.

7. Conclusions

1. Based on the known mathematical models of the components of an underwater complex, a mathematical model was developed of one-dimensional motion of a propelled underwater vehicle under conditions of perturbing influence of a tether cable for the synthesis and study of automatic control system of its motion. It is a system of nonlinear differential equations with one equation of the first order and one equation of the second order and it includes the curves of action of a screw propeller, which are set in graphic form. Perturbing effect of a tether cable on an underwater vehicle hull is modeled by using a known mathematical model of dynamics of flexible connection.

2. A method of inverse dynamics was improved for the synthesis of high-precision automatic control systems of underwater complexes with low sensitivity to parametric and coordinate perturbations. The improvement is based on the principle of decomposition of a reference model of the control system by which it is formed as a set of reference submodels according to the structure of the object. Decomposition of a reference model provides a possibility to apply the method of inverse dynamics in the problems of synthesis of high-preci-

sion automatic control systems of underwater complexes, the nonlinear elements of which are set in arbitrary form.

3. We designed a system of automatic control of one-dimensional motion of underwater vehicle as a part of an underwater complex with the use of the method of inverse dynamics based on the principle of decomposition of a reference model. In the work we presented three variants of a reference model of an automatic control system: based on the accordance with the structure of a mathematical model of the object, based on the accordance with the structure of an object presented in the form of Cauchy, as well as in the form of arbitrary functions of time. The first variant makes it possible not to execute transformations of a mathematical model of the object. The second and the third variants allow setting desired dynamics to each phase coordinate of the object in the form, accordingly, of differential equations of the first order and arbitrary functions of time.

4. Computer simulation of the designed automatic control system of an underwater complex displayed that the transitional process to eliminate error of the coordinate of the vehicle corresponds to the reference one. Insignificant deviations of the real and the reference processes are caused by approximation of the inverse model of a screw propeller and the assumption about the first order of a mathematical model of the thruster. After eliminating the error, the controlled magnitude strictly follows the set one without delay.

References

1. Rowinski, L. Pojazdy glebinowe. Budowa i wyposazenie [Text] / L. Rowinsi. – Gdansk: Przedsiebiorstwo Prywatne “WiB”, 2008. – 593 p.
2. Blincov, V. S. Privjaznye podvodnye sistemy [Text] / V. S. Blincov. – Kyiv: Naukova dumka, 1998. – 232 p.
3. Kim, D. P. Teorija avtomaticheskogo upravlenija. Vol. 2 [Text]: uch. pos. / D. P. Kim // Mnogomernye, nelinejnye, optimal’nye i adaptivnye sistemy. – Moscow: FIZMATLIT, 2004. – 464 p.
4. Bojchuk, L. M. Metod strukturnogo sinteza nelinejnyh sistem avtomaticheskogo upravlenija [Text] / L. M. Bojchuk. – Moscow: «Jenergija», 1971. – 112 p.
5. Krut’ko, P. D. Obratnye zadachi dinamiki upravljaemyh sistem: Nelinejnye modeli [Text] / P. D. Krut’ko. – Moscow: Nauka, 1988. – 326 p.
6. Krut’ko, P. D. Obratnye zadachi dinamiki v teorii avtomaticheskogo upravlenija. Cikl lekcij [Text]: uch. pos. / P. D. Krut’ko. – Moscow: Mashinostroenie, 2004. – 576 p.
7. Deng, W. Study on simulation of remotely operated underwater vehicle spatial motion [Text] / W. Deng, D. Han // Journal of Marine Science and Application. – 2013. – Vol. 12, Issue 4. – P. 445–451. doi: 10.1007/s11804-013-1215-9
8. He, M. Analysis of a propeller wake flow field using viscous fluid mechanics [Text] / M. He, C. Wang, X. Chang, S. Huang // Journal of Marine Science and Application. – 2012. – Vol. 11, Issue 3. – P. 295–300. doi: 10.1007/s11804-012-1135-0
9. Lavrov, N. G. Primenenii koncepcii obratnyh zadach dinamiki k probleme upravlenija uglovym dvizheniem spuskaemogo apparata [Text] / N. G. Lavrov, E. Je. Strashilin, L. N. Shalimov // Vestnik JuUrGU. Serija: Komp’juternye tehnologii, upravlenie, radiojelektronika. – 2009. – Issue 26 (159). – P. 4–9.
10. Blajer, W. A case study of inverse dynamics control of manipulators with passive joints [Text] / W. Blajer, K. Kołodziejczyk // Journal of Theoretical and Applied Mechanics. – 2014. – Vol. 52, Issue 3. – P. 793–801.
11. Nadtochij, V. A. Syntez reguljatora dyferentu pidvodnogo aparatu pry roboti zovnishn’ogo nachipnogo obladnannja [Text] / V. A. Nadtochij // Elektronne vydannja «Visnyk NUK». – 2014. – Issue 3. doi: 10.15589/evn20140309
12. Chen, Y. Robust adaptive inverse dynamics control for incertain robot manipulator [Text] / Y. Chen, G. Mei, G. Ma, S. Lin, J. Gao // International Journal of Innovative Computing, Information and Control. – 2014. – Vol. 10, Issue 2. – P. 575–587.
13. Kusumoputro, B. Direct inverse neural network control of a double propeller boat model using a backpropagation neural networks [Text] / B. Kusumoputro, K. Priandana // International Journal of Information Technology & Computer Science. – 2015. – Vol. 22, Issue 1. – Avaialble at: http://ijitcs.com/volume%2022_No_1/Benyamin%20Kusumoputro.pdf
14. Zmeu, K. V. Prognozirujushhee inversnoe nejroupravlenie pnevmoprivodom v uslovijah nekontroliruemyh vozmushhenij [Text] / K. V. Zmeu, N. A. Markov, B. S. Notkin // Informatika i sistemy upravlenija. – 2011. – Issue 4 (30). – P. 116–123.
15. Calvo-Rolle, J. L. Adaptive inverse control using an online learning algorithm for neural networks [Text] / J. L. Calvo-Rolle, O. Fontenla-Romero, B. Pérez-Sánchez, B. Guijarro-Berdiñas // Informatica. – 2014. – Vol. 25, Issue 3. – P. 401–414. doi: 10.15388/informatica.2014.20
16. Chen, H. Model predictive controller design for the dynamic positioning system of a semi-submersible platform [Text] / H. Chen, L. Wan, F. Wang, G. Zhang // Journal of Marine Science and Application. – 2012. – Vol. 11, Issue 3. – P. 361–367. doi: 10.1007/s11804-012-1144-z
17. Park, B. S. Neural network-based tracking control of underactuated autonomous underwater vehicles with model uncertainties [Text] / B. S. Park // Journal of Dynamic Systems, Measurement, and Control. – 2014. – Vol. 137, Issue 2. – P. 021004. doi: 10.1115/1.4027919
18. Ramesh, R. Heading control of ROV ROSUB6000 using non-linear model-aided PD approach [Text] / R. Ramesh, N. Ramadass, D. Sathianarayanan, N. Vedachalam, G. A. Ramadass // International Journal of Emerging Technology and Advanced Engineering. – 2013. – Vol. 3, Issue 4. – P. 382–393.
19. Lukomskij, Ju. A. Upravlenie morskimi podvizhnymi ob’ektami [Text]: uchebnik / Ju. A. Lukomskij, V. M. Korchanov. – Sankt-Peterburg: Jelmor, 1996. – 320 p.

20. Blincov, O. V. Matematychna model' dynamiky prostorovogo ruhu kabel'-trosa pryv'jaznoi' pidvodnoi' systemy [Text] / O. V. Blincov // Zbirnyk naukovyh prac' NUK. – 2012. – Issue 5-6. – P. 61–63.
21. Spravochnik po teorii korablja. Vol. 1 [Text] / Ja. I. Vojtkunskogo (Ed.) // Gidromehanika. Soprotivlenie dvizheniju sudov. Sudovye dvizhiteli. – Leningrad: Sudostroenie, 1985. – 768 p.
22. Blincov, O. V. Syntez systemy avtomatychnogo keruvannja uporamy rushii'v pryv'jaznogo pidvodnogo aparata v rezhymi kvazistacionarnogo prostorovogo ruhu [Text] / O. V. Blincov // Zb. nauk. prac' NUK. – 2008. – Issue 1 (418). – P. 135–141.
23. Blincov, S. V. Teoretychni osnovy avtomatychnogo keruvannja avtonomnymy pidvodnymy aparatamy [Text]: monografija / S. V. Blincov. – Mykolaiv: NUK, 2014. – 222 p.

UDC 007.52
DOI: 10.15587/1729-4061.2016.74873

DEVELOPMENT OF EXECUTIVE SYSTEM ARCHITECTURE OF THE CONVERTING CLASS

I. Lutsenko
Doctor of Technical Sciences, Professor*
E-mail: delo-do@i.ua
E. Fomovskaya
PhD, Associate Professor, Head of Department*
E-mail: fill.fo@mail.ru
O. Serdiuk
Postgraduate student
Department of computer systems and networks
SIHE «Kryvyi Rih National University»
XXII Partz'yizdu str., 11,
Kryvyi Rih, Ukraine, 50027
E-mail: olgajs28@gmail.com
*Department of Electronic Devices
M. Ostrogradskii Kremenchug National Universitet
Pervomayskaya str., 20,
Kremenchug, Ukraine, 39600

Представлені результати досліджень, що були проведені з метою виявлення структури виконавчої системи перетворювального класу. Встановлено, що виконавча система перетворювального класу складається з технологічної підсистеми, підсистеми контролю, підсистеми обліку, підсистеми координації та підсистеми оптимізації. Встановлено, що особливості конкретної виконавчої системи перетворювального класу проявляються виключно в рамках особливості функціонування базового технологічного механізму

Ключові слова: система перетворення, підсистема координації, підсистема контролю, підсистема обліку

Представлены результаты исследований, которые были проведены с целью выявления структуры исполнительной системы преобразовательного класса. Установлено, что исполнительная система преобразовательного класса состоит из технологической подсистемы, подсистемы контроля, подсистемы учета, подсистемы координации и подсистемы оптимизации. Установлено, что особенности конкретной исполнительной системы преобразовательного класса проявляются исключительно в рамках особенности функционирования базового технологического механизма

Ключевые слова: система преобразования, подсистема координации, подсистема контроля, подсистема учета

1. Introduction

The category "system" is one of the central concepts of cybernetics as a science about general control principles. The analysis of steady patterns indicates that system objects are differentiated depending on solvable task: digestion system, heating system, crushing system, movement system etc.

It is logical to assume that all these system objects, providing transformation of physical products by interaction with other systems shall have the one internal architecture.

At the same time the studied system has not just to execute the own function, but execute it in the best way, that is optimally. It means that parameters optimization of input system products is its internal function.

Considering that every business connected with transformation of physical products includes a set of the interacting systems of the converting class, the synthesis of the internal structure of such systems is an important scientific task.

2. Literature review and the problem statement

Proceeding from general conceptions about the system as an indivisible essence, it is possible to present its structure in the form of subsystems. Each subsystem has to carry out one or several uniform functions. Nevertheless, these conceptual ideas are very often broken.

So, in the work [1] it is proposed to consider a subsystem as the part of the system, selected by some sign according to the purposes and research problems in which it can independently be accepted as a system.