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TASKS STATEMENT FOR MODERN AUTOMATIC CONTROL THEORY OF UNDERWATER COMPLEXES WITH FLEXIBLE TETHERS

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Abstract

The definition of a new class of control objects is proposed. It is an underwater complex with flexible tethers (UCFT) for which there is the need to automate motion control under uncertainty and nonstationarity of own parameters and external disturbances. Classification of marine mobile objects and characteristics of the flexible tethers as UCFT elements is given.

The basic UCFTs configurations that are used in the implementation of advanced underwater technologies are revealed. They include single-, double- and three-linked structures with surface or underwater support vessels and self-propelled or towed underwater vehicles.

The role of mathematical modeling in tasks of motion control automation is shown. The tasks of UCFT mathematical modeling are formulated for synthesis and study of its automatic control systems. Generalized structures of mathematical models of UCFT basic elements are proposed as the basis for the creation of simulating complex to study the dynamics of its motion.

The tasks of UCFT identification as a control object are formulated. Their consistent solution will help to obtain a UCFT mathematical model.

The basic requirements for UCFT automatic motion control systems are determined. Their satisfaction will ensure implementation of selected underwater technology.

Areas of development of synthesis methods of UCFT automatic control systems are highlighted.

Keywords: underwater complex, flexible tether, automatic control system, underwater vehicle.

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1. Introduction

A wide range of underwater operations is performed using tethered underwater systems (TUS), which are well studied and described in the scientific and technical literature [1, 2]. A typical single-linked TUS contains a tethered underwater vehicle (UV), which is connected with the help of the tether cable (TC) to a control station (CS) located on a surface support vessel (SV) (**Fig. 1**).

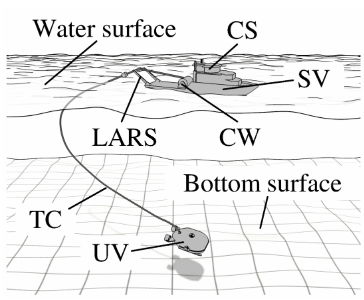

Fig. 1. Single-linked tethered underwater system and support vessel

Additionally the SV is equipped with a launch-and-recovery system (LARS) and a cable winch (CW). Support vessels aren't included in the TUS, because the TUS can be applied using a variety of carriers, including stationary, for example, to place a CS on the shore or in the dock.

Usually underwater missions, performed by TUSs, are divided into underwater search, operations on extended objects and point objects. Such missions are carried out in four classic underwater technologies [1, 3]:

– a UV operation from the SV anchorage;
– operation of a UV with an SV equipped with dynamic positioning means;
– operation of a UV with an SV in the drift;
– coordinated and controlled motion of a UV and an SV.

The TUS development is laid in the direction of the vessel's support role decreasing and the technological role increasing. Unmanned surface vehicles with remote control are developing rapidly, including in the role of support vessels of TUSs [4, 5].

The modern underwater technologies require coordinated control of SVs and UVs, i. e. all the elements of the marine complex, each of which is a substantially non-linear control object [3]. In this regard we propose to consider all the elements of the marine complex, connected by flexible tethers (FT), as a single control object that creates a new class of control objects – an underwater complex with flexible tethers (UCFT). The presence of mechanical connections by tethers between UCFT elements significantly complicates the problem of synthesis of their automatic control systems (ACS).

2. Literature review and problem statement

The development of SVs and UVs automatic control systems is laid in the direction of increasing their accuracy and providing controlled motion when they move on the given trajectory under uncertainty and nonstationarity of their own parameters and perturbations.

For the tethered UV of the working class in [6] it is proposed an ACS of its heading based on a PID-like controller. It provides smooth control at low speed, typical for UV of the working class, which limits its application to other UV classes. In addition, the quality of this ACS depends on the accuracy of the mathematical model (MM) of the object.

In [7] it is proposed the system of automatic pitch stabilization for the tethered UV by the method of inverse dynamics for operations on point objects. However, during the controller synthesis the UV mathematical model has been significantly simplified, which reduced control accuracy.

The system of obstacle avoidance and trajectory planning for an unmanned surface vehicle was proposed in [8]. The automatic control system of the UV with four degrees of freedom was proposed in [9]. In these works for the ACS synthesis the method of sliding mode control was used. The main disadvantage of the sliding mode control is the chattering effect of control signal that can damage the equipment. Smoothing this effect leads to a limited range of object parameters, which provide adequate control quality. The impact of FT disturbances easily forces out the control object from the determined limits.

The system of high-precision UV depth control based on an adaptive fuzzy controller in the sliding mode was proposed in [10]. The authors managed to smooth the chattering effect of the control signal and the effect of disturbances was approximated by a fuzzy adaptive algorithm. The output of the developed controller is the control force that requires development of an additional controller for the driving device. Such controller was proposed in [11] using a similar approach. But the work does not provide information on the application of these controllers for UVs with multiple degrees of freedom. Also, under significant FT influence the received ACS doesn't provide the necessary control quality.

The system of automatic stabilization of surface vessel by the "backstepping" method was proposed in [12]. But to control an SV as a part of a UCFT in such system it should be taken into account FT perturbations. Moreover, its application to the vessel motion on a given curvilinear trajectory requires further research.

The system of automatic heading control for surface vessel's steering was proposed in [13]. The main part of the ACS is the unit of dynamic adjustments designed to counteract the disturbance of

waves, which is synthesized on the basis of H_2-optimization theory. This study uses a linearized equation of the object, so qualitative steering control is provided with a certain constant values of object parameters and deteriorates when they change or when significant FT disturbances affect the vessel.

A time-optimal ACS of UV single-dimensional motion under uncertainty was proposed in [14]. The synthesis is based on a study of the dynamic properties of the control object through a series of experiments at different initial conditions. But the usage of proposed ACS is appropriate only for one-dimensional UV motion on account of significant amount of experiment.

The analysis of publications shows that the current state of UCFT control theory is as follows:

– tasks of UCFT control are formulated as isolated cases of implementation of individual modes of motion of tethered UVs and their SVs;

– proposed UV ACSs has high sensitivity to FT perturbations;

– onboard ACSs of surface vessels are intended for their conduct on a given route and do not provide high dynamic control accuracy when driving on difficult paths trajectories;

– existing ACSs of surface vessels do not take into account FT perturbations and with their significant impact do not provide the necessary control quality;

– there is no single approach to ACS synthesis of UCFT motion as a system with multiple controlled multidimensional objects;

– classic technologies of underwater operations are designed for TUSs and they do not realize the full potential of coordinated controlled motion of single-linked and multilinked UCFT.

3. The aim and objectives of research

The aim of this research is the formulation of tasks of the automatic control theory of the new class of marine objects – underwater complexes with flexible tethers, which solution forms the theoretical basis for the synthesis of highly efficient automatic control systems of their motion under uncertainty and nonstationarity of their own parameters and perturbations.

To achieve this aim the following tasks are stated:

– definition of the UCFT as a class of control objects and their components as elements of this class;

– selection of typical UCFT configurations that are used in the implementation of advanced underwater technologies;

– formulation of the problem of UCFT mathematical modeling;

– formulation of the identification problem of UCFTs and its components as the control objects;

– determination of requirements to ACSs of UCFTs;

– determination of areas of improvement of the UCFT automatic control theory.

4. Research results

4. 1. The underwater complex with flexible tethers as the control object

4. 1. 1. Definition of "underwater complex with flexible tethers" term

Let us introduce the definition of the UCFT. Any UCFT consists of two types of elements:

– element with lumped parameters – moving object (MO);

– element with distributed parameters – flexible tether (FT).

Let's consider the typical signs of UCFT:

– any MO, which is a part of some UCFT, has a mechanical connection to other MO of the UCFT through a FT; the MO connection can be direct, that some two MOs are interconnected by flexible tether, or indirect, that is through the third MO of UCFT;

– if two MO mechanically connected by a flexible tether, they set forms a UCFT;

– if some MO has no mechanical connection to any MO of UCFT, then this MO is not a part of the UCFT;

– at least one MO of a UCFT must be underwater (underwater vehicle, submarine, etc.).

So, the UCFT is a set of moving objects directly or indirectly interconnected by flexible tethers and designed to perform cooperatively an underwater mission.

4. 1. 2. Analysis of moving objects and flexible tethers as elements of UCFT

According to the environment in which the motion is performed, there are three groups of MO [15]: marine MO (MMO), air MO and ground MO (**Fig. 2**).

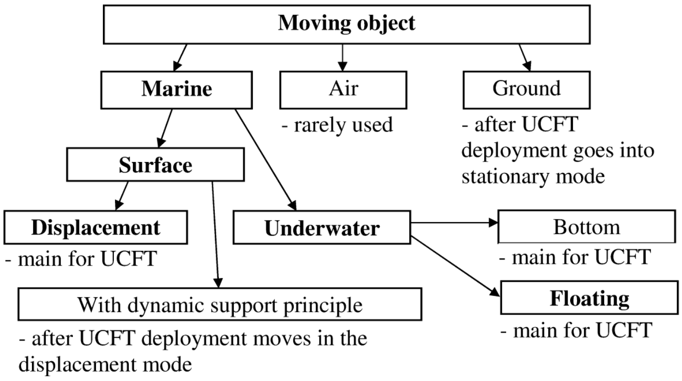

Fig. 2. Classification of moving objects according to the motion environment

Air MOs in UCFTs are mainly used to solve the defensive problems, such as finding and neutralizing underwater mines [16]. Typical underwater technologies are successfully implemented using the other MO classes.

Ground MOs can be used as a mobile control stations and in the performance of underwater operation their motion is not required, i. e. in operative UCFT control a ground MO can be considered as a stationary object.

Modern UCFTs contain mainly MMOs, i. e. MOs, decisive influence on the motion of which have water environment. The basic classification features of an MMO as a control object is the classification by the nature of the external environment influence and by the method of motion [15]. For the former sign MMOs are divided into the following groups: displacement surface vessels, vessels with dynamic support principles, underwater floating submarines and vehicles, bottom UVs.

MMOs by the method of motion are divided into self-propelled and non-self-propelled ones. Self-propelled MOs are moved using own propulsors, non-self-propelled (sinking, buoyant and towed) instead of propulsors are equipped with systems of orientation and stabilization in space.

The main types of MMO, which are used as a part of UCFT, are displacement surface vessels, underwater floating and bottom UVs [17, 18]. The latter have mechanical contact of propulsors with bottom, that's why external perturbations have little impact on their control quality. The greatest difficulty is ACSs synthesis of surface displacement vessels and floating tethered UVs of two types: self-propelled UV (SUV) and towed UV (TUV).

Flexible tethers of UCFTs are tether cables, tow cables, hoses, steel or synthetic ropes etc. and they perform at least one of three functions [15]:

– function of information exchange between MMOs of a UCFT;

– load-carrying function;

– supply function (power, gas, liquids, etc.).

The most common type of FTs that connect UVs with surface vessels is a tether cable with a circle in cross-section, the diameter of which depends largely on the UV power consumption. The SV anchorage is also provided by an FT – an anchor chain.

4. 2. Basic configurations of underwater complexes with flexible tethers

The most simple are UCFTs with single-linked structure. They provide the basic feasibility of underwater operations and usually consist of surface or underwater SVs and SUVs or TUVs (**Fig. 3**).

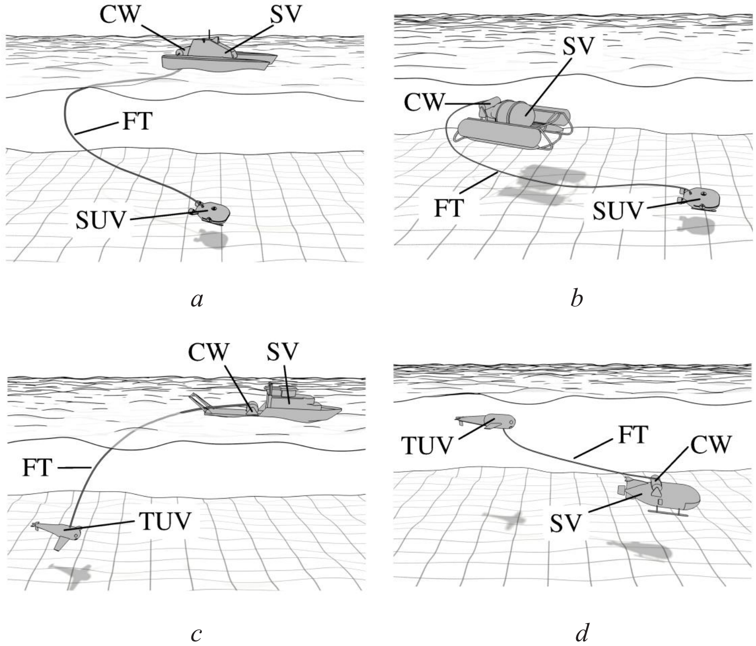

Fig. 3. Single-linked underwater complexes with flexible tethers: *a* – surface support vessel with self-propelled underwater vehicle; *b* – underwater support vessel with self-propelled underwater vehicle; *c* – surface support vessel with towed underwater vehicle; *d* – underwater support vessel with towed underwater vehicle

Multilinked structures may contain additional SVs, UVs and underwater garages (UG) and provide opportunities unachievable for their single-linked variants [19]. Typical and prospective double-linked and three-linked UCFTs are shown in **Fig. 4, 5** respectively.

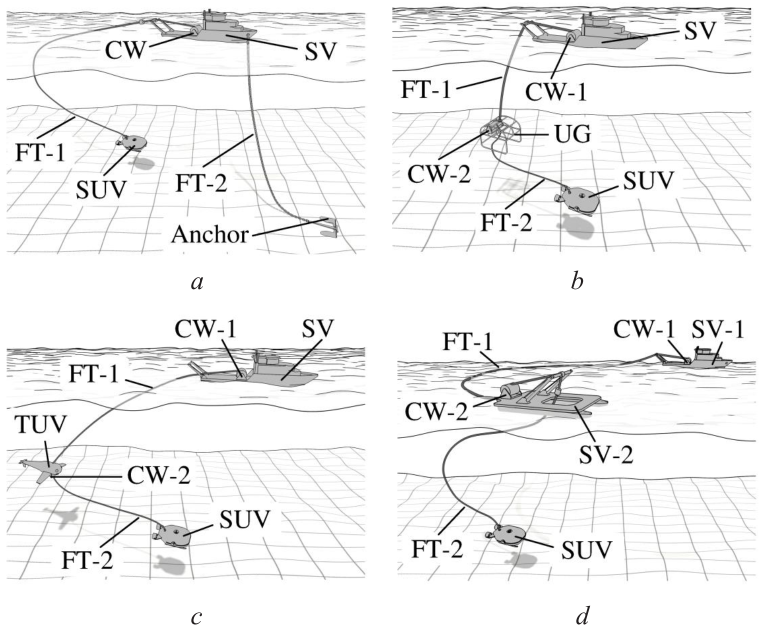

Fig. 4. Double-linked underwater systems with flexible tethers: *a* – support vessel with anchor and self-propelled underwater vehicle; *b* – support vessel, underwater garage and self-propelled underwater vehicle; *c* – support vessel, towed and self-propelled underwater vehicles; *d* – basic and additional support vessels and self-propelled underwater vehicle

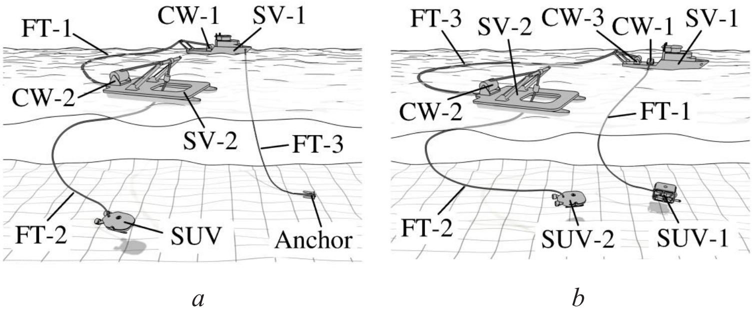

Fig. 5. Three-linked underwater complexes with flexible tethers: *a* – the basic support vessel with anchor, additional support vessel and self-propelled underwater vehicle; *b* – two support vessels and two self-propelled underwater vehicles

The SV anchoring converts a single-linked UCFT into a double-linked one (**Fig. 4, *a***). Such UCFT contains two FTs: the tether cable (FT-1) and the anchor chain (FT-2). The length of the FT-1 is controlled by a CW, the length of the FT-2 is guided by a vessel windlass.

To operate at depths of over 100 m the serial connection of an SV, a UG and a SUV is used (**Fig. 4, *b***). Main hydrodynamic disturbances are created on the FT-1 and affect the UG that operates as a cantledge.

To ensure coordinated motion of a SUV and a surface SV, a TUV is used. Its bearing surfaces compensate the basic hydrodynamic disturbance that is formed on the FT-1 (**Fig. 4, *c***).

The schemes with a UG and a TUV as an intermediate link make it possible to significantly reduce the disturbance of the FT-2, that influence the SUV, and to extend its working area.

Double-linked scheme with two surface SVs are used to extend the working area of a SUV in the horizontal plane relative to the basic SV (SV-1) (**Fig. 4, *d***). The additional low-tonnage SV (SV-2) supports the SUV on the surface.

For operations in shallow water in difficult navigation conditions where the approach of the main SV (SV-1) directly into the operation area is difficult, an additional low-tonnage SV (SV-2) is applied. The SV-1 is held in near the operation area by an anchor through an anchor chain (FT-3) and the SUV is launched from the SV-2 (**Fig. 5, *a***).

Variant of a three-linked UCFT is shown in (**Fig. 5, *b***). The main operation at a point object is performed by a SUV-1, which is connected via FT-1 with the main SV (SV-1). The third person view is provided by a SUV-2, it is connected to an additional SV (SV-2) through FT-2. Connection of SV-2 and SV-1 is held through the FT-3. This ensures separation of flexible tethers of SUVs and reduces risk of entanglement.

UCFT configurations are not limited by represented variants. To increase the efficiency of underwater search or operations with point objects UCFTs with series-parallel UVs connection schemes are used. In this regard, development of the UCFT control theory is perspective towards control of multilinked UCFTs of different configurations.

4. 3. The task of mathematical modeling of underwater complexes with flexible tethers

4. 3. 1. Role of mathematical modeling in the motion control theory of underwater complexes with flexible tethers

The aim of UCFT mathematical modeling is to solve three major problems:

– investigation of the UCFT properties as a control object;

– UCFT ACSs synthesis;

– investigation of UCFT ACSs effectiveness.

The UCFT mathematical model allows to investigate controllability and maneuverability of MMO that it contains, and the boundaries of their operation areas.

Mathematical modeling plays a key role in UCFT ACS synthesis, since a number of synthesis methods are based on the use of mathematical models of control object elements. Therefore the problem of UCFT and their elements mathematical modeling is not limited to the development

of MM of controlled UCFT motion. Solution of ACS synthesis problems may require appropriate synthesis of direct or inverse UCFT and their elements models submitted in the required form.

Finally, investigation of the effectiveness of new ACSs primarily carried out by computer simulation, based on the accurate UCFT model.

The known simulators are designed primarily to study the motion of surface vessels and UVs separately. For example, in [20] the vessel simulator is proposed that takes into account its interaction with other vessels and with the ground in the collision. In [21] simulation system is developed for the study of a fuzzy controller of an underwater vehicle, and the model does not take into account the FT dynamics.

Development of the UCFT modeling complex considering dynamics of all its elements and their mutual influence today is one of the main tasks of UCFT mathematical modeling.

4. 3. 2. Problem statement for developing of mathematical model of the dynamics of underwater complex with flexible tethers

It is proposed to divide into stages the development of the MM of UCFT:

– development of the UCFT MM structure;

– development of the MM structure for each MMO as a part of UCFT;

– development of the MM of MMO elements;

– development of the FT MM.

The UCFT MM structure determines the amount of MMOs in its composition and their interaction through FTs within the UCFT. The MMO MM structure defines the elements of which it is composed, and coordinates their interaction within the MMO. Development of the MMO MM comes to development of the MM for its elements: a hull, a driving device, bearing surfaces, etc. The mathematical model of MMO must be obtained in a way that FT impacts are presented as the input values. Accordingly, the development of the FT MM should be obtained in a form that MMO influences on it are at its inputs. This will allow to combine the MMO and FT mathematical models in a single modeling complex.

The motion of the MMO as a rigid body in all its diversity is described by equations [3]:

$$\left.\begin{aligned} \dot{V} &= \Phi(V, N); \\ \dot{P} &= KV; \end{aligned}\right\} \tag{1}$$

$$V = \left[\vec{v}\ \vec{\omega}\right]^T;\ \ P = \left[\vec{r}\ \vec{q}\right]^T;\ \ N = \left[\vec{F}\ \vec{M}\right]^T;\ \ \Phi = \left[\varphi_1\ \varphi_2\ \varphi_3\ \varphi_4\ \varphi_5\ \varphi_6\right]^T;$$

$$\vec{v} = \left\{v_x, v_y, v_z\right\};\ \ \vec{\omega} = \left\{\omega_x, \omega_y, \omega_z\right\};\ \ \vec{r} = \left\{x, y, z\right\};\ \ \vec{q} = \left\{\theta, \varphi, \psi\right\};$$

$$\vec{F} = \left\{F_x, F_y, F_z\right\};\ \ \vec{M} = \left\{M_x, M_y, M_z\right\},$$

where V – the matrix of MMO velocity kinematic parameters (time derivative is dotted); P – the matrix of MMO positional kinematic parameters; N – the matrix of forces and moments acting on the MMO; Φ – the nonlinear matrix function, which is a matrix-column of scalar nonlinear functions φ_i, i=1, 2, ..., 6; K – kinematic connection matrix between coordinate systems measuring 6×6; $\vec{v}$ and $\vec{\omega}$ – vectors of translational and rotary MMO velocities respectively, their components are usually expressed as projections on the axes of the MMO body-fixed coordinate system; $\vec{r}$ and $\vec{q}$ – vectors of translational and rotary MMO coordinates respectively, $\vec{r}$ vector connects the start of some basic coordinate system and the center of MMO mass, elements of $\vec{q}$ vector represent the Euler angles; $\vec{F}$ and $\vec{M}$ – vectors of the resultant forces and torques respectively.

Vectors $\vec{F}$ and $\vec{M}$ are formed on the principle of superposition of three components: reactive forces and moments, propulsive forces and moments, external forces and moments [18]. The set of control actions coming to driving devices and steering drives forms control vector or a set of MMO control actions $U = \left\{u_1, u_2, \ldots, u_j, u_{j+1}, \ldots, u_m\right\}$. Outputs of the MMO MM are its kinematic parameters – elements of V and P matrix.

Forces and moments of the FT are classified as external. For FT simulation it is proposed to use the MM of its dynamics [22]:

$$m\ddot{\vec{r}}_i = \vec{F}_i; \ \vec{F}_i = \vec{f}\left(\vec{r}_{i-1}, \vec{r}_i, \vec{r}_{i+1}, \frac{d\vec{r}_i}{dt}, L\right), \tag{2}$$

where $\vec{F}_i$ – vector of the resultant force acting on the elementary FT section, i=1, 2, ..., n; $\vec{r}_i$ – coordinates of the elementary FT section; L – length of the released FT part.

Coordinates of root $\vec{r}_1$ and running $\vec{r}_n$ FT ends are determined based on positional MMO kinematic parameters to which they are connected, and are the FT MM inputs. The FT MM outputs are a tension force on root $\vec{F}_1$ and running $\vec{F}_n$ FT ends, which are input values for the MMO MM. The control action for flexible tether is the length of its released part L. Thus, mutual influence of all UCFT elements is considered in modeling the motion dynamics, including the operative change of FT length.

Releasing and spooling back of the FT are modeled based on the MM of CW dynamics [23]:

$$\dot{L} = R\omega; \ \dot{\omega} = f\left(M_{EM}, M_L\right); \ M_L = RF_1; \ M_{EM} = f\left(u_w, \omega\right), \tag{3}$$

where u_w – CW control signal, M_{EM} – driving moment of CW motor , ω – angular velocity of the CW drum, M_L – retarding torque of the CW drum, R – CW drum radius.

So, the UCFT MM consists of sets of MMO, FT and CW mathematical models that have generalized structures represented by equations (1), (2) and (3) respectively. Each of the MM may vary depending on the respective constituent elements of a UCFT and accepted assumptions.

4. 4. Problem statement for identification of underwater complex with flexible tethers as a control object

The UCFT is a complex multidimensional multiply connected object. The task of its identification it is proposed to resolve on the basis of decomposition principle as the following set of tasks, consistent solution of which will help to get the UCFT mathematical model:

– structural UCFT identification in general;
– structural identification of UCFT elements;
– parametric identification of UCFT elements.

4. 4. 1. Analysis of structural identification process for underwater complex with flexible tethers

As a result of structural UCFT identification, initial imagination of a UCFT as a control object is obtained. At this stage it is necessary to:

– determine the number of MMOs of which the UCFT consists of;
– determine which MMOs are interconnected with FTs;
– determine full FT length values;
– determine which MMO has a CW;
– determine UVs location on SVs in a folded UCFT state;
– classify each MMO by the influence nature of the environment and the method of motion.

Each element of the UCFT is identified after structural UCFT identification.

4. 4. 2. Analysis of structural and parametric identification process of elements of underwater complex with flexible tethers

The motion of MMOs (hulls, driving devices, bearing surfaces) and FTs today is well studied and the control theory has in its arsenal mathematical models of its elements of varying degrees of adequacy [3, 18, 22].

The task of structural identification comes to analysis of MMO design, selection and laying out mathematical models of its elements. At the stage of MMO structural identification it is important to determine which kinematic parameters are controlled, i. e. depend on U.

The structure of FT mathematical models varies depending on a method, used for its simulation. Therefore, the task of FT identification is the choice of structure and determination of numerical parameters of its MM.

The main problem of parametric identification of UCFT elements is identification of hydro and aerodynamic MMO parameters. Today the problems of parametric identification are solved by the methods of basin and sea natural experiments and computational fluid dynamics methods [24].

4. 5. Definition of basic requirements for ACS of underwater complexes with flexible tethers

Marine environment, where UCFTs are operated, is characterized by nonstationarity of parameters and uncertainty of its influence on UCFT elements. UCFT elements are also has nonstationarity and uncertainty of inherent parameters. Besides, it is not always possible to get accurate MMs of their elements. In this regard, the UCFT ACS must be characteristic of parametric and structural adaptability.

UCFT ACS quality can be estimated on the basis of classical quality criteria, which can be divided into four groups [25]: criteria of accuracy, stability, time and comprehensive criteria. Quality requirements for UCFT ACSs are developed by forming the required quality index for each controlled MMO parameter.

The UCFT control task is formed as the control task of each MMO and FT consisting UCFT. Control tasks are formulated in various definitions. The most common task for the MMO is the trajectory motion as a function of time t, for the FT – the task is to minimize tension in its running end [23]:

$$P = P_g(t); \quad L = L_g\Big|_{|\vec{F}_n| \to \min},$$

where P_g – the matrix of given MMO positional parameters, L_g – given length of the released FT part.

The task of MMO stabilization can be considered as a special case of its trajectory motion: $P_g(t) = \text{const}$. Vertical component of tension force F_{ny} is minimized for TUVs: $L = L_g\big|_{F_{ny} \to \min}$.

As an example, a typical problem of underwater search using a single-linked TUV-based UCFT can be formalized in the following form:

$$\begin{aligned}
P_{SVg} &= \left[x_{SVg}(t) \quad NaN \quad z_{SVg}(t) \quad NaN \quad NaN \quad NaN\right];\\
P_{UVg} &= \left[NaN \quad y_{UVg}(h_g) \quad NaN \quad NaN \quad NaN \quad NaN\right];\\
E_{SVg} &= \left[e_{SVgx} \quad NaN \quad e_{SVgz} \quad NaN \quad NaN \quad NaN\right];\\
E_{UVg} &= \left[NaN \quad e_{UVgy} \quad NaN \quad NaN \quad NaN \quad NaN\right],
\end{aligned}$$

where P_{SVg} – the matrix of given SV positional kinematic parameters; x_{SVg} and z_{SVg} – SV given coordinates on the surface; P_{UVg} – matrix of given TUV positional kinematic parameters; y_{UVg} – given TUV vertical coordinate; h_g – given TUV height above bottom; E_{SVg} and E_{UVg} – matrices of static errors for the SV and the TUV respectively that define quality criteria for the ACS; e_{SVgx}, e_{SVgz}, e_{UVgy} – allowable values of static errors for the SV and the TUV for coordinates x_{SVg}, z_{SVg}, and y_{UVg} respectively; NaN (not a number) – the indefinite matrix element.

And at any time there is the condition:

$$\begin{aligned}
r &\le (1-k)L_{max};\\
r &= \left|\vec{r}_{UVg} - \vec{r}_{SVg}\right|,
\end{aligned}$$

where r – distance between the SV and the TUV in their motion on the given trajectories; $\vec{r}_{UVg}$ – vector of given TUV translational coordinates in the base coordinate system; $\vec{r}_{SVg}$ – vector of given SV translational coordinates in the base coordinate system; L_{max} – full tether length; k – spare factor of the tether length, $k \in [0, 1]$.

The ACS should provide motion of UCFT elements along the given trajectories complying the desired quality indexes, which ensures the implementation of selected underwater technology.

Thus, the basic requirements that must satisfy the UCFT ACS for the given underwater mission should be formed in the following sequence:

– ensuring the implementation of selected underwater technology;

– ensuring motion of UCFT elements along the given trajectory;

– ensuring the ACS compliance to defined quality indexes.

Underwater technology is chosen based on the mission, which is to be performed by the UCFT. Control tasks for UCFT elements in the form of defined trajectories of their motion are formed based on the selected underwater technology. Then criteria of control quality are chosen and their indexes are determined.

4. 6. Determination of development directions of the automatic control theory of underwater complexes with flexible tethers

Today, the automatic control theory has a wide variety of approaches to control of complex nonlinear objects that can be used to control the UCFT elements.

Despite the wide range of methods of ACS synthesis, PID controllers are used for control the majority of UV of industrial production [26]. The choice of PID controllers for controlling technical objects is due to their simplicity and effectiveness in specific conditions. Usually, PID controllers don't consider nonlinearity of control object, which leads to poor control quality and system instability. Compensation of nonlinearities allow to ensure satisfactory control quality using PID controllers [6]. But such ACSs are susceptible to parametric errors of MM of object and do not provide high control quality. Use of PID-like controllers for UCFT control requires development of high-accuracy MMs of UCFT elements, including the FT dynamics. The task of getting MMs is complicated by stochastic nature of the aquatic environment impact on UCFT motion.

High-accuracy control of nonlinear objects under uncertainty is provided by ACSs synthesized by sliding mode control methods [27]. Improvement of these methods is seen in the reduction of chattering effect of a control signal without reducing the quality control.

It is known about ACS of an autonomous UV based on artificial neural networks (ANN) [28]. Application of ANN to UCFT control in conditions of FTperturbations is one of the main areas of development of control theory of UCFT as an object that is operated under uncertainty.

The methods of the inverse dynamics concept are promising for UCFT ACS synthesis, among them are the method of inverse dynamics, adaptive inverse control, direct-inverse control.

The method of inverse dynamics (ID) makes it possible to synthesize high-accuracy ACSs for complex nonlinear objects, including UCFTs [29]. Development of inverse models for UCFT elements, which parts can be specified including graphical or tabular form, is a prerequisite for its use.

The method of adaptive inverse control of nonlinear objects is based on approximation of inverse dynamics of control object as a function of time [30]. In contrast to the classical ID method, the system is operated under minimum structural certainty of the object. This approach for the UCFT ACS synthesis is promising, but it is needed to increase the dynamic accuracy of obtained ACSs.

Direct-inverse control is used for the synthesis of controllers in conditions of parametric uncertainty. One of the elements of these ACSs is inverse object model in the form of an ANN, which imitates its inverse dynamics. Direct-inverse control has been used successfully for both surface [31] and underwater [32] MMOs. Application of this method to ensure coordinated control of MMOs of UCFT is perspective.

Modern methods of ACS synthesis allow to obtain controllers for UVs and surface vessels. However, the problem of coordinated automatic control of all UCFT elements in conditions of FT perturbations in the scientific literature is not covered.

Development of UCFT ACS synthesis methods is proposed to perform in the following areas:

– application of known methods of ACS synthesis for UCFT control under uncertainty;

– improvement of the known synthesis methods including the methods of inverse control concept for high-accuracy control of UCFT elements in conditions of FT perturbations;

– development of new methods of coordinated automatic control of UCFT elements for implementation of selected underwater technology.

5. Conclusions

1. Definition of a new class of control objects - underwater complex with flexible tethers is proposed. It consists of rigid and flexible bodies that have mechanical interaction between them, and for which there is the need to automate motion control under uncertainty and in nonstationarity of inherent parameters and external disturbances.

2. The basic configurations of underwater complexes with flexible tethers, which are used in the implementation of advanced underwater technologies, are revealed. They include complexes with single-linked, double-linked and three-linked structures. Surface component contains one or more support vessels or unmanned remotely operated vessels, underwater component contains one or more self-propelled or towed underwater vehicles.

3. The tasks of mathematical modeling of controlled motion of an underwater complex with flexible tethers are formulated. It is to develop and consolidate the mathematical models of elements of the underwater complex. Solution of the task of mathematical modeling will allow to explore the underwater complex features as a control object, synthesize and investigate the effectiveness of its automatic control systems. Generalized structures of mathematical models of a marine moving object, a flexible tether and a cable winch are proposed as the basis for the creation of modeling complex to study the motion dynamics of underwater complexes with flexible tethers.

4. The problems of identification of an underwater complex with flexible tethers as a control object are formulated based on a decomposition principle. It consists of structural identification of the complex in general, structural and parametric identification of its elements.

5. The basic requirements for automatic control systems of underwater complexes with flexible tethers are defined. These include requirements to ensure the implementation of a selected underwater technology, the motion of elements of the complex by given trajectories, the adequacy of automatic control systems to quality criteria.

6. Directions of development of synthesis methods of automatic control systems for underwater complexes with flexible tethers are defined. They lie in improvement of the known control methods and development of new control methods. Improvement of known methods is proposed to perform in order to provide high-accuracy control of elements of underwater complex in conditions of perturbations of flexible tethers. Development of new methods of coordinated control of underwater complexes elements is proposed to perform in order to ensure implementation of the selected underwater technology.

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