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Method of Synthesis of Automatic Correction Systems of Underwater Vehicles Linear Displacements

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Abstract

In this work the synthesis method of system of automatic correction of underwater vehicle linear displacements is described. Arbitrary non-zero values of underwater vehicles angles of roll and trim arise under the influence of external forces and torques. Proposed system automatically changes corresponding thrusters thrusts depending on current values of said angles. It provides high-accuracy underwater vehicle moving in given direction.
Besides, developed system allows to eliminate underwater vehicle displacements from given spatial trajectory which caused by vehicle asymmetry and different values of added mass of fluid and viscous friction coefficients when underwater vehicle moves along different degrees of freedom.
As result of using of proposed correction, operator can control desired torque vector of underwater vehicle without considering of appearance of arbitrary angles of roll and trim.
Results of performed numerical simulations have confirmed high efficiency of functioning of synthesized system.

Keywords: underwater vehicle; control system; automatic correction; linear displacements; Doppler log

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1. Introduction

Today research and technological works are already performing by means of remotely operated underwater vehicles (UV) and manned UV in depths of oceans. Fields of use of UV are expanding, therefore requirements to control systems (CS) of UV are continuously increasing. CS of UV should provide high accuracy movement of ones in water environment.

Operators manually set desired direction of UV motion in process of underwater operations with aid of command unit. The success of underwater operations depends on accuracy of UV motions in desired direction. Today many methods of synthesis of precision CS of UV already developed [1-6]. Existing CS can effectively control the UV movement only if UV have not uncontrolled angles of roll and trim. However, often in process of UV moving angles of roll and trim appear under influences of torque impacts by grasped cargo, underwater cable, asymmetry of UV and other perturbing factors.

In some cases, it is impossible to compensate unwanted angular displacements of UV with help of thrusts created by UV thrusters, because mounting scheme of thrusters of majority of UV do not allow to control the angles of roll and trim. Furthermore, permanent stabilization of angles of roll and trim in manual mode provides additional load to operator. Stabilization of roll and trim in automatic mode requires to use of special servo-loop systems [7], but it lead to additional expenditure of energy.

Uncontrollable changes of UV spatial orientation lead to UV offsets from given direction. Operator in manual mode can eliminate changes of UV spatial orientation if he has visual contact with a target. Angles of roll and trim can be eliminated in automatic mode if UV has a high-accuracy navigation system. However, efficient control of UV is very difficult when UV has angles of roll and trim. It inevitably reduces quality of underwater technical operations.

As a result, the problem of ensuring the precision movement of UV in given directions arise when UV have uncontrollable angles of roll and trim.

2. Statement of problem

In the paper, the task of development of synthesis method of effective system of automatic correction of control signals of UV linear movements is indicated. This system should provide high-accuracy UV motion in desired directions when UV has arbitrary changeable angles of roll and trim.

3. Definition of expressions for automatic correction of vector of linear displacements of UV.

UV schematically showed on Fig. 1. UV has angular offset of roll γ and angular offset of trim α. Angles of roll and trim are accurately measured by onboard gyroscopes. With centre of weights C of UV, which coincides with centre of his size, the origins of semi-combined XYZ and body-fixed $X^*Y^*Z^*$ with UV right rectangular coordinate systems (SC) are combined. If angles of roll γ and trim α are equal to zero then axes of SC XYZ and relevant axes of SC $X^*Y^*Z^*$ are coincide. Herewith Z-axis is directed along the upward vertical. X^*-axis is coincide with longitudinal axis of UV. X-axis is coincide with projection of X^*-axis onto horizontal plane.

Thrust vector $\tau^*(t) = [\tau_x^*, \tau_y^*, \tau_z^*]^T$ is always formed in SC $X^*Y^*Z^*$, inasmuch as longitudinal axis of UV thrusters are bound with SC $X^*Y^*Z^*$. Desired program vector $\tau(t) = [\tau_x, \tau_y, \tau_z]^T$ is formed by operator or program device in SC XYZ (see Fig. 1). Vector $\tau^*(t)$ determines desired direction of UV movement in absolute SC $X_aY_aZ_a$. If external influences of torque and force are equal to zero then UV has angles of roll γ and trim α equal to zero due to metacentric stability of UV. In this case, vector $\tau^*(t)$ coincides with direction of vector $\tau(t)$. Magnitude of vector $\tau^*(t)$ is forming proportional to vector $\tau(t)$ by CS of UV.

Obviously that if angles of roll γ and trim α are not equal to zero then vectors $\tau^*(t)$ and $\tau(t)$ do not coincide and UV moves along direction of vector $\tau^*(t)$ but not along right direction of vector $\tau(t)$. For keeping UV motion in right direction thrusters thrusts must be change with considering of γ and α that new torque vector

$\tau_p(t) = [\tau_{px}, \tau_{py}, \tau_{pz}]^T$ appears instead of vector $\tau^*(t)$ in SC $X^*Y^*Z^*$. Wherein vector $\tau_p(t)$ must be coincide with vector $\tau(t)$ in space.

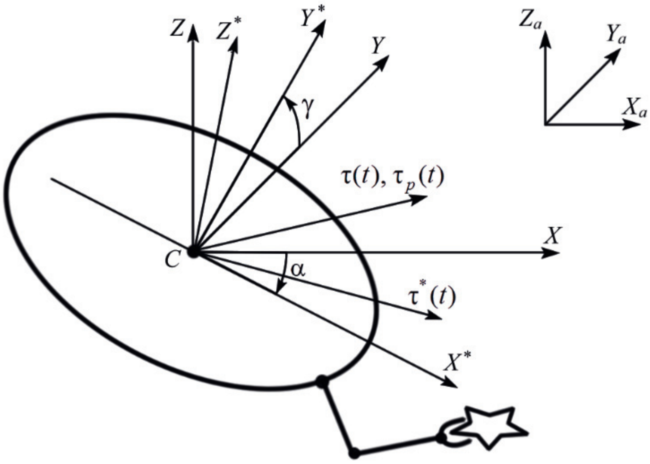

Fig. 1. Layout of axes of SC *XYZ* and $X^*Y^*Z^*$ on UV.

If elements of vector $\tau(t)$ in SC XYZ are known then elements of vector $\tau_p(t)$ in SC $X^*Y^*Z^*$ can be obtained by expression [8]:

$$\tau_p(t) = R^T \tau(t), \tag{1}$$

where $R \in R^{3x3}$ - matrix of rotation SC $X^*Y^*Z^*$ relative to XYZ, T – symbol of transposition.

For definition of elements of matrix R rotation of UV with SC $X^*Y^*Z^*$ must be presented as sequence of elementary rotations. In this case, axes relative to which measure angles of corresponding rotations of SC $X^*Y^*Z^*$ and sequence of these rotations must be selected such that angles α and γ will be really measured by onboard gyroscope [9]. This condition is carried out at following sequence of elementary rotations of CS $X^*Y^*Z^*$: firstly SC $X^*Y^*Z^*$ rotates around axis Y at angle α (matrix of elementary rotation $R_{Y,\alpha}$ corresponds to it), after SC $X^*Y^*Z^*$ rotates around axis X^* at angle γ (matrix of elementary rotation $R_{X^*,\gamma}$ corresponds to it). Matrixes of elementary rotations are submitted as [10]:

$$R_{Y,\alpha} = \begin{bmatrix} C\alpha & 0 & S\alpha \\ 0 & 1 & 0 \\ -S\alpha & 0 & C\alpha \end{bmatrix}, R_{X^*,\gamma} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\gamma & -S\gamma \\ 0 & S\gamma & C\gamma \end{bmatrix}, \tag{2}$$

where $S\alpha = \sin\alpha$; $S\gamma = \sin\gamma$; $C\alpha = \cos\alpha$; $C\gamma = \cos\gamma$.

With regard to expression (2), matrix R for described sequence of rotations of SC $X^*Y^*Z^*$ with UV is given by:

$$R = R_{Y,\alpha} R_{X^*,\gamma} = \begin{bmatrix} C\alpha & S\alpha S\gamma & S\alpha C\gamma \\ 0 & C\gamma & -S\gamma \\ -S\alpha & C\alpha S\gamma & C\alpha C\gamma \end{bmatrix}. \tag{3}$$

It needs to be emphasized, that for determining elements of vector $\tau_p(t)$ in expression (1) only matrix (3) can be used. Because any matrix compiled by different sequence of elementary rotations can not be implemented using angles γ and α which are measured by onboard gyroscopes.

After substituting of transposed matrix R in equation (1) we have:

$$\tau_p(t) = \begin{bmatrix} \tau_x C\alpha - \tau_z S\alpha \\ \tau_x S\alpha S\gamma + \tau_y C\gamma + \tau_z C\alpha S\gamma \\ \tau_x S\alpha\, C\gamma - \tau_y S\gamma + \tau_z C\alpha C\gamma \end{bmatrix}.$$

As result of using proposed correction, operator can control desired torque vector $\tau(t)$ without considering the appearance of arbitrary angles of roll α and trim γ. Thus, developed system should provide UV movement in desired direction in SC $X_aY_aZ_a$.

4. Investigation of system

Mathematical model [3] was used for research of functioning and effectiveness of system of correction of UV linear displacements. Mathematical model has been simplified to six differential equations describing only the translational motion of UV:

$$M\dot{v} + D(v)v + g(\eta) = \tau^*(t),$$

$$\dot{\eta} = J(\eta)\, v(t)\,,$$

where $M \in R^{3\times3}$ - mass of UV and added mass of fluid matrix; $D(v) \in R^{3\times3}$ - hydrodynamic forces matrix; $g(\eta) \in R^3$ - vector of hydrostatic forces; $v(t) = [v_x, v_y, v_z]^T$ - vector of current speed of UV translational motion in SC $X^*Y^*Z^*$; $J(\eta) \in R^{3x3}$ - matrix of transition from SC $X^*Y^*Z^*$ to SC $X_aY_aZ_a$; $\eta = [x_a, y_a, z_a]^T$ - position vector of point C in SC $X_aY_aZ_a$.

UV model parameters have next variables: $m_a = 300\ kg$ - mass of UV; $\lambda_{11} = 120\ kg$, $\lambda_{22} = 140\ kg$, $\lambda_{33} = 140\ kg$ ($\lambda_{ij} = 0,\ i \neq j,\ i,j = \overline{(1,3)}$) - corresponding added mass; $Y_c = 0.02\ m$ – metacentric height of UV; $d_{1x} = 40\ kgc^{-1}$, $d_{1y} = 50\ kgc^{-1}$, $d_{1z} = 50\ kgc^{-1}$ - viscous friction coefficients which correspond to linear dependence of hydrodynamic forces on UV speed on its segregate degrees of freedom; $d_{2x} = 15\ kgm^{-1}$, $d_{2y} = 25\ kgm^{-1}$, $d_{2z} = 25\ kgm^{-1}$ viscous friction coefficients which correspond to quadratic dependence of hydrodynamic forces on UV speed.

With funds of adaptive correction [1] all thrusters of UV are presented in form of aperiodic elements of first order with constant time $T_d = 0.1c$ and amplification coefficients $K_d = 2$. In the model it described by corresponding differential equations of first order.

When modeling UV has α = 30^0, and $\tau(t) = [15,0,0]^T$. In this case, UV should move along straight line in horizontal plane of SC $X_aY_aZ_a$. Simulated movement of UV in SC $X_aY_aZ_a$ shown on Fig. 2. Movements x_{a1} and z_{a1} correspond to UV movement without use of synthesized system. Movements x_{a2} and z_{a2} correspond to UV movement with use of synthesized system.

This figure shows that presence of unaccounted trim leads to unplanned UV displacements along axis Z_a on 10m during 70s. Using synthesized correction which forms vector $\tau_p(t)$ allows 6.6 times reduce offset z_{a2} along axis Z_a from prescribed straight-line trajectory of its motion. But this offset still reaches 1.5m. Reason of it is asymmetry of UV and different values of added mass of fluid and viscous friction coefficient when UV moves for different degrees of freedom.

If these minor deviations in UV movement are unacceptable, it can be eliminated by operator or automatically by additional correction of vector $\tau(t)$. At automatic correction of thrust vector it is advisable to use information about current direction of velocity vector $v(t)$ which is determined by absolute Doppler log. System that provides automatic correction of vector $\tau(t)$ using absolute log will be discussed below.

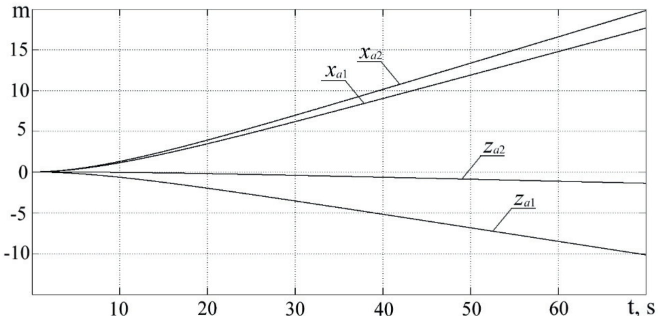

Fig. 2. Translational motion of UV.

5. Additional automatic correction of thrust vector of UV

Modern Doppler logs can accurately identify elements of vector $v(t)$ in SC $X^*Y^*Z^*$ [11]. At displacement of actual motion direction of UV, which has non-zero angles α and γ, from desired direction given by vector $\tau_p(t)$ in SC $X^*Y^*Z^*$, between vectors $v(t)$ and $\tau_p(t)$ appears non-zero angle $\varphi = \arccos\left(\frac{\tau_p(t)\, v(t)}{\|\tau_p(t)\|\,\|v(t)\|}\right)$ (see Fig. 3). Obviously, for UV movement in direction determined by vector $\tau_p(t)$, CS of UV should provide nulling angle φ. CS makes it by forming a new thrust vector $\tau_d(t) = \tau_p(t) + \tau_k(t) \neq \tau_p(t)$, which lies in plane which created by vectors $\tau_p(t)$ and $v(t)$ (see Fig. 3), where $\tau_k(t) = k\,\frac{\mu(t)}{\|\mu(t)\|} \in R^3$ - additional thrust vector which is perpendicular to vector $\tau_p(t)$ and directed towards compensation angle φ and lies in same plane as vectors $\tau_p(t)$, $v(t)$; k - positive coefficient which value gets out experimentally taking into account construction of UV; $\mu(t) = \tau_l(t) - v(t) \in R^3$ - vector defining direction of vector $\tau_k(t)$; $\tau_l(t) = \frac{\tau_p(t)}{\|\tau_p(t)\|}\|v(t)\|\cos\varphi$. If $\|\mu(t)\| = 0$ then CS of UV forms vector $\tau_k(t) = 0$. If $\|\tau_p(t)\| = \|v(t)\| = 0$ then angle φ is not calculated as UV has no movement.

Block diagram of automatic servo-loop system that ensures condition φ →0 is shown on Fig. 4. Following notation introduced in Fig. 4: VFU –unit of forming of vector $\tau_p(t)$ according to expression (1); H - gyro unit for measuring angles α and γ; AL - absolute Doppler log; PS - propulsion system of UV; CU1 - unit of calculation of angle φ; CU2 – unit of calculation of vector $\tau_k(t)$; $\tau_d^*(t)$ - real thrust vector which generated by UV propulsion system and acting on UV in process of movement; $f(t) \in R^6$ - vector of external forces and torques which affects on UV and leads to appearance of non-zero angles α and γ.

6. Investigation of system of complex correction of UV thrusts

Results of numerical simulation of linear UV displacement along horizontal plane with using synthesized complex control system are shown on Fig. 5. In the beginning of movement and further UV had invariable angle of trim ($\alpha = 30^0$), $k = 10$ and driver unit forms the desired thrust vector $\tau(t) = [15,0,0]^T$ in the SC XYZ .

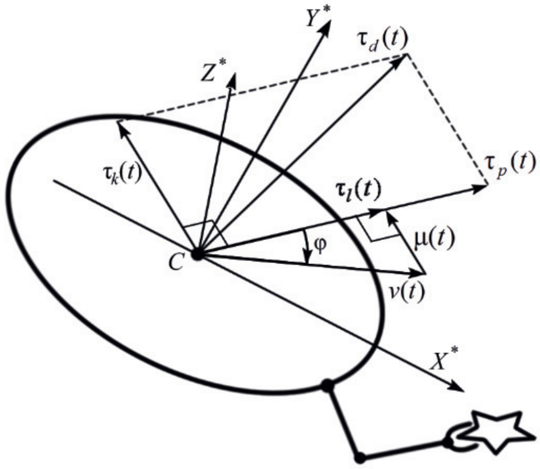

Fig. 3. UV and corrected thrust vector.

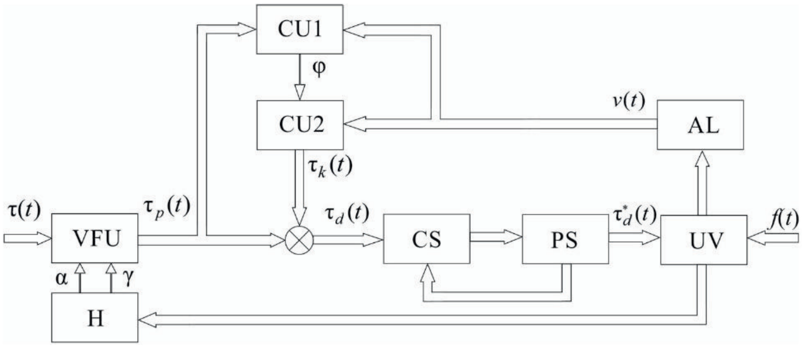

Fig. 4. Generalized scheme of synthesized system.

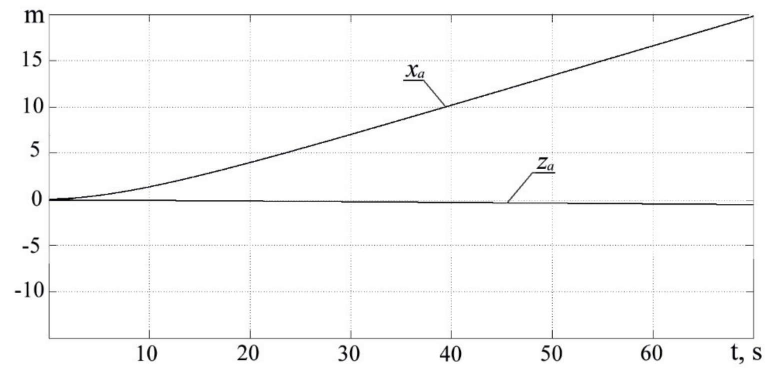

Fig. 5. Simulation results of synthesized complex system of correction of linear UV displacements.

In this figure shown that even if UV has large-scale angle of trim then UV moves with high accuracy in horizontal plane in direction which define by vector $\tau(t)$. Deviation of UV movements in given horizontal plane does not exceed 0.3m during 70s. This deviation occurs due to dead zone in determination of value of φ [12]. In view of simulation results it can be argued that use of synthesized complex control system allows to automatically consider and successfully compensate influences of angles of roll and trim when desired UV linear movement to the target.

Conclusion

In this paper the method of synthesis of systems of automatic correction of UV linear displacements was viewed. At presence of arbitrary non-zero values of angles of roll and trim proposed system automatically changes corresponding thrusters thrusts depending on current values of said angles. It provides high-accuracy UV moving along given direction in absolute SC.

Developed system has simple practical implementation and does not require installation of additional equipment and navigation systems for UV.

The results of mathematical simulation confirm high precision and efficacy of proposed system of automatic correction of UV linear displacements.

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