Study of Maneuverability the AUV flexibly Coupled to the Surface Repeater

V V Kostenko¹, I G Mokeeva¹, A Yu Tolstonogov¹

¹Institute for Marine Technology Problems FEB RAS, 5a Sukhanova Street, Vladivostok 690091, Russia

E-mail: kosten.ko@mail.ru

Abstract. The towed surface radio communication module (SRCM) allows the high-speed communication channel between the control station and an autonomous underwater vehicle (AUV) to be organized and significantly simplifies the navigation support. Herewith, disturbances by the communication cable acting on the SRCM and AUV are significantly affecting the whole system's parameters. The paper aims to calculate the additional drag force acted on the vehicle by affecting the towed SRCM and communication cable on the AUV in steady conditions and along typical maneuvering trajectories. A model of an underwater tethered motion control system considers the AUV dynamics, and the communication cable is proposed. A kinematic model of the SRCM has been developed. This model determines the submerging of the communication module and hydrodynamic resistance during towing. The paper presents the results of modeling the tethered system's movement along typical trajectories typical for survey-search AUV. The results allow the additional requirements to the vehicle's propulsion system and the required additional buoyancy of the SRCM to be obtained.

1. Introduction

It is possible to increase the AUV work efficiency by providing high-speed communication with the operator's station in real-time. Simultaneously, it becomes possible to quickly obtain large amounts of information accumulated by vehicle equipment during the survey. The surface radio communication module solves this problem and allows refining the AUV global position [1-6] based on the satellite navigation system (SNS).

This technical solution makes it possible to carry out underwater works in areas without a hydroacoustic navigation system. The errors in determining coordinates accumulated by the vehicle's onboard navigation system are proposed to periodically correct using the float GPS/GLONASS system installed on the SRCM. However, significant forces disturbing on the vehicle by the communication cable and SRCM are noticeable. It affects the maneuverability and movement accuracy along a given trajectory of the vehicle.

The research aims to evaluate the parameters of the AUV movement and disturbances by towing the SRCM. To achieve this goal, it is necessary to develop the tethered system's structure and simulate the tethered motion system along typical trajectories of the AUV survey based on the well-known dynamic models of the SRCM, the communication cable, and the AUV.
2. Model of the Tethered System Motion Control

Figure 1 shows the structure of the control system aimed to simulate the tethered system.

Figure 1 uses the following notation:
- $\lambda$ is vector of added masses and moments of inertia of an AUV;
- $m_a$, $Q_a$, $M_o$ are mass, residual buoyancy and moment of stability of the vehicle, respectively;
- $H$, $V$, $\varphi$, $\psi$ are target values for AUV depth, velocity, heading, and pitch, respectively;
- $u = [u_x, u_y, u_\varphi, u_\psi]^T$ is the motion control vector;
- $F_{DPK} = [F_{dx}, F_{dy}, F_{d\varphi}, F_{d\psi}]^T$ is the vector of control actions for the propulsion system;
- $F_{res} = [R_{sx}, R_{sy}, R_{sz}, M_{sx}, M_{sy}, M_{sz}]^T$ is the vector of hydrodynamic forces and moments of a vehicle;
- $R_{sx}$ is hydrodynamic resistance force of the SRCM;
- $Q_n$ is the maximum residual buoyancy of the fully submerged SRCM;
- $F_x = [F_{rx}, F_{ry}, F_{rz}]^T$ is vector of disturbance force of the cable to the vehicle;
- $v_a = [v_{ax}, v_{ay}, v_{az}]^T$ is vector of linear velocities of the vehicle in the body reference frame;
- $\omega_a = [\omega_{ax}, \omega_{ay}, \omega_{az}]$ is vector of angular velocities of the vehicle in the body reference frame.

The method for calculating the response at the ends of a cable connection is based on solving nonlinear differential equations of an elastic thread's dynamics with partial derivatives for independent variables - the arc coordinate and time [11,12]. In this case, the differential equations of motion of the thread are integrated, taking into account the initial and boundary conditions. The force effects of the SRCM due to its residual buoyancy $Q_n$ and hydrodynamic resistance $R_{sx}$ are the boundary conditions.
at the upper running end for the flexible coupling equation. The boundary conditions at the lower (root) end are the conditions for connecting the cable with the towing SRCM. The initial conditions should provide for the thread's configuration and the speed of its points at the initial moment. It can be obtained from a preliminary calculation of the statics of the cable line in a stationary flow, due to the flow rate and the absolute initial speed of movement of the AUV and SRCM. One of the approaches to constructing a mathematical model of cable dynamics is its representation in a discrete model, a system of concentrated masses connected by springs. The use of discrete models allows one to obtain dynamic equations in a system of nonlinear ordinary differential equations (ODE). This approach is the most popular in solving problems of tethered systems' dynamics with the determination of cable reactions $F_x$, $F_y$ and $F_z$ since the vehicle's dynamics are also described by the ODE system [11, 12].

As a prototype of the AUV for SRCM towing, a hybrid AUV “Chilim” developed by the Institute of Applied Mathematics and Mechanics of the Far East Branch of the Russian Academy of Sciences [13] was used.

In accordance with the functional purpose, the design of the SRCM was determined (Figure 2).

![Figure 2](image_url)

**Figure 2.** The design of the towed surface radio communication module (SRCM).

The hydrodynamic resistance and buoyancy of the SRCM are dependent on its deepening level. Let $H_n$ is the immersion depth of the point $O_{w1}$ (located at the waterline of the SRCM in the absence of vertical disturbance from the cable) and $\Delta h_n$ is the additional module's draft. It corresponds to the buoyancy reserve $Q_n$ for compensation the vertical reaction of the cable $F_{yan}$. Figure 3 illustrates the forces acting on the SRCM during towing at the steady speed for the vertical cable response's boundary values.
Figures 3. Forces acting on the SRCM during towing, (Left image corresponds to $F_{y_{0}} = 0$ N, right one corresponds to $F_{y_{0}} = Q_{n}$).

Figure 3 uses the following notation:

- $Q_{m}$ is the center of mass of the SRCM;
- $O_{d1}$ is center of volume of the SRCM at minimum draft ($F_{y_{0}} = 0$ N);
- $O_{c2}$ is center of volume of the SRCM at maximum draft ($F_{y_{0}} = Q_{n}$);
- $O_{w1}$ is waterline level of SRCM at $F_{y_{0}} = 0$ N;
- $O_{w2}$ is waterline level of SRCM at $F_{y_{0}} = Q_{n}$.

Let us take the assumption that the hydrodynamic resistance of the SRCM is linearly dependent on its depth $H_{n}$. Then the actual resistance of the module $R_{xt}^{\phi}$ can be calculated by the following ratio.

\[
R_{xt}^{\phi} = \begin{cases} 
R_{xt} \frac{\Delta h_{n} + H_{n}}{2\Delta h_{n}}, & \text{at } 0 \leq H_{n} < \Delta h_{n}, \\
R_{xt}, & \text{at } H_{n} \geq \Delta h_{n},
\end{cases}
\]

(1)

where $R_{xt}$ is the maximum value of the hydrodynamic resistance of the SRCM according to the formula (2) under the condition $H_{n} = \Delta h_{n}$:

\[
R_{xt} = 0.5 \cdot C_{xt} \cdot \rho \cdot V_{c}^{2} \cdot U_{n}^{2/3},
\]

(2)

where:
- $C_{xt}$ is coefficient of hydrodynamic resistance of SRCM;
- $\rho$ is density of water;
• $U_n$ is the displacement of a fully submerged SRCM, providing its maximum additional buoyancy $Q_n$;
• $V_c$ is steady-state speed of the SRCM.

Taking the assumption about the linear dependence of the additional buoyancy of the SRCM on its deepening, we obtain the following equation.

$$
Q_n^b = Q_n \frac{H_n}{\Delta h_n}, \text{ at } 0 \leq H_n < \Delta h_n, \\
Q_n^b = Q_n, \text{ at } H_n \geq \Delta h_n;
$$

where $Q_n = 50$ N, $\Delta h_n = 0.4$ m are buoyancy and SRCM draft to compensate for the vertical reaction of the cable, respectively. The SRCM immersion depth is dependent on the vertical response, which is preliminarily determined by the dynamic cable model [12]. Taking into account the fulfillment of the requirement of sufficiency of the SRCM buoyancy reserve $F_{\text{req}} \leq Q_n$, the following equation can be written.

$$
H_n = \frac{\Delta h_n}{Q_n} F_{\text{req}}.
$$

3. Simulation of the Movement of an Underwater Tethered System

Modeling of the robotic complex consisted of the hybrid AUV “Chilim”, the communication cable, and the SRCM was carried out based on the equation of propulsion dynamics of the “Chilim” [13], the equations describing the movement of the SRCM obtained in Section 2 and the equations for vehicle movement in water [14]. The following constants were used in the simulation:

• $m_a = 30$ kg is dry weight of the vehicle;
• $\lambda_{a1} = 0.5$ kg, $\lambda_{a2} = 35$ kg, $\lambda_{a3} = 27$ kg are additional masses of the vehicle;
• $J_x = 0.2$ N·m·s$^2$, $J_y = 6.6$ N·m·s$^2$, $J_z = 6.2$ N·m·s$^2$ are axial moments of inertia;
• $\lambda_{a4} = 5$ N·m·s$^2$, $\lambda_{a5} = 30.9$ N·m·s$^2$, $\lambda_{a6} = 28.5$ N·m·s$^2$ are additional moments of inertia;
• $Q_y = +5$ N is the residual buoyancy of the vehicle;
• $M_o = 15$ N·m is the moment of stability of the vehicle.

Hydrodynamic positional forces $R_x, R_y, R_z$ and moments $M_{ax}, M_{ay}, M_{az}$ were determined based on the results of flowing simulation the 3D model of the vehicle [13].

During the simulation, the "meander" trajectory of the vehicle survey was carried out. At the initial stage, both the AUV and the SRCM were located on the surface at 20 meters between each other. After that, the vehicle has submerged on 10 meters’ depth and went forward 50 meters long with 1 m/s velocity and further went along the "meander" trajectory. Figure 4 illustrates the obtained simulation results. The blue line denotes the trajectory of the SRCM movement on the top plot in Figure 4, the red line indicates the trajectory of the AUV, and the dashed line shows the communication cable between them.
Figure 4. The results of movement modeling of the tethered system along the “meander” trajectory at 1 m/s velocity.

4. Conclusion
The following conclusions could be obtained based on the results of the research.

- The structure of the motion control system model of the tethered system was proposed. The models of the dynamics of the underwater vehicle, its propulsion system, the cable communication line, and the surface radio communication module were determined.
- The maneuvering parameters of the AUV and SRCM and the force reactions at the ends of the communication cable under typical survey mode of the AUV were determined during the modelling.
- The total disturbance force by towing the SRCM during vehicle moving in a horizontal plane along the "meander" trajectory at 1 m/s velocity at a depth of 10 m does not exceed 20 N.

5. References
[1] Kraige Dave Retractable UUV Antenna Buoy with Smart Tether GPS KCF Technologies, US Naval Sea Systems Command SBIR 04: T020
[2] Race Roger E, Jacob C Piskura and David S 2014 Sanford Towed antenna system and method U.S. Patent No 8,813,669
[3] Retractable UUV Antenna Buoy with Smart Tether GPS KCF Technologie Inc, 2011 (www.kcftech.com, 24.07.2017)
[4] Nishida, Yuya, Junichi Kojima, Yuzuru Ito, Kenkichi Tamura, Harumi Sugimatsu, Kangsoo Kim, Taku Sudo, and Tamaki Ura 2015 Development of an autonomous buoy system for AUV" In OCEANS 2015-Genova pp 1-6 (IEEE)
[5] Kostenko V V, Lvov O Yu 2017 Combined systems of communication and navigation for autonomous underwater robot equipped with a float towed unit Podvodnye issledovaniya i robototekhnika 1(23) pp 31-43
[6] Bykanova A Yu, Kostenko V V, Lvov O Yu 2017 Varianty primeneniya poplavkovogo modulya svyazi i navigacji v sostave podvodnyh robototechnicheskikh kompleksov Proceedings of the 7th Scientific and Technical Conference “Technical Problems of the World Ocean Development” (Russia, Vladivostok) pp 112-118 ISBN 978-5-600-01917-1

[7] Kostenko V V, Mokeeva I G 2009 Study of the influence of a communication cable on the maneuverability of a remotely controlled underwater vehicle Podvodnye issledovaniya i robototekhnika 1(7) pp 22-27

[8] Kostenko V V, Mokeeva I G, Tolstonogov A Yu 2017 Features of motion control of AUV with towed equipment (in russian) Proceedings of the 7th Scientific and Technical Conference “Technical Problems of the World Ocean Development” (Russia, Vladivostok) pp 361-366 ISBN 978-5-600-01917-1

[9] Inzartsev A V, Kiselev L V, Kostenko V V, Matvienko Yu V, Shcherbatyuk A F Underwater Robotics: Systems, Technologies, Application IMTP FEB RAS (Vladivostok) p 368 ISBN 978-5-7311-0486-79

[10] Kostenko V V, Tolstonogov A Yu, Mokeeva I G 2019 The Combined AUV Motion Control with Towed Magnetometer 2019 IEEE Underwater Technology (UT)

[11] Kostenko V V, Mokeeva I G 2013 Modelirovanie dinamiki tipovyh rezhimov dvizheniya privyaznoj sistemy «TNPA – kabel' svyazi» Proceedings of the 5th Scientific and Technical Conference “Technical Problems of the World Ocean Development” (Russia, Vladivostok) pp 382-388 ISBN 978-5-8044-1409-3

[12] Kostenko V V, Mokeeva I G, Tolstonogov A Yu 2018 Control the movement of autonomous unmanned underwater vehicle with a towed magnetometer IZVESTIYA SFedU. ENGINEERING SCIENCES 1(195) pp 78-89

[13] Goy V A, Kostenko V V, Naidenko N N, Mihaiov D N, Rodkin D N 2015 Opyt razrabotki i ispytanyi teleupravlyaemogo neobitaemogo podvodnogo apparata s avtonomnym istochnikom pitaniya Proceedings of the 6th Scientific and Technical Conference “Technical Problems of the World Ocean Development” (Russia, Vladivostok) pp 101-106 ISBN 978-5-8044-1363-2

[14] Kiselev L V, Matvienko Yu V, Inzartsev Yu V, Inzartsev A V 2006 O nekotoryh zadachah dinamiki i upravleniya prostranstvennym dvizheniem ANPA Podvodnye issledovaniya i robototekhnika 2(2) pp 13-26

Acknowledgements
Developing the tethered motion control system model was conducted under the support of the Ministry of Science and Education grant, Russian Federation 13.1902.21.0012 “Fundamental Problems of Study and Conservation of Deep-Sea Ecosystems in Potentially Ore-Bearing Areas of the Northwestern Pacific.”