On the Behavior of an Underwater Remotely Operated Vehicle in a Uniform Current

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This paper presents a series of analyses on the behavior of an underwater remotely operated vehicle (ROV) with the umbilical cable in uniform current. The hydrodynamic mathematical model including the coupled effect of the current and the umbilical cable is proposed here to deal with 6 degrees of freedom motions of the ROV. Because of the umbilical cable on the ROV, the present problem is the two-point boundary value problem with respect to a set of first-order ordinary differential equation systems, which are solved by applying the multistep shooting method. The corresponding hydrodynamic coefficients of the underwater vehicle used in the hydrodynamic model are obtained by the planar motion mechanism (PMM) test technique. Three different current speeds are considered to investigate the current effect on the ROV's operations including forward motion, ascending motion, and descending motion. The present results reveal that the current indeed significantly affects the operations of the ROV, and the mathematical numerical model developed here can serve as a useful tool to offer some valuable information for the anticurrent ROV design.

Keywords: hydrodynamics (general); maneuvering; unmanned marine vehicles

1. Introduction

In order to observe the underwater environment and execute complex technical work in the ocean, the underwater remotely operated vehicle (ROV) is one of the necessary and important underwater technical systems that can achieve such missions. Recently, the related researches and designs for the ROV have been well made by many researchers. For example, Deam and Given (1983) summarized the vast research on the ROV and proposed five steps to develop the ROV. Nomoto and Hattori (1986) also made a detailed analysis on the performance of the deep-ocean ROV, JAMSTEC Dolphin 3K, whose main mission is to support the manned submersible, Deep Ocean 2000, to investigate the operational location at the water depth 3,300 m. Their technical analyses were also extended to the JAMSTEC Kaiko, and the maximum operation depth could reach 11,000 m.

Generally the deep-sea-operated vehicle systems typically consist of a large support vessel, a winch, umbilical cable, and ROV. However, most of the numerical models for predicting the motion of the ROV neglect the umbilical cable and current effects because of complexity and difficulty. Therefore, only few authors deal with this kind of problem including the effects due to the umbilical cable and current. Ablow and Schechter (1983) proposed an implicit finite difference method to simulate an underwater cable, which has been frequently referenced in the relevant literatures. However, their algorithm will become singular if the tension in the cable is lost. Burgess (1992) indicated the internal forces generated by the cable curvature could avoid the singular behavior of the implicit finite difference scheme, which was made by implementing three additional rotational equations of motion. Burgess (1994) also carried out several studies on the current effect on marine cable deployment. He found a significant variation in the current profile for different locations and time. Banerjee (1995) developed an underwater cable dynamics model and a realistic control system that allows deployment, regulation, and retrieval of an unmanned underwater vehicle tethered to a ship. His algorithm can be used to answer many design questions related to the operation of ROV. Recently, Feng and Allen (2004) extended the numerical scheme developed by Milinazzo et al. (1987) and presented a finite difference method to evaluate the effects of the umbilical cable on an underwater flight vehicle, which showed that the numerical scheme is effective and provided a means for developing a feed-forward controller to compensate for the cable effects.

As we know, most of ROVs are operated smoothly only in weak current, and few are designed with the anticurrent capability, which is an important function to the ROV in the special ocean circumstance. In order to offer enough information on the current effect to the design of anticurrent ROV, a mathematical model including the coupled effects of the cable and current is necessary. Besides, the numerical technique for simulating the ROV maneuvering behavior is also important. The general nonlinear model for the dynamics of ROV can be derived either using a Newtonian or a Lagrangian method (Coute & Serrani 1996, Fossen 1994). In order to understand the behavior of the underwater vehicle maneuvering in the ocean current, the mathematical model with the umbilical cable effect based on the formulas with 6 degrees of freedom motions (Fossen 1994) is formulated here. The corresponding hydrodynamic coefficients about the maneuvering characteristics of the ROV are obtained by planar motion mechanism (PMM) test technique (Hou 2005). The corresponding two-point boundary-value problem with respect to the umbilical cable connecting to the ROV is solved by the multistep shooting method, which based on the search method developed by Hooke and Jeeves (1961). The compact hydrodynamic model with 6 degrees of freedom motions and the numerical solution technique are described in the following sections.
2. Mathematical model

The motions of the underwater vehicle are analyzed by two coordinate systems shown in Fig. 1, that is, the inertial coordinate system O-XYZ and the body-fixed coordinate system o-xyz. Three translation displacements, X (surge), Y (sway), Z (heave), and three Euler angles, roll (ϕ), pitch (θ), and yaw (ψ), represent the position and attitude of the underwater vehicle with respect to the inertial frame, respectively. The instantaneous velocity and angular velocity with respect to body-fixed frame are represented by (u, v, w) and (p, q, r), respectively. The velocities of the ROV can be solved by the following 6 degrees of freedom equations of motions.

2.1. Surge

\[ (m - X_W)\ddot{u} + mz_G q - my_G r = -m(y_G q + z_G r) \]
\[ + (mx_G - mw + Z_W)q + (mx_G + mw - Y_W)\dot{r} \]
\[ + (X_w + X_{ub})u - (W - B)\sin \theta + F_{Tx} + F_{Cx}(1) \]

2.2. Sway

\[ (m - Y_W)\ddot{v} - mz_G p + mx_G r = p(mz_G p + mw - Z_W)u \]
\[ + q(mx_G + mw - X_W)u - mw(x_G p + y_G q) \]
\[ + (Z_w + Z_{wub})\dot{v} - (W - B)\cos \theta \sin \phi + F_{Ty} + F_{Cy}(2) \]

2.3. Heave

\[ (m - Z_W)\ddot{w} + y_G q - x_G p = p(mz_G p + mw - Z_W)u \]
\[ + q(mx_G + mw - X_W)u - mw(x_G p + y_G q) \]
\[ + (X_w + X_{ub})\dot{w} - (W - B)\cos \theta \cos \phi + F_{Tz} + F_{Cz}(3) \]

2.4. Roll

\[ -mz_G q + my_G p + (I_z - K_p)\dot{p} - I_{xy} q - I_{xy} r = \]
\[ u(x_G q - y_G p) - u(mz_G p - mw - Y_W) \]
\[ + (I_{xy} + I_{xy} - I_{xy} + N_r)q - (I_{xy} q + I_{xy} p - I_{xy} q) \]
\[ + M_G q) + (K_q + K_{qq})p + (K_r W - y_B W)\cos \phi \cos \psi - (x_B W - x_B B)\sin \phi \cos \psi + M_{Tz} + M_{Cy}(4) \]

2.5. Pitch

\[ mz_G q - mx_G p + (I_y - M_q)\dot{q} - I_{xy} r = \]
\[ -u(mz_G p - mw + Z_W) - u(mx_G + y_G q) + u(z_G q + x_G p + X_W u) \]
\[ - mx_G - mu - (I_{xy} q + I_{xy} p + I_{xy} r + N_r)q + (I_{xy} q + I_{xy} p + I_{xy} r + N_r) q \]
\[ + I_{xy} q - I_{xy} p + K_q)q + (M_q - M_{qq})p + (x_G W - x_B B)\cos \phi \cos \psi + M_{Tz} + M_{Cy}(5) \]

2.6. Yaw

\[ -my_G q + mz_G p - I_{xy} q + (I_z - N_r)\dot{r} = \]
\[ -u(mx_G r + mw - Y_W) - u(mx_G q) + u(y_G q + X_W u) \]
\[ + (I_{xy} q + I_{xy} p + I_{xy} r + K_q) p + (I_{xy} q + I_{xy} p + I_{xy} r + K_q) p \]
\[ - (I_{xy} q + I_{xy} p + I_{xy} r + K_q) p + (I_{xy} q + K_q) p + (x_G W - x_B B)\cos \phi \cos \psi + (y_G W - y_B B)\sin \theta \]
\[ + M_{Tz} + M_{Cy}(6) \]

The velocities of the ROV are assumed to be small, and therefore some coupling terms are neglected in equations (1) to (6). m and I are the mass and related mass moment of inertia, respectively. The definitions of all hydrodynamic coefficients about the maneuvering characteristics are related variables of the vehicle; that is, \( X_w, X_{ub}, X_{ux}, Y_w, Y_{ux}, Y_{uw}, Z_w, Z_{uw}, Z_{uw}, K_p, K_{pq}, K_{q}, M_q, M_{pq}, M_{qq}, P_r, P_{rr}, N_r, N_{rr}, \) and so forth, are obtained by using the PAM test technique (Hou 2005). W and B are weight and buoyancy, respectively, whereas \((x_G, y_G, z_G)\) and \((x_B, y_B, z_B)\) are the center of gravity and the center of buoyancy, respectively. The variables \((F_{Tx}, F_{Ty}, F_{Tz}, M_{Tz}, M_{Ty}, M_{Tz})\) and \((F_{Cx}, F_{Cy}, F_{Cz}, M_{Cz}, M_{Cy}, M_{Cz})\) are forces and moments due to the thruster and the umbilical cable, respectively, and are described below.

2.7. Force and moment on the ROV caused by the thruster

The ROV model (the Deep Ocean Triggerfish) considered in the present study, is equipped with four thrusters as shown in Figs. 2 and 3; that is, \( T_1, T_2, T_3, T_4 \) are installed horizontally and are responsible for the forward motion, while \( T_3 \) and \( T_4 \) are installed vertically with inclined angle \( \theta_T \) to induce sideward, ascending, and descending motions. Assume \((z_{ct}, y_{ct}, x_{ct})\) is the center of the \( i \)th thruster, then the co-

Fig. 1 The coordinate systems for underwater vehicle

Fig. 2 The top view scheme for the thruster arrangement

Fig. 3 The after view scheme for the thruster arrangement
responding resultant force and moment induced by each thruster can be obtained by
\[
F_T = F_{T_1} + F_{T_2} + F_{T_3} = (T_1 + T_2) \hat{i} + (T_3 - T_4) \cos \theta \hat{j} + (T_3 + T_4) \sin \theta \hat{k}
\]
(7)
\[
M_T = M_{T_1} + M_{T_2} + M_{T_3} = (y_c T_3 \sin \theta - x_c T_3 \cos \theta + y_c T_4 \sin \theta + x_c T_4 \cos \theta) \hat{i} + (x_c T_1 + x_c T_2 - x_c T_3 \sin \theta - x_c T_3 \cos \theta) \hat{j} + (y_c T_3 \cos \theta - y_c T_4 \sin \theta) \hat{k}
\]
(8)
where \(\theta\) is set to be 45 deg in the present study. The relationship between the thrust force and the revolution of the propeller rps is obtained using the regression method and shown as below
\[
T_1 = T_2 = -0.0002 \text{ rps}^4 + 0.4164 \text{ rps}^2
\]
(9)
\[
T_3 = T_4 = -0.0015 \text{ rps}^4 + 0.8027 \text{ rps}^2
\]
(10)

2.8. Force and moment on the ROV caused by the umbilical cable including the current effect

The umbilical cable plays an important role in offering the power supply and communication function between the ROV and the support vessel. However, the management and attachment of the cable and the drag relative to the current cause some restrictions on maneuverability of the ROV. Therefore, the estimation of the corresponding effect caused by the umbilical cable and the current will be helpful while we are doing the analysis on the ROV's maneuvering behaviors. However, most researchers neglect the effect of the umbilical cable because of the complexity, especially including the current effect. In the present study, for simplifying the problem, the following assumptions are made to solve the corresponding configuration and tension of the umbilical cable attached to the ROV:

- The umbilical cable is inextensible
- The umbilical cable can only resist tension force, not for bending moment and compression force.
- The hydrodynamic force on the umbilical cable can be resolved into tangential component and normal component.

The coordinate system for analyzing the umbilical cable is shown in Fig. 4. The \(\overline{z}\)-axis is assumed to coincide with the \(\overline{x}\)-axis. The origin \(\overline{O}\) coincides with the end point of the umbilical cable. \(\theta\) is the angle between \(\overline{xOz}\) plane and the plane which includes the tangential line passing through the point \(\overline{A}\) and perpendicular to \(\overline{xOy}\) plane. \(\varphi\) is the angle between the tangential line passing through the point \(\overline{A}\) and \(\overline{xOy}\) plane. \(i_x, i_y, i_z\) are the unit vector along the cable length \(s\), \(\theta\), and \(\varphi\), respectively, and perpendicular to each other. Both \(i_x\) and \(i_z\) are located on the vertical plane.

Considering the configuration of the umbilical cable and the equilibrium state of the external force on the cable, we can obtain the following linear differential equations
\[
\frac{d\overline{z}}{ds} = \cos \varphi \times \cos \theta
\]
(11)
\[
\frac{dy}{ds} = \cos \varphi \times \sin \theta
\]
(12)
\[
\frac{dz}{ds} = \sin \varphi
\]
(13)
\[
\frac{dT}{ds} = w \sin \varphi - R_s
\]
(14)
where \(s\) is the arc length from the origin to the point \(\overline{A}\) on the cable. \(T\) is the tension force along the cable. \(w\) is the cable weight per unit length in the water. \(R_x, R_y, \text{ and } R_z\) are the forces per unit length due to the current in \(i_x, i_y, \text{ and } i_z\) directions, respectively, and defined as:
\[
R_x = \frac{1}{2} \rho C_l V^2 \sin \psi \cos \psi |\sin \psi| \cos \varphi
\]
(17)
\[
R_y = R_{nx} \cos \left(\varphi - \frac{\pi}{2}\right) + R_{ny} \sin \left(\varphi + \frac{\pi}{2}\right)
\]
(18)
\[
R_z = R_{nx} \cos \varphi \cos \left(\varphi + \frac{\pi}{2}\right) + R_{ny} \sin \varphi \cos \left(\varphi + \frac{\pi}{2}\right) + R_{nz} \sin \left(\varphi + \frac{\pi}{2}\right)
\]
(19)
in which
\[
R_{nx} = \frac{1}{2} \rho C_n V^2 \sin \psi |\sin \psi| \cos \left(\psi - \frac{\pi}{2}\right)
\]
(20)
\[
R_{ny} = \frac{1}{2} \rho C_n V^2 \sin \psi |\sin \psi| \sin \left(\psi - \frac{\pi}{2}\right) \cos \gamma
\]
(21)
where \( \rho \) is the water density, \( t \) is the diameter of the cable, \( C_n \) is the normal drag coefficient, \( C_r \) is the tangential drag coefficient, \( V \) is current velocity relative to the cable, \( \psi \) is the angle between current and cable, \( \gamma \) is the angle between \( \hat{x} \) plane and the plane composed of \( i \), direction and current direction. The direction of the current is assumed to be coincident with the \( X \)-axis.

Applying the fourth Runge Kutta numerical method to the equations (11) to (16), we can solve the tension force \( T \) on the cable and the related plane angles, \( \theta \) and \( \varphi \). Then the components of the tension force and moment, that is, \( (F_{xT}, F_{yT}, F_{zT}, M_{xT}, M_{yT}, M_{zT}) \), with respect to body-fixed system can be obtained by the coordinate transformation.

The current force effect on ROV can be considered by using the relative velocity \( v_r \), to replace the ROV velocity \( v \) in the equations of motions, that is, \( v_r = v - v_c \), where \( v_c \) is the current velocity.

Besides, the underwater length of the umbilical cable considered here is assumed to be released from a winch drum with feed-forward controller, and therefore the cable length will change with the ROV motions. The releasing model of the cable can be referred to Feng and Allen (2004).

Because the equations (11) to (16) are a set of first-order ordinary differential equation system with the two-point boundary-value problem, it is rather difficult to solve the solution. Here, based on the direct search method (Hooke & Jeeves 1961), a multistep shooting method is applied to solve this problem:

1. Select the connected point between the umbilical cable and the ROV as the start point and assign its initial value of \( (T, \theta, \varphi) \) and the multistep intervals of \( \Delta T, \Delta \theta, \Delta \varphi \) for each variable.
2. Calculate the solution of the other end point of the cable at free surface near the support ship, i.e., \( (\bar{x}, \bar{y}, \bar{z}) \), with respect to an initial decreasing or increasing step interval, i.e., \( (T + \Delta T, \theta + \Delta \theta, \varphi + \Delta \varphi), (T - \Delta T, \theta - \Delta \theta, \varphi - \Delta \varphi) \), and compare with those obtained from the values of \( (T, \theta, \varphi) \). Then select the better one whose value is closer to the exact coordinate of the object point as the new base point, for example, \( (T, \bar{\theta} + \Delta \bar{\theta}, \bar{\varphi}) \).
3. Restart the new base point selected at Step (2), move further step intervals to calculate another function value of objective points, i.e., \( (T + \Delta T, \theta + \Delta \theta, \varphi), (T - \Delta T, \theta - \Delta \theta, \varphi) \), and again compare with the base point \( (T, \bar{\theta} + \Delta \bar{\theta}, \bar{\varphi}) \) to track the better one as the new next base point, for example, \( (T, \bar{\theta} + \Delta \bar{\theta}, \bar{\varphi} - \Delta \bar{\varphi}) \).
4. Repeat the Step (3) with the further step intervals for each variable and track the better one until the function values of variables with respect to all possible increments and decrements are tested.
5. If the above local shooting is invalid, then reduce the step interval to half, i.e., \( (\Delta T_{\text{new}} = \Delta T/2), \Delta \theta_{\text{new}} = \Delta \theta/2), \Delta \varphi_{\text{new}} = (\Delta \varphi/2) \), and repeat the above similar local shooting procedure.
6. Repeat the Step (5) until the errors of the ith step intervals are sufficiently small or equal the allowable error limit, i.e., \( \Delta T_i \leq \varepsilon_i, \Delta \theta_i \leq \varepsilon_i, \Delta \varphi_i \leq \varepsilon_i \), then stop shooting, and the last optimal point is the final solution.

3. Results and discussion

A commercial ROV (Deep Ocean Triggerfish), with the principal dimension of 1.09 m (length) \( \times \) 0.53 m (beam) \( \times \) 0.41 m (depth) is adopted as the numerical model for calculations. The ROV is neutrally buoyant, and its weight is 46 kg. All hydrodynamic coefficients of maneuvering characteristics and related variables for the ROV can be referred to Hou (2005), which were obtained by PMM technique. The initial umbilical cable length \( (L) \) are set to be 100 m, and corresponding initial plane angles, \( \theta = 0^\circ \) and \( \varphi = 5^\circ \), are also assumed. The initial cable conditions must be physically correct; therefore, they are determined by running the multistep shooting method once in advance. The uniform currents with speed \( U = 0.1, 0.5, \) and 1.0 m/s are considered, and the current direction is toward positive X-axis; that is, inertial coordinate system, whereas the ROV heads against the current in the present study. After running the multistep method, the initial positions of the connected point to the ROV are set at \((-96.42 \text{ m}, 0 \text{ m}, 24.74 \text{ m})\), \((-85.99 \text{ m}, 0 \text{ m}, 24.43 \text{ m})\), and \((-94.66 \text{ m}, 0 \text{ m}, 24.78 \text{ m})\) for current speed \( U \) = 0.1 m/s, 0.5 m/s, and 1.0 m/s, respectively, and the corresponding initial tension forces are set to be 31 N, 70 N, and 211 N, 70 N, and 200 N. The end point at the free surface near supported vessel is assumed to be fixed at \((0 \text{ m}, 0 \text{ m}, 0 \text{ m})\). Under the present assumptions, motions and forces for sway, roll, and yaw will not appear theoretically because the configurations of the ROV and cable in uniform current are symmetrical.

The different operations for ROV in different uniform currents, that is, forward, ascending, and descending, are shown in Figs. 5 to 17.

3.1. Forward motion

Figure 5 is the simulation of the ROV doing the forward motion in uniform current with 0.1 m/s. Both thrusters \( T_1 \) and \( T_2 \) are set to be 24 rps; that is, total thrust/weight = 0.768, and the initial ROV speed is 0.3 m/sec. The thrusters \( T_3 \) and \( T_4 \) are set to be 0 rps to make the pure forward motion. The results in Fig. 5 show that the ROV oscillates upward and the surge velocity \( u \), the heave velocity \( w \), and the
pitch angle also regularly oscillate. It means that the ROV will move forward up and down with varied pitch angle as we can see from the trajectory simulation shown in Fig. 6, which also shows the ROV gradually ascends with the increasing umbilical cable length while the ROV is moving forward. The corresponding phenomena can be ascribed to the effects of the coupled effect of cable and current. The force and moment of the umbilical cable including the current effect are shown in Fig. 7 for reference. The oscillatory surge force $F_{sc}$ causes the oscillatory surge speed, while the oscillatory heave force $F_{hv}$ and pitch moment $M_{hv}$ cause the oscillatory heave and pitch motions, respectively. However even the motion is oscillatory and the cable surge force $F_{sc}$ is mostly negative, the ROV still move forward for about 15 m in 50 sec because the current speed is only 0.1 m/s and thrust force is large enough. The results in Fig. 7 also reveal that the heave force $F_{hv}$ is on average negative, that is, upward, and consequently leads to upward heave velocity; therefore, the ROV has the tendency to ascend.

In order to investigate the effect of the current speed on the motion behavior of the ROV, the results for the stronger current with 0.5 and 1.0 m/s are also shown in Figs. 8 to 10 and Figs. 11 to 13, respectively. After comparing with the results...
If the ROV moves forward without current, the heave and pitch motion are also oscillated due to the cable effect as shown in Fig. 14. Based on the steady-state results of forward motion simulation, the amplitudes of heave and pitch motions at different current speed are also shown in Fig. 15 for reference. The results reveal that the heave and pitch motions generally become larger with current effect except current with 0.1 m/s. It is also interesting to see that heave and pitch motions have similar tendency with respect to the current speed.

3.2. Ascending motion

Because the small current does not affect the ROV motion significantly, here we only consider cases with stronger current speed, that is, 0.5 and 1.0 m/s. Figures 16 to 18 are the results for the ROV doing the pure ascending motion in uniform current with 0.5 m/s, and the thrusters $T_3$ and $T_4$ are set to be $-5$ rps, that is, total thrust/weight = 0.084, while $T_1$ and $T_2$ are set to be 0. From Fig. 16, it is interesting to find that the ROV descends instead of ascends, which means the motion of the ROV is significantly affected by the current and cable. Although the heave velocity is upward with respect to the body-fixed coordinate, the positive pitch moment makes the ROV bow up and the negative surge force makes the ROV move backward with respect to the body-fixed coordinate. Consequently, the resultant velocity makes the ROV descend as shown in Fig. 17. Therefore, it cannot achieve the ascending mission under the present operation and another operation must be considered in order to solve this problem. Since the ROV moves backward and bows up, we need to afford some forward power to resist the current effect to increase the forward speed of the ROV. Here we adjust $T_1$ and $T_2$ to 15 rps, that is, total thrust/weight = 0.37, and recalculate the results as shown in Figs. 19 to 21. The results show that the ascending motion is indeed improved by adding the forward thrust. The pitch angle is negative and small, and the forward surge velocity incorporating with the upward heave.
velocity make the ROV ascend well as shown in Fig. 20. The similar discussion can be applied to the case in the stronger current with 1.0 m/s as shown in Figs. 22 to 24, in which the larger forward thrust are also needed; that is, $T_1$ and $T_2$ are adjusted to 24 rps with total thrust/weight $= 0.768$. In this case, although the motions are significantly oscillatory especially for the pitch motion, the ascending mission of the ROV can still be achieved.

### 3.3. Descending motion

From the above results, we understand that the forward thrust is important to make the ROV maintain the suitable attitude to execute the ascending mission in uniform current. Therefore, it is concluded that it might need the same treatment for the descending mission. Here the same operation as that for ascending motion is firstly applied, that is, $T_3$ and $T_4$ are set to be 5 rps with total thrust/weight $= 0.084$, while $T_1$ and $T_2$ are set to be 15 rps with total thrust/weight $= 0.37$, for the current with 0.5 m/s. The simulations are shown in Figs. 25 to 27. Although the results show that the descending mission is successful, the descending depth is small, that is,
about 0.8 m in 30 sec. It ascribes to the small resultant downward velocity that includes the effects of heave velocity, surge velocity, and pitch angle. This fact also indicates that the downward thrust may be too small; therefore, we adjust \( T_3 \) and \( T_4 \) to 10 rps, that is, total thrust/weight = 0.29, and recalculate the results as shown in Figs. 28 to 30. From the new results, we find that the descending performance is improved and the descending depth increases about 4 m. In this case, heave velocity, surge velocity, and pitch angle finally reach a steadily constant value and so do the cable forces on the ROV, see Figs. 28 and 30. The trajectory is shown in Fig. 29, and we can see the ROV descends with a constant positive pitch angle after running about 3 sec referring to Fig. 28.

Considering the stronger current with 1.0 m/s, we first set 5 rps for the thrusters \( T_3 \) and \( T_4 \), and 24 rps for thrusters \( T_1 \) and \( T_2 \). The simulation results are shown in Figs. 31 to 33. It is again interesting to find that the ROV is ascending instead of descending, that is, Figs. 31 and 32, which means that the downward thrust force may be too small and consequently the resultant velocity due to the heave velocity and surge velocity is upward. Therefore, a new operation must be applied. Here we again adjust \( T_3 \) and \( T_4 \) to 10 rps, and it indeed works as we find in Figs. 34 to 36. From Fig. 34, we can see the ROV descends about 3.3 m, although there is some oscillatory disturbance caused by the coupled oscillatory surge, heave, and pitch motions. That means the thrust power added is sufficient to induce a downward velocity and consequently makes the ROV descend.
4. Conclusions

In the paper, a series of analyses for the maneuvering behaviors of the ROV including forward motion, ascending motion, and descending motion in uniform current have been investigated. Based on that, the following conclusions can be drawn:

When the ROV is operated to do the forward motion in uniform current, it moves not only forward but also upward gradually. The upward movement is caused by the upward heave force from the umbilical cable.

When operating the ascending motion in stronger current, we must offer not only enough upward thrust power, but also some suitable forward thrust power to resist the current effect. The similar conclusion can be applied to the case for descending motion.

The attitude of the ROV varied with the appearance of the current, which also seriously affects the operation of the ROV. However, the present study finds that the suitable thruster adjustment may improve the attitude of the ROV and make the operation smoother.

The effect of the current force on the umbilical cable will simultaneously affect ROV motions because the umbilical cable is connected to the ROV. Conclusively, both umbilical cable and ocean current indeed affect the motion behaviors of the ROV significantly and must be paid careful attention.

The strong current is a troublesome problem for the ROV's operation in the ocean. Based on the numerical model developed in the paper, we may offer some valuable information to the anticurrent technique for the operation of the ROV.

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