UUV's Hydrodynamic Modeling and its Simulation and Experimental Studies

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***Abstract*—This paper presents an UUV's hydrodynamic modeling method, where the hydrodynamic coefficients are calculated using both of theoretical and empirically-derived formulas. The vehicle is developed for the purpose of overcoming strong sea current. For this reason, the vehicle has the flattened ellipsoidal exterior and is designed to be symmetric along all three rectangular coordinates in 3D space. The calculated hydrodynamic coefficients are used in the MatLab simulation through which we can evaluate the vehicle's various performances. Also, some of experimental studies are carried out in the water tank environment to verify the vehicle's modeling.**

Keywords—UUV (Unmanned Underwater Vehicle); hydrodynamic coefficients; vehicle modeling; hydrodynamic damping; added mass

I. INTRODUCTION

In this paper, a sort of simplified simulation model for an UUV with the flattened ellipsoidal exterior as in Fig. 1 is considered. This vehicle is designed to be operated in the strong current environment [1]. For this reason, the vehicle is designed to have flattened ellipsoidal shape so as to minimize the hydrodynamic damping, and also to be symmetric along all three rectangular axes in 3D space. Under these considerations, for the vehicle's hydrodynamic damping and added mass, only diagonal components are considered. For this simplified model, the hydrodynamic coefficients are calculated using theoretical and empirically-derived formulas [2-4].

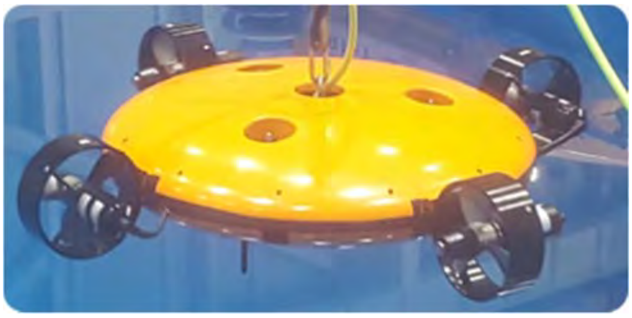

FIGURE I. UUV FLATFORM WITH THE FLATTEND ELLIPSOIDAL EXTERIOR.

One of the most important specification of this vehicle is its maximum forward speed. Simulation study using the calculated coefficients shows the maximum forward speed is up to 3.2m/s which is much larger than the 2.1m/s of experimental result in the water tank environment. At first, in the simulation, four horizontal thrusters are modeled without consideration of the fact that the maximum thrust force will be reduced in compliance with the increasing of fluid speed flow through the propeller [5]. With the consideration of this thruster's thrust saturation phenomenon, the maximum forward speed of simulation result is decreased to 2.56m/s, which is still larger than the experimental result. This difference will be analyzed in Simulation and Experimental Studies Section.

II. VEHICLE MODELING

A. Vehicle Kinematics and Dynamics

Underwater vehicle's kinematics and dynamics can be expressed as follows [1,4].

$$\dot{\eta} = C_b^n \nu, \tag{1}$$

$$M_{RB}\dot{\eta} + C_{RB}\nu = \sum F_{ext}, \tag{2}$$

where $\eta = [x, y, z, \phi, \theta, \psi]^T$ is the vehicle's position and attitude vector defined in the navigation frame (local NED-frame), and $\nu = [u, v, w, p, q, r]^T$ is the linear and angular velocity vector defined in the vehicle's body-fixed frame; C_b^n denotes the coordinate transformation matrix from the body-fixed frame to the navigation frame, and M_{RB} is rigid-body inertia matrix and C_{RB} is Coriolis and centripetal matrix. For detailed C_b^n, M_{RB}, and C_{RB}, refer to [1].

According to the vehicle's mechanical dimensions and profile parameters (refer to Appendix), the inertia moments are calculated as in Table 1.

TABLE I. INERTIA MOMENTS

Parameters	Value	Unit
I_{xx}	1.28e-001	m
I_{yy}	4.35e-001	m
I_{zz}	5.43e-001	m

In (2), the sum of external forces and moments can be expressed as

$$\sum F_{ext} = F_{hydrostatics} + F_{drag} + F_{added\_mass} + F_{control}, \tag{3}$$

where $F_{hydrostatics} = [0, 0, 0, -z_g W c\theta s\phi, -z_g W s\theta, 0]^T$ with W the rigid body weight.

B. Hydrodynamic Damping F_{drag}

As seen in Appendix, the vehicle is symmetric along all three rectangular axes. So we can neglect the movement-induced moments $A_{b|b|}$ with $A = \{K, M, N\}$ and $b = \{u, v, w\}$, and the rotation-induced forces $B_{a|a|}$ with $B = \{X, Y, Z\}$ and $a = \{p, q, r\}$ [8]. Furthermore, to simplify the vehicle's model and therefore can avoid complicated mathematical calculations, we make the following assumptions similar to [2]

- We neglect linear and angular coupled terms.
- We neglect any damping terms greater than second-order.

Consequently, hydrodynamic damping component F_{drag} is simplified as

$$F_{drag} = [X_{u|u|}u|u|, Y_{v|v|}v|v|, Z_{w|w|}w|w|, K_{p|p|}p|p|, M_{q|q|}q|q|, N_{r|r|}r|r|]^T. \tag{4}$$

Corresponding coefficients are calculated using the following formulas

$$X_{u|u|} = Y_{v|v|} = -0.5\rho c'_{dc}\pi aR - 4 \times (0.5\rho s_D c_{dD}), \tag{5}$$

$$Z_{w|w|} = -0.5\rho c_{dc}\pi R^2 - 4 \times (0.5\rho s_F c_{dF}), \tag{6}$$

$$K_{p|p|} = M_{q|q|} = 2\left[-0.5\rho c_{dc} \times \int_0^R D(r)r^3dr - 2x_{TF}^3 \times (0.5\rho s_F c_{dF})\right], \tag{7}$$

$$N_{r|r|} = 2\left[-0.5\rho c'_{dc} \times \int_0^R D'(r)r^3dr - 2x_{TD}^3 \times (0.5\rho s_D c_{dD})\right], \tag{8}$$

where all profile parameters are defined in Appendix and their calculated values are also listed in Appendix. It is worth mentioning that all axial drag coefficients in Table A-1 are derived through empirical graph as Fig. 2.4 in [3].

Calculated hydrodynamic damping coefficients are as in Table 2.

TABLE II. HYDRODYNAMIC DAMPING COEFFICIENTS

Parameters	Value	Unit
$X_{u\|u\|}$	-6.74e+001	kg/m
$Y_{v\|v\|}$	-6.74e+001	kg/m
$Z_{w\|w\|}$	-5.38e+002	kg/m
$K_{p\|p\|}$	-3.73e+001	$kg \cdot m^2/rad^2$
$M_{q\|q\|}$	-3.73e+001	$kg \cdot m^2/rad^2$
$N_{r\|r\|}$	-6.92e+001	$kg \cdot m^2/rad^2$

C. *Added Mass* F_{added_mass}

As seen in Fig. 1, due to its symmetric in all three axes, only the diagonal terms of the added mass matrix are considered in this paper. These terms are estimated through empirical graph as Fig. 4.8 in [3], and chosen as in Table 3.

TABLE III. ADDED MASS COEFFICIENTS

Parameters	Value	Unit
$X_{\dot{u}}$	-1.75e+001	kg
$Y_{\dot{v}}$	-1.75e+001	kg
$Z_{\dot{w}}$	-2.09e+002	kg
$K_{\dot{p}}$	-5.03e+000	$kg \cdot m^2/rad$
$M_{\dot{q}}$	-5.03e+000	$kg \cdot m^2/rad$
$N_{\dot{r}}$	-1.17e+000	$kg \cdot m^2/rad$

III. SIMULATION AND EXPERIMENTAL STUDIES

For conditions and parameters used in the simulation, refer to [1]. In addition to [1], in this paper we consider the fact that the thruster's maximum thrust force decreases in compliance with the increase of fluid speed flow through the propeller. According to the thruster's specifications [5], we can get the approximated relationship between the maximum thrust force versus fluid flow speed as in Fig. 2, from which we can get the following equation

$$F_{max}(U) = c_r g(0.4732U^2 - 7.2475U + 54.9799), \tag{9}$$

where F_{max} denotes the maximum thrust force, $c_r = 0.4536$ and g is the standard gravity, U is the fluid speed flow through the thruster's propeller.

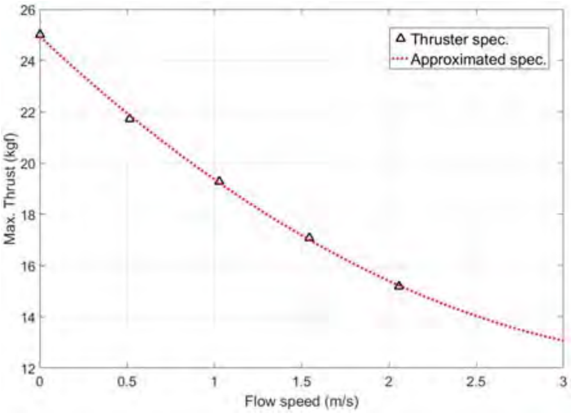

FIGURE II. HORIZONTAL THRUSTER'S MAXIMUM THRUST FORCE VS. FLOW SPEED.

Fig. 3 shows the maximum forward speed simulation result, from which we can see the maximum forward speed is up to 3.2m/s.

Also, we carry out some of experimental tests in the engineering basin, see Fig. 4. Fig. 5 shows the maximum forward speed test result while keeping vehicle's heading, from which we can see the maximum forward speed is about 2.1m/s. This speed is lower than the simulation result of 2.56m/s. One reason about this difference is that there are quite number of coupled and complicated hydrodynamic terms neglected to be included in the simulation model. The second reason is that the drag component caused by the tether cable does not considered in the simulation. In fact, during the water tank test, there is always longer than 10m of tether cable whose diameter is about

12mm submerged in the water. So the drag component caused by tether cable might be significant.

IV. SUMMARY

In this paper, a sort of hydrodynamic modeling method has been presented for an UUV. Vehicle's hydrodynamic coefficients are calculated using both of theoretical and empirically-derived formulas. MatLab based simulation study is carried out to evaluate the vehicle's various performance, also some of experimental studies are carried out in the water tank environment to verify the vehicle's modeling.

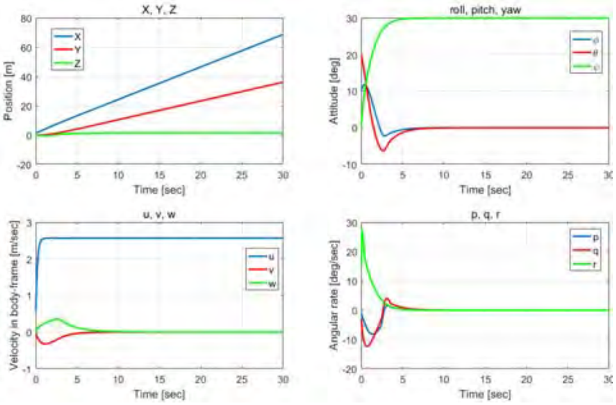

FIGURE III. VEHICLE'S MOTION INFORMATION IN THE MAXIMUM SPEED SIMULATION.

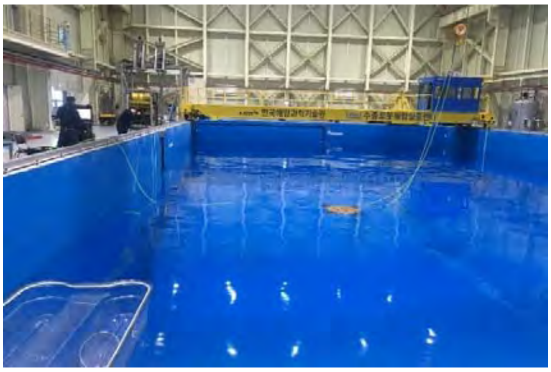

FIGURE IV. FIGURE 4. EXPERIMENTAL TEST SETUP.

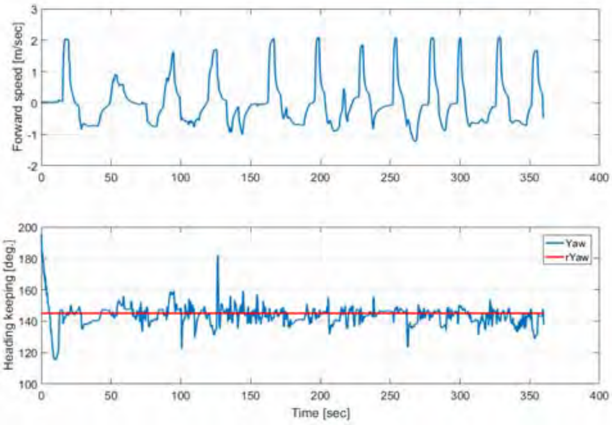

FIGURE V. EXPERIMENTAL TEST RESULT OF MAXIMUM FORWARD SPEED WITH HEADING KEEPING.

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APPENDIX. THE VEHICLE'S PROFILE PARAMETERS

A. *Profile Parameters Used in the Calculation of Damping Coefficients*

TABLE A-1. VEHICLE'S PROFILE PARAMETERS USED IN THE CALCULATION OF DAMPING COEFFICIENTS

Parameters	Value	Unit	Description
a	1.28e-001	m	Semi-minor axis of ellipsoid
R	4.35e-001	m	Semi-major axis of ellipsoid
x_{TF}	5.43e-001	m	Distance from the thruster center to the Z-axis
x_{TD}	5.43e-001	m	Distance from the thruster center to the Z-axis
s_F	1.63e-001	m^2	Cross-section area of ellipsoid
s_D	2.30e-002	m^2	Cross-section area of horizontal thruster
c_{dc}	1.12e+000	-	Axial drag coefficient along Z-axis
c'_{dc}	3.00e-001	-	Axial drag coefficient along X and Y axes
c_{dF}	6.30e-001	-	Axial drag coefficient of thruster along its axis
c_{dD}	9.00e-001	-	Axial drag coefficient of thruster along its lateral side

B. Vehicle's Mechanical Dimensions