Computation of Hydrodynamic Coefficients of Portable Autonomous Underwater Vehicle

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Abstract

Hydrodynamic coefficients in the motion equations of any underwater vehicle are inherent characteristics of the body geometry, the geometry and location of control surfaces and other appendages and separation of centers of gravity and buoyancy. This paper reports the prediction of values of straight-line hydrodynamic coefficients for a portable autonomous underwater vehicle (PAUV) by using empirical methods and Computational Fluid Dynamics (CFD), which is being developed by Northwestern Polytechnical University for ocean reconnaissance. At the same time, hydrodynamic coefficients test results in wind tunnel are shown in this paper. And computational results by empirical methods and CFD are compared with experimental results from wind tunnel tests of the same PAUV. It is proved that the trends in variation of forces and moments are captured well by CFD.

Keywords: PAUV, Hydrodynamic coefficient, CFD, Wind tunnel

Introduction

As a new generation of Autonomous Underwater Vehicles, a kind of low cost, small and portable vehicles have been developed, such as REMUS (Remote Environmental Measuring UnitS), which could provide an affordable means of performing scientific researches, including coastal ocean survey, pollution identification and source tracking, in the coastal ocean, bays and estuaries, etc.(Allen, B. Stokey, R. etc.). In recent years, Chinese researchers in universities or institutes began to study the portable autonomous underwater vehicle (PAUV) and to design and fabricate PAUV, which is small, low-speed and accessible AUV. As well known, the controllability and motion stability characteristics of underwater vehicles are commonly evaluated in terms of hydrodynamic coefficients (HDCs) or hydrodynamic derivatives, which are used in the rigid body equations of motion to express the external forces acting on the vehicle due to its motion in the fluid (Abkowitz M. A.). And coefficients in non-dimensional form are considered to be inherent characteristics of the body geometry, the geometry and location of control surfaces and other appendages of AUV.

Shape and hydrodynamic layout design of a PAUV, which is being developed by Northwestern Polytechnical University (NWPU), are described in this paper. In order to ensure optimized maneuvering characteristics for the vehicle to meet its designated roles, the hydrodynamic coefficients need to be gotten during initial design phase. In this paper, methods of computing these parameters are described, including empirical methods, numeric simulation method, and full-scale model wind tunnel tests.

System Description of Hydrodynamic Layout

Hull shape

The Shape of NWPU PAUV was designed according to minimize drag based on torpedo shape. Fig.1 shows the vehicle bare body shape. The bare vehicle is 1850mm long with a columniform body diameter of 200mm. The head section shape and tail section shape are all designed based on Granville series. The axial length of head section (L_h) is 150mm and the length of tail section (L_A) is 450mm.

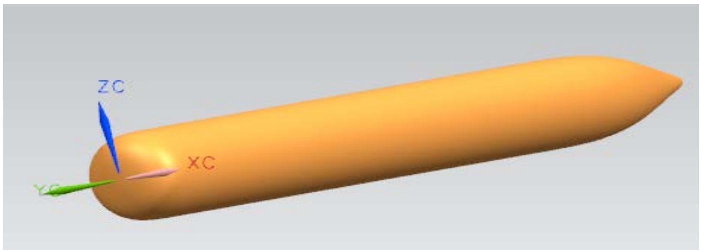

Figure 1. Bare body shape of NWPU PAUV

Layout of Rudders

The rudder (Fig. 2) was designed based on aerofoil form for two reasons: one is low speed and the other is motion stability. The hydrodynamic layout is cruciform arrangement (Fig. 3).

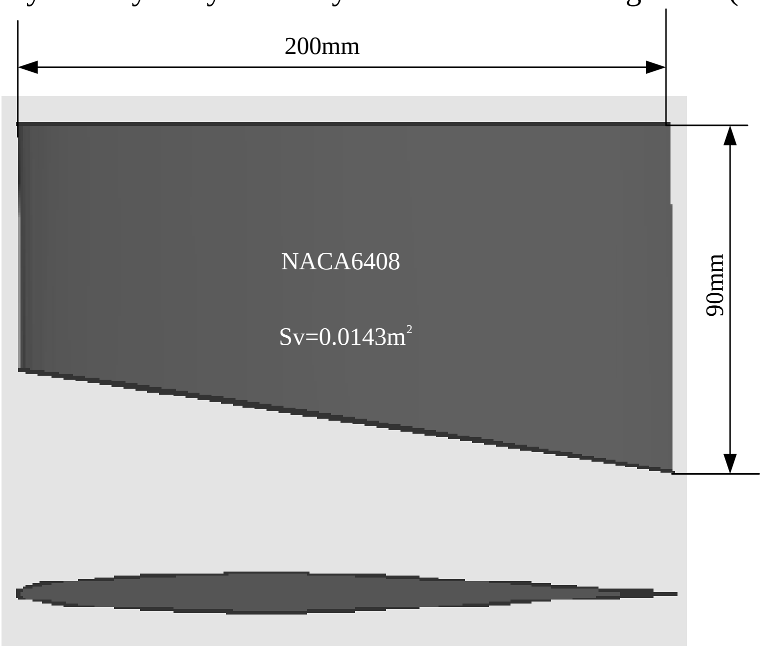

Figure 2. Rudder

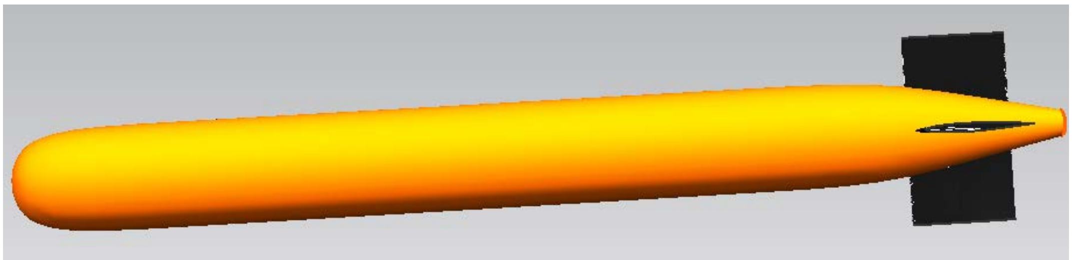

Figure 3. Hydrodynamic layout of NWPU PAUV

So the vehicle's specifications are given in Table 1.

Table 1. Specifications and characteristics of NWPU PAUV

Items	Specifications and characteristics
Dimension	Φ 200mm(D)×1850mm(L)
Weight	50kg
Displacement	0.051m^3
Maximum depth	150m

Operation time	40h
Speed	3-5knots
Main thruster	single screw propeller

Empirical Calculation of Main Linear Hydrodynamic Coefficients

The controllability and motion stability characteristics of UUV are commonly evaluated in terms of hydrodynamic coefficients or hydrodynamic derivatives, which are used in the rigid body equations of motion to express the external forces acting on the vehicle due to its motion in the fluid (W. S. Richardson, P. B. Stimson, etc.). So, in initial design phase, it is important to evaluate main hydrodynamic coefficients by using empirical methods. It is well known that main hydrodynamic coefficients include drag coefficient, lift coefficient, lateral force coefficient, pitch moment coefficient, yaw moment coefficient and roll moment coefficient. The forces and moments are nondimensionalized by $0.5\rho v^2 S$ and $0.5\rho v^2 SL$ respectively, where ρ is the density of water, v is velocity of wind, S is max transect area, and L is the length of the PAUV.

For PAUV with torpedo shape, empirical calculation of main hydrodynamic coefficients is shown as follows (Y. W. Zhang, etc):

A. *Drag Coefficient*

$$\mathrm{C}_{\mathrm{d}(\Omega)} = K*(2.07 - 18.44T_A - 4.15 l_r + 73.25 T_A l_r + 3.26 l_r^2 + 10.81 T_A T_F - 56.96 T_A l_r^2 - 38.34 T_A T_F l_r + 37.75 T_A T_F l_r^2) C_{fb} \quad (1)$$

$$T_A = \frac{4\mathrm{V}_A}{\pi D L_A L_A^{'}}$$

$$l_r = 1 - \frac{L_c}{L}$$

$$T_F = \frac{2\mathrm{V}_h}{\pi D L_h^2}$$

$$C_{fb} = 1.328\sqrt{R_e},\ R_e < 5\times10^5$$

$$C_{fb} = \frac{0.455}{(\lg R_e)^{2.58}} - \frac{1700}{R_e},\ 5\times10^5 < R_e < 5\times10^7$$

$$C_{fb} = \frac{0.455}{(\lg R_e)^{2.58}},\ 5\times10^7 < R_e$$

where, K is correctional coefficient, [1.1,1.15], V_A is volume of tail section of bare body, L_A is length of tail section, $\mathrm{L}_\mathrm{A}^{'}$ is nominal axial length of tail section, L_c is length of columniform section. V_h is volume of head section of bare body, L_h is length of head section, C_{fb} is friction drag coefficient of plate in fluid.

B. *Lift Coefficient*

$$C_y = C_{yb} + C_{yfh} + C_{yrh} \quad (2)$$

where, C_{yb} is lift coefficient of bare body, C_{yfh} is lift coefficient of horizontal fins, C_{yrh} is lift coefficient of elevators.

$$C_{yb} = [2 - 2\zeta_k(1-\eta_k^2) - C_{d0}]\alpha \quad (3)$$

$$\zeta_k = 0.15 \sim 0.2$$

$$\eta_k = \sqrt{S_A / S}$$

where, C_{d0} is drag coefficient of bare body when attack angle (α) is zero, S_A is area of tail end section, $S=\frac{\pi}{4}D^2$ is max transect area of body.

$$C_{yfh}=5.6\frac{5.5\lambda}{5.5\lambda+5.6}\frac{2A_f}{S}\alpha \tag{4}$$

where, λ is ratio of span to chord of fin, A_f is area of fin.

$$C_{yrh}=2\pi\frac{\lambda_r}{2+\lambda_r}(0.5+0.734\bar{a}+0.6\sqrt{A_r/A_f})\frac{2A_r}{S}\delta_h \tag{5}$$

where, λ_r is ratio of span to chord of rudder, $\bar{a}=\frac{a}{D}$, a is span of rudder, A_r is area of rudder, δ_h is the deflection angle of rudder .

C. *Lateral Force Coefficient*

As the symmetry of shape, the calculation methods of lateral force coefficient are similar with lift coefficient.

D. Pitch Moment Coefficient

$$M_Z=M_{zb}+M_{zfh}+M_{zrh} \tag{6}$$

where, M_{zb} is pitch moment coefficient of body, M_{zfh} is pitch moment coefficient of horizontal fins, M_{zrh} is pitch moment coefficient of elevators.

$$M_{zb}=2(0.62+0.013\frac{L}{D})\frac{V}{\frac{\pi}{4}D^2L} \tag{7}$$

where, V is the volume of body.

$$M_{zfh}=-C_{yfh}\frac{L_{fh}}{L} \tag{8}$$

where, L_{fh} is distance of lift point of horizontal fins from origin of body coordinate.

$$M_{zrh}=-C_{yrh}\frac{L_{rh}}{L} \tag{9}$$

where, L_{rh} is distance of lift point of elevators from origin of body coordinate.

E. *Yaw Moment Coefficient*

As the symmetry of shape, the calculation methods of yaw moment coefficient are similar with pitch moment coefficient.

It is noticeable that the origin of coordinate is at the buoyancy center of PAUV.

Numeric Simulation

Grid Generation

Quality of grid generation in numerical simulation takes an important role to gain accurate simulation results of hydrodynamic coefficients. So, most of the human time and effort required in numerical simulation analysis (for example CFD) studies is spent in grid generation.

For studying rectilinear flow past the PAUV, the intermediate volume was meshed using tetrahedral elements, creating an unstructured mesh around the PAUV in a rectangular domain. The length of rectangular is 5L with width is 5D and height is 5D, which can be seen in Fig. 4.

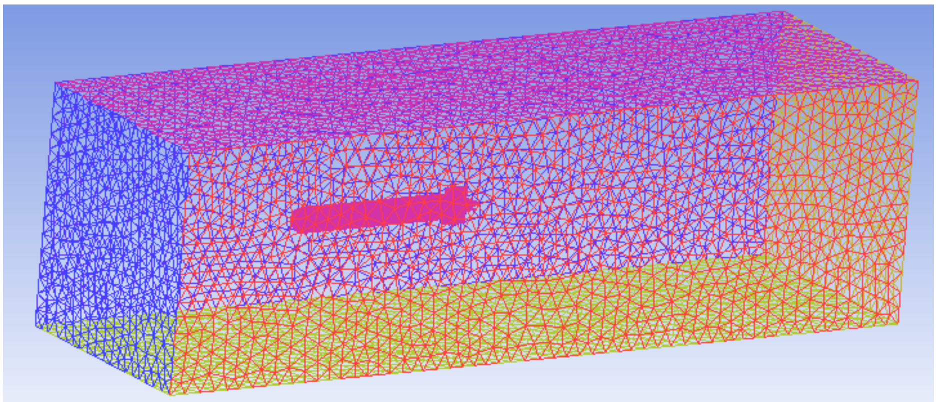

Figure 4. Rectilinear flows at various angles of attack

To evaluate the rectilinear hydrodynamic coefficients, the PAUV was to be placed at various angles of attack. This was efficiently implemented by rotating the enclosing rectangular domain of the specified angle, and then re-meshing (unstructured mesh) the intermediate volume.

Governing Equations

Since the velocity of PAUV changed from3 to 5 knots, the Reynolds number is not high for the flow to be simulated. Also the Reynolds-averaged Navier-Stokes (RANS) equations were used in this paper.

Solver Settings

The 3-dimensional double precision segregated solver was used for steady flow and the SIMPLE algorithm was selected for pressure-velocity coupling. First order upwinding was adopted initially, followed by second order upwinding after the solution residuals had dropped by about 3 orders of magnitude. Residuals of continuity, velocities and turbulence parameters were monitored and convergence criteria were set as 10^{-6} for all residuals.

Turbulence Model

Renormalization Gradient $k-\varepsilon$ model was adopted as turbulence model in this paper.

Model Wind Tunnel tests

According to the shape and hydrodynamic layout of the PAUV, full-scale model wind tunnel test at the same Reynolds number with numerical simulation was accomplished.

For the symmetry of shape and hydrodynamic layout, side slip angle (Fig. 5) and elevators deflection angle (Fig. 6) change tests are accomplished, and the wind velocity is 26.5m/s.

Figure 5. Side slip angle change test

Figure 6. Elevators deflection angle change test

Results

For the NWPU PAUV, based on test data processing, the main hydrodynamic coefficients or derivative are listed in Tab. 2 by empirical method, numeric simulation and wind tunnel tests.

Table 2. Results of main hydrodynamic coefficients or derivatives

Parameters	Empirical method	Numeric simulation	Wind tunnel test
C_d	0.1650	0.1673	0.1726
C_y^{α}	2.8631	2.7512	2.6896
m_z^{α}	0.5621	0.5532	0.5608
C_z^{β}	-2.8631	-2.7512	-2.6896
m_y^{β}	0.5621	0.5532	0.5608
m_x^{β}	0.0025	0.0022	0.0031

According to Tab. 2, the results of empirical method, numeric simulation and wind tunnel test are almost consistent.

Conclusions

For initial design of UUV, quick answers are sought to question like effects of variation in size and location of control surfaces, adequacy of dynamic stability and maneuverability. So computation of hydrodynamic coefficients is important in initial design phase of UUV's design.
The computational results in this paper aim at maneuvering analysis of the NWPU PAUV. The max error for main hydrodynamic coefficients or derivatives comparing wind tunnel test is less than 10%.
For accurately evaluating NWPU PAUV motion characters, rotary hydrodynamic coefficients computational methods are due to further study.

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References

Allen, B. Stokey, R. Austin, T. and Forrester, N, REMUS: A small, low cost AUV; system description, field trials and performance results. pp. 994–1000.
Abkowitz, M.A. (1969) ,.Stability and Motion Control of Ocean Vehicles, MIT Press, Massachusetts.
W. S. Richardson, P. B. Stimson and C. H. Wilkins (1963), Current measurements from moored buoys. *Deep-Sea Research*, Vol.10,3,pp.369-388
A. Ray, S. N. Singh, V. Seshadri (2009), Evaluation of linear and nonlinear hydrodynamic coefficients of underwater vehicles using CFD. 28th International Conference on Ocean, Offshore and Arctic Engineering.
Y. W. Zhang (1998), Shape design of torpedo, NWPU Press, Xi'an.