Maneuverability Design and Analysis of an Autonomous Underwater Vehicle for Deep-sea Hydrothermal Plume Survey

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***Abstract*—SIA is developing a new type asymmetric AUV (SIA-4500AUV) for the purpose of deep-sea hydrothermal plume survey. To ensure the navigational safety in seamount area, the AUV is designed as fish-like vertical flat main hull to improve the maneuverability in vertical plane. This study focused on maneuverability design and analysis of this new type AUV by CFD simulation and captive model experiments. First, we introduce the NACA-like main hull line design, rudder design, and thruster location design by CFD simulation. And then, to understand the performance of the new AUV, captive model experiments in wind tunnel and rotating arm basin were conducted to get all hydrodynamics for maneuverability research, and in another hand, we computing the hydrodynamics of the AUV by CFD simulation to compared with experiments, the compared results show that CFD simulation can work well in the hydrodynamics performance research for this new type asymmetric body AUV. The design of asymmetric AUV is a new try compared to axisymmetric body in AUV design field. The maneuverability design and analysis by captive model experiments and CFD simulation will provide a helpful reference to other new type asymmetric AUV.**

Keywords—AUV; Maneuverability; CFD; Hydrodynamics; Hydrothermal Plume

Hydrodynamic coefficients symbols (Partly)

Y'_v	Lateral force coefficient by sway	Z'_w	Vertical force coefficient by heave
N'_v	Yaw moment coefficient by sway	M'_w	Pitch moment coefficient by heave
Y'_r	Lateral force coefficient by yaw	Z'_q	Vertical force coefficient by pitch
N'_r	Yaw moment coefficient by yaw	M'_q	Pitch moment coefficient by pitch

I. Introduction

A new type asymmetric autonomous underwater vehicle (AUV), *SIA-4500AUV*, is under developing in Shenyang Institute of Automation (SIA) Chinese Academy of Sciences (CAS) for China Ocean Mineral Resources Research and Development Association (COMRA). *SIA-4500AUV* is designed for 4500m working depth, and will be used for deep-sea hydrothermal plume survey, and will also play roles in seafloor marine magnetic survey and polymetallic sulfides detection.

Compared with traditional cruising axisymmetric AUV, *SIA-4500AUV* will work in complex seamount area, and take pictures near seabed at 5m height. To ensure the navigational safety in these dangerous working environment, the AUV should have strong maneuverability in the vertical plane, to escape from colliding with seamount quickly by moving upward.

In order to improve maneuverability in vertical plane, *SIA-4500AUV* is designed as fish-like profile, and with vertical flat transverse section, as shown in the Fig.1. The AUV has equipped with two rotatable thrusters that can turn ±90 deg in stern, and in the bow of AUV, two sets of tunnel thrusters, one set in the vertical plane, and another in the horizontal plane. The rotatable thruster is a new type high performance maneuver device, has been used in *Sentry* AUV by WHOI (2011)[1], rotatable thruster AUV by SIA (2012)[2], and so on.

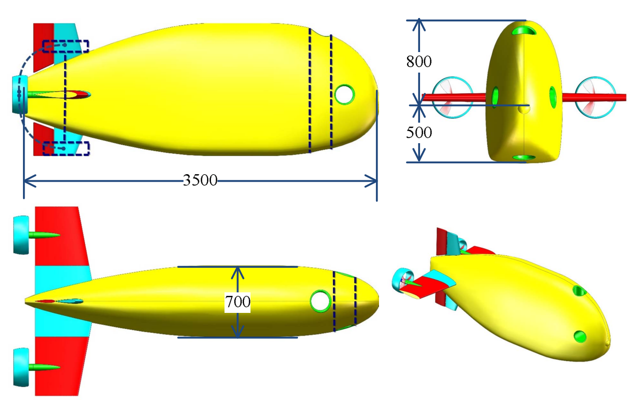


Fig. 1. SIA-4500AUV

For this new hull line, to verify the hydrodynamic performances, the maneuverability of AUV need to be designed and analyzed in detail. Additionally, because of the asymmetry, in surge movement with zero angle of attack, the lift force and pitching moment will become bigger when the velocity increased. So, the hull line should be optimized to minimize the lift force and pitching moment.

At present, lots of AUVs are designed as axisymmetric body, the research about hydrodynamics performance of those AUV has been well developed, such as Prestero (2001) studied the maneuverability of *REMUS* AUV[3], and Azarsina (2010) have a research about *MUN Explorer* AUV[4]. And SIA also have the similar study in the last few years, shch as HU (2008) studied the *SMAL01* AUV[5], and ZHU (2011) researched the *Sea-Wing* glider motion control based on the hydrodynamics performance analysis[6]. In *OCEANS* conference, similar research can be found also, such as, Azarsina (*OCEANS* 2008)[7], Williams (*OCEANS* 2008)[8], and so on.

And, only there is a little research about hydrodynamics performance of the asymmetric body, such as *NPS Phoenix* AUV in NPS[9], and North pole ARV in SIA[10]. The two vehicles are quadrate profile, and *SIA-4500AUV* is streamline profile.

We focus on the maneuverability design and analysis of the new asymmetric AUV with fish-like vertical flat section by Computational fluid dynamics (CFD) and captive model experiments in wind tunnel and rotating arm basin.

II. MANEUVERABILITY DESIGN

As shown in section I, compared with traditional cruising AUV, *SIA-4500AUV* should have more strong maneuverability in the vertical plane. To meet this requirement, we make the maneuverability design in detail, and three important aspects are shown in below: main hull line, rudder and stabilizer, and vertical location of thruster.

A. *Main hull line*

In order to improve the maneuverability in vertical plane, the main hull of AUV is designed as fish-like profile, that can reduce hull resistance in frequency heaving motion. And also, to reduce hull resistance in surging motion, the hull line is designed similar as NACA aerofoil. To meet the balance between equipment arrangement and resistance, the principal dimension is 3.5m(L) x 0.7m(W) x 1.3m(H), with 1300kg weight in air, and with 2knots cruising speed (max 3knots).

The challenge for this asymmetric AUV is additional lift force and lift pitching moment from aerofoil hull when motion with zero attack angle, which would disturb navigation control. To minimize this force and moment, the main hull line was optimized many cases, at last, the lift force has been decreased to near zero, and lift pitching moment will be balanced by rudders and stabilizers.

Lift force at 3 knots was extracted, Z=1.02N. The forces are from CFD simulation, the relative pressure of main hull from CFD is shown in the Fig.2.

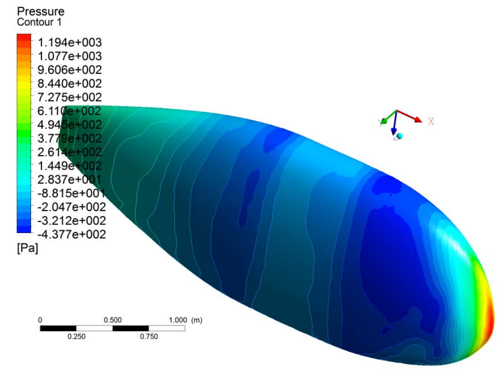


Fig. 2. Pressure distributions on the main hull surface by CFD

B. *Rudder and stabilizer*

Rudder and stabilizer should not only have enough area to meet the need of stability of AUV navigation in horizontal plane and vertical plane, but also banlance lift force and pitching moment. To acquire the area of rudder and stabilizer, the hydrodynamics of bare body is computed by CFD, and then calculate the hydrodynamic coefficients of bare body.

The hydrodynamic coefficients of AUV is made up of bare body main hull (mh) and rudder/stabilizer (ap). For example, the yaw moment coefficient is shown in equation (1),

$$N_r' = \left(N_r'\right)_{mh} + \left(N_r'\right)_{ap} \tag{1}$$

According to the motion stability theory, the judgment parameter of AUV motion stability is shown in equation (2), the parameter K_{hd} and K_{vd} must not less than 1, if not, the AUV would out of control[11].

$$K_{hd} = \frac{l_r'}{l_\beta'} = \frac{-N_r'/\left(m'-Y_r'\right)}{-N_v'/Y_v'}, K_{vd} = \frac{l_q'}{l_\alpha'} = \frac{-M_q'/\left(m'+Z_q'\right)}{-M_w'/Z_w'} \tag{2}$$

The hydrodynamic coefficients of main hull from CFD is shown in Table I.

TABLE I. MAIN HULL HYDRODYNAMIC COEFFICIENTS

Horizontal Plane		**Vertical Plane**	
Items	***Value(10^{-3})***	***Items***	***Value(10^{-3})***
$\left(Y_v'\right)_{mh}$	-98.945	$\left(Z_w'\right)_{mh}$	-22.650
$\left(N_v'\right)_{mh}$	-88.959	$\left(M_w'\right)_{mh}$	26.179
$\left(Y_r'\right)_{mh}$	6.624	$\left(Z_q'\right)_{mh}$	8.588
$\left(N_r'\right)_{mh}$	-5.178	$\left(M_q'\right)_{mh}$	-1.436

The minimum area of rudder/stabilizer can be calculated from Equ. (2). After trade-off with lift force (and moment), the rudder/stabilizer with 0.3m^2 in vertical and 0.8m^2 in horizontal.

C. *Vertical location of thruster*

The thrusters are fixed with rudder, and can turn ±90 deg, and the vertical location of thruster/rudder has obvious influence to pitching moment, and finally disturb navigation control system. The location is 0.1m above zero water-line, and the lift pitch moment is minimized. The pitching moment hydrodynamic coefficient from CFD is $M'_{*} = 0.519 \times 10^{-3}$, the value is small and show a fine location.

The low level additional pitching moment can be balanced by pitching angle of AUV and micro-steering, and in another hand, the AUV can nosingup soon using the moment, to prove the navigation safety near seamount.

III. HYDRODYNAMICS FROM CFD SIMULATION AND CAPTIVE MODEL EXPERIMENTS

To understand the maneuverability of the new AUV, captive model experiments in wind tunnel and rotating arm basin and CFD simulation were conducted and compared each other.

The velocity of captive model experiments is calculated according to Reynolds-Similarity principle, as shown in equation (3). The cruising speed of AUV is 2kn, and wind tunnel model is scaled 1/2, considering the effect of viscosity, the wind velocity in wind tunnel is 18.1m/s. with the same criterion, rotating arm tangential velocity is 1.092m/s.

$$\left(\frac{\rho VL}{\mu}\right)_{AUV} = \left(\frac{\rho VL}{\mu}\right)_{Model} \quad (3)$$

The test cases for captive model experiments and CFD simulation are same. The cases for wind tunnel experiments and CFD simulation are shown in Table II. And the cases for rotating arm basin and CFD simulation are shown in Table III.

TABLE II. WIND TUNNEL EXPERIMENTS

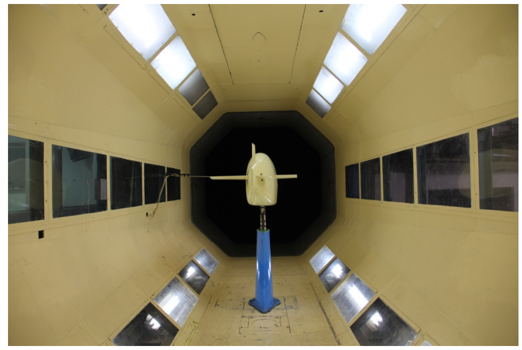
Horizontal plane	β =-3°, 0°, 3°, 6°, 9°, 12°,(α =0°)
Vertical plane	α =-12°, -9°, -6°, -3°, 0°, 3°, 6°, 9°, 12°, (β =0°)
Coupling	α =-12°, -9°, -6°, -3°, 0°, 3°, 6°, 9°, 12°, (β =-3°, 0°, 3°, 6°, 9°, 12°)

TABLE III. ROTATING ARM BASIN EXPERIMENTS

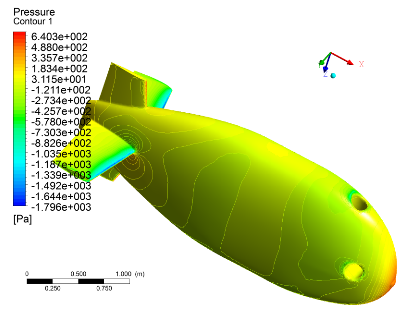
Horizontal plane	Rotating radius items: 5 β=-3°, 0°, 3°, 6°, 9°, 12°,(α=0°)
Vertical plane	Rotating radius items: 5 α=-12°, -9°, -6°, -3°, 0°, 3°, 6°, 9°, 12°, (β=0°)
Coupling (Horizontal)	Rotating radius items: 5 α=0°, ±5°, ±10°, ±12°
	Rotating radius items: 5 φ=0°, ±5°, ±10°, ±15°
Coupling (Vertical)	Rotating radius items: 5 β=0°, ±5°, ±10°, ±12°
	Rotating radius items: 5 φ=0°, ±5°, ±10°, ±15°

Fig.3 shows the wind tunnel experiments and pressure distributing from CFD simulation. And Fig.4 shows the rotating arm basin experiments and pressure distributing from CFD simulation. Fig.5-Fig.6 show the hydrodynamics from captive model experiments and CFD simulation (partly).

Those curves from the Fig.5 and Fig.6 show that CFD simulation has small error compared with model experiment.

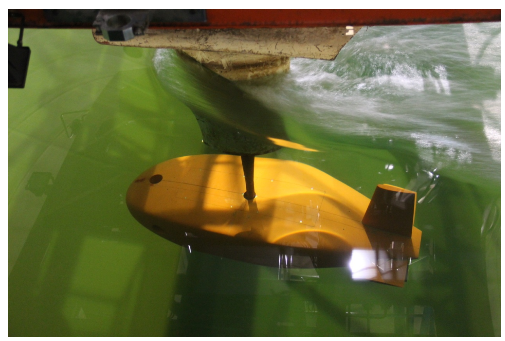


a).Wind tunnel experiments;

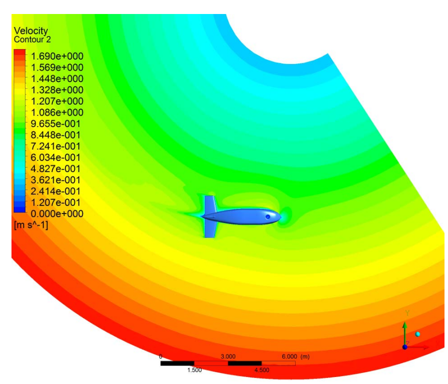


b).Pressure (CFD simulation)

Fig. 3. Wind tunnel experiments and CFD simulation



a).Rotating arm basin experiments;



b).Pressure (CFD simulation)

Fig. 4. Rotating arm basin experiments and CFD simulation

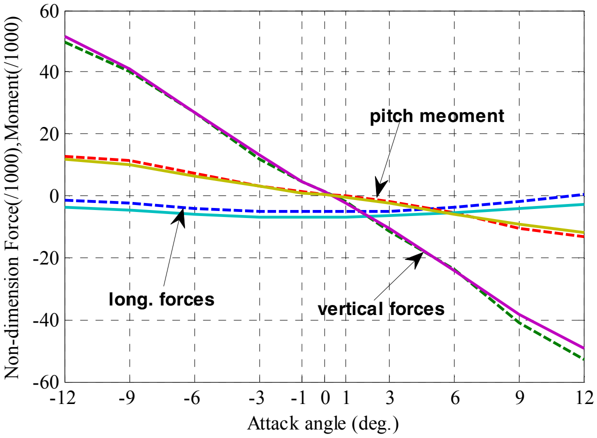


Fig. 5. Hydrodynamics (non-dimensions) in vertical plane vary with attack angles in wind tunnel (real line is from CFD, dashed line is from model experiments)

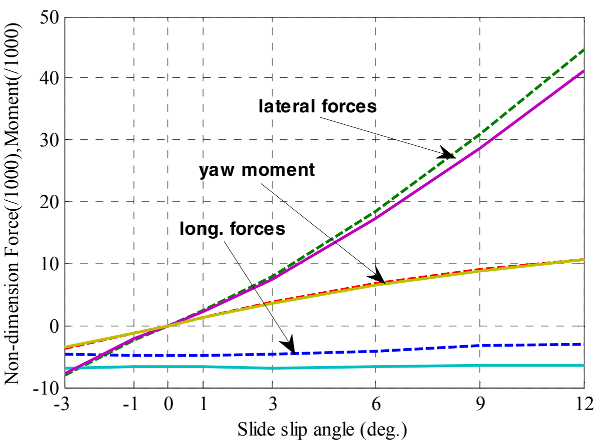


Fig. 6. Hydrodynamics (non-dimensions) in horizontal plane vary with slide slip angles in wind tunnel (real line is from CFD, dashed line is from model experiments)

IV. MANUVERABILITY ANALYSIS

The tool for maneuverability analysis is hydrodynamic coefficients of AUV, and the all hydrodynamic coefficients can be obtained from hydrodynamics that acquired from CFD simulation or captive model experiments by regression analysis based on least squares theory. The hydrodynamic coefficients can also be used for control system research. In this section, we analyze the maneuverability of *SIA-4500AUV* at three typical criteria, stability of motion, reversed velocity, balance parameter in cruising.

A. Stability of motion

Motion stability of AUV is the basic performance, which determined the motion control system. From the table below, we can find that the motion of AUV in vertical plane is static stability (the parameter is negative), and in horizontal plane is dynamic stability (the parameter is bigger than 1), and the reserve is moderate.

TABLE IV. STABILITY OF MOTION

Judgment Parameters		AUV
Ver. Plane	coefficient of static unstability l'_α	-0.216
Hor. Plane	coefficient of static unstability l'_β	0.386
	damping force comparative arm l'_r	0.746
	coefficient of dynamic stability K_{hd}	1.935

B. Reversed velocity

Reversed velocity is important criteria for maneuverability in vertical plane. The criteria shows the heave performance of AUV with rudder and other maneuver device at minimum working velocity. From the table below, we can find that the minimum working velocity that rudder can work well in heave is 1.5kn, that is less than cruising speed.

TABLE V. REVERSED VELOCITY

	Rev. Vel. (kn.)	Rules
Rudder	1.5	less than cruising speed
Bow tunnel thruster	non.	-

C. Balance parameter in cruising

SIA-4500AUV is asymmetric body, and will bring lift force and pitching moment when AUV is cursing. The method to balance these force and moment is cruising with pitching angle. The table in below shows that the pitching angle is small, it would not impact the cruising.

TABLE VI. BALANCE PARAMETER IN CRUISING

Vel. (kn.)	Balance angle of elevator(^{o})	Balance pitch angle(^{o})
2.0	1.1	0.4
3.0	0.9	0.2

V. CONCLUSION

SIA-4500AUV is designed for the purpose of deep-sea hydrothermal plume survey. To meet the special requirement of the mission, this study presents the maneuverability design and analysis of the *SIA-4500AUV*.

A new type fish-like asymmetric vertical-flat main hull was designed to improve maneuverability in vertical plane to meet the navigational safety in complex mountainous seabed. The main hull line is designed similar as NACA airfoil to reduce the seawater resistance and save power cost, and line is optimized to minimize the zero-attack-angel lift force and pitching moment.

To study the maneuverability of this new type asymmetric AUV, captive model experiments in wind tunnel and rotating arm basin and CFD simulation were conducted and compared each other. By analyzing the hydrodynamics forces and moment, it is proved that the *SIA-4500AUV* is maneuverable, and stability reserve is moderate. And we also analyzed other hydrodynamic performance to verify the maneuverability.

The design of asymmetric AUV is a new try compared to axisymmetric body in AUV design field. The maneuverability design and analysis by captive model experiments and CFD simulation will provide a helpful reference to other new type asymmetric AUV.

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REFERENCES

[1] James C. Kinsey, Dana R. Yoerger. Michael V. Jakuba, Rich Camilli, Charles R. Fisher, Christopher R. German, "Assessing the deepwater horizon oil spill with the Sentry autonomous underwater vehicle," 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, September 25-30, 2011, San Francisco, CA, USA, pp. 261-267

[2] LING Bo, LI Shuo, ZENG Jun-bao, "Research on motion control of AUV based on rotatable thruster," Machinery Design & Manufacture, iss.1, pp. 155-157, January 2012

[3] Timothy Prestero, "Verification of a six-degree of freedom simulation model for the REMUS autonomous Underwater vehicle," Master thesis, Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, September 2001

[4] Azarsina Farhood and Williams Christopher, "Manoeuvring simulation of the MUN Explorer AUV based on the empirical hydrodynamics of axi-symmetric bare hulls," Applied Ocean Research, vol. 32, iss.4, pp. 443-453, October 2010

[5] Zhiqiang HU, Yang LIN, "Computing the hydrodynamic coefficients of underwater vehicles based on added momentum sources," Proceedings of the International Offshore and Polar Engineering Conference,ISOPE, pp. 451-456, 2008

[6] ZHU Xinke, YU Jiancheng, WANG Xiaohui, "Sampling path planning of underwater glider for optimal energy consumption," Robot, 2011, 33(3):360-365

[7] F. Azarsina, C.D. Williams, M.T. Issac, "Modelling the hydrodynamic sway force exterted on the bare-hull of an axi-symmetric underwater vehicle in lateral acceleration manoeuvres," *OCEANS* 2008

[8] Christopher D. Williams, Ralf Bachmayer, Brad de Young, "Progress in Predicting in Predicting the Performance of Ocean Gliders from At-Sea Measurements," *OCEANS* 2008

[9] Anthony J. Healey, David Lienard, "Multivariable sliding-mode control for autonomous diving and steering of unmanned underwater vehicles," IEEE JOURNAL OF OCEANIC ENGINEERING, vol.18, NO.3, pp.327-339, JULY 1993

[10] LI Shuo, ZENG Junbao, WANG Yuechao, "Navigation under the arctic ice by autonomous & remotely operated underwater vehicle," Robot, 2011, 33(4):509-512.

[11] SHI Shengda, "Submarine maneuverability," national defence industry press, Beijing, China, 1995