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Analysis and innovation of key technologies for autonomous underwater vehicles

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Abstract: As the mission needs of the autonomous underwater vehicles (AUV) have become increasingly varied and complex，the AUVs are developing in the direction of systematism, multifunction, and clustering technology, which promotes the progress of key technologies and proposes a series of technical problems. Therefore, it is necessary to make systemic analysis and in-depth study for the progress of AUV's key technologies and innovative applications. The multi-functional mission needs and its key technologies involved in complex sea conditions are pointed out through analyzing the domestic and foreign technical programs, functional characteristics and future development plans. Furthermore, the overall design of a multi-moving state AUV is proposed. Then, technical innovations of the key technologies, such as thrust vector, propeller design, kinematics and dynamics, navigation control, and ambient flow field characteristics, are made, combining with the structural characteristics and motion characteristics of the new multi-moving state AUV. The results verify the good performance of the multi-moving state AUV and provide a theoretical guidance and technical support for the design of new AUV in real complex sea conditions.

Key words: autonomous underwater vehicle (AUV); key technology; overall design; complex sea condition

1 Introduction

Modern autonomous underwater vehicle (AUV) is an intelligent unmanned platform to perform a variety of military and civilian missions in complex marine environment, which can better meet the needs, such as scientific research, military operations and commercial applications. It can also make full use of the marine resources. As the mission needs have become increasingly varied and complex, the AUV is developing into systematic, multifunctional groups, and clustering technology. Existing AUV with single function has been unable to meet the needs of the current mission. More importantly, the design theory of the AUV in complex sea conditions should be further improved to adapt to the conceptual design of the AUV, which ensures that the multi-function AUV can resist environmental disturbances and be able to complete various tasks flexibly. Therefore, the overall design and corresponding key technical issues of a multi-moving state AUV in complex sea conditions have important theoretical significance and engineering value to raise domestic AUV technologies.

AUVs can be divided into two types according to the functional and kinetic characteristics: one is the cruise and information type for investigation, search and cargo transportation, which generally carries out motion control relying on the rudder and propeller during its consecutive voyage mission; the other is the hover and work type for underwater objects' inspection and operation, which holds position and attitude while working in water, so it generally requires several thrusters and control surfaces to provide desired control force and torque. Differences in function of the two kinds of AUVs determine quite different structure and its maneuvering characteristics. Therefore, a model of AUV is difficult to serve a variety of mission requirements simultaneously. With the improvement of technology standards, people often require that AUV has good seakeeping and maneuverability with a flexible maneuverability and stability control system, which can be able to complete the trajectory tracking control problem in complex sea conditions [1]. AUVs need to cruise in different sea depths according to different situations. For example, AUVs are required to float near the surface to receive GPS signals regularly so as to ensure proper position and heading. At this point, the

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force and motion characteristics of AUVs affected by the sea are different from those of the deep dive state. The mathematical model of AUVs' motion is highly nonlinear because of currents, waves' interaction changing with time and location [2]. Furthermore, the motion control system of AUVs is a multi-input and multi-output system, which has a contradiction between system complexity and control accuracy.

The international development forefront of the AUVs is closely followed in this work. The smallness, modularity, economization and reliability are the design goals of a new AUV. A multi-moving state AUV provided with the functions such as the submarine vectorial thrust, landing on the sea bottom, wheel driving on the ground and crawling on the ground is developed and a number of key theoretical issues, such as kinematics and dynamics, navigation control and the ambient flow field in complex sea conditions, are studied systematically, which provides an important theoretical basis and technical guidance for the further production of an experimental prototype.

2 Advances and challenges

Because the AUVs are very important in national defense and scientific research, most countries are constantly researching various advanced AUVs to enhance defense capabilities. The AUVs are applied mainly in the military aspects such as the underwater search, surveillance, anti-submarine warfare, reconnaissance, and navigation. In the past decades, there are about 60 AUVs development programs and 200 AUVs were built in the world, most still in the testing phase [3]. With the development of the offshore industry, AUVs' commercial purposes also appear and grow, which makes the AUVs have a broader development and application prospects.

The United States of America is in a leading position in the AUV field compared with other countries in the world. American technology dominates the direction of global AUV. The number of USA military AUV is increasing continuously, and the more well-known research institutions are WHOI, MBARI and MIT etc. So far, a variety of AUVs of the U.S. Navy have entered experimental stage, and some models have been fitted out [4]. In November 2004, The U.S. Navy announced the "AUV UUV master plan" to elaborate AUV mission, technology objectives and development proposals by the theory and exploration results of military transformation, technology development, platform construction and other aspects. To meet the needs of the Navy transformation and further reduce development costs of the AUVs, the plan also recommended the principle of modularization, universalness and compatibility to integrate various existing AUV projects and explore the new generation functional AUV.

Other countries also have a great interest in developing AUVs and have actively carried out the research in this area. NATO laid a course named "M02015 unmanned underwater vehicle development program" in April 2000 to develop various uses of AUVs [5]. In recent years, the British Ministry of Defense has accelerated research on AUVs. July 2002, the British Materiel Administration has developed a three-year demonstration program of AUV to lay the foundation for the future short, medium and long-term development plans of AUVs [6]. Japan has invested hundreds of millions of dollars to develop AUVs, whose AUV technology has reached a high level, but the Japanese AUVs are primarily applied in civilian deepwater exploitation, rarely used in the military field [7]. Russia began to develop AUVs as early as the 1960s, mainly used for mine detection, mine hunting, searching and detection sinking submarines, etc, which lags behind developed countries in Europe and America [8]. The technology research of Chinese AUVs started late and made some breakthroughs under the 863 support until the 1990s [9]. In recent years, Tianjin University has developed two new AUVs. One is the AUV using temperature difference as a driving energy; the other is the AUV with the function of underwater landing and prolonged sitting bottom measurement.

AUVs generally used for long-distance cruising observations don't have the hover and landing capabilities from the terms of the application. The seafloor robots usually only carry out submarine job, but don't have navigational functions of high mobility. Therefore, a multi-moving state AUV provided with the functions, such as the submarine vectorial thrust, landing on the sea bottom, wheel driving on the ground and crawling on the ground become the design direction for all countries.

The overall design of a multi-moving state AUV in this work is proposed, as shown in Fig. 1. The main and accessory structures can be separated. The heave system, vectorial thruster, measurement and communication module, maneuverability module and control system are designed. The structure and working principle of each system have made a detailed analysis, which guarantees that the multi-moving state AUV has the functions such as the submarine vectorial thrust, landing on the sea bottom, wheel driving on the ground and crawling on the ground. The innovative design and kinematic analysis of each major machine show that the new AUV designed in this work is fully in accordance with the design goals and functional requirements.

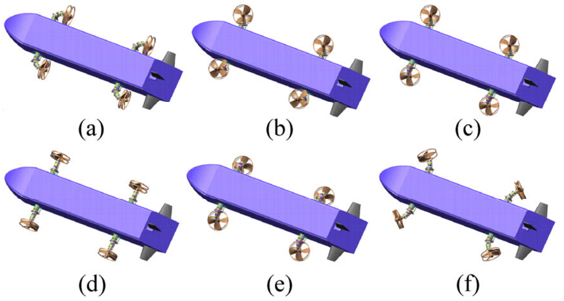

Fig. 1 Typical motions of vectored thruster AUV: (a) Cruising forward; (b) Vertical descend; (c) Transverse turning; (d) Wheeled moving or transverse pushing; (e) Landing sea-bottom or vertical ascending; (f) Pivot steering or crawling on sea-bottom

3 Innovative design based on key technologies

The research on new multi-purpose AUV involves the key technologies, such as thrust vector technology, propeller design technology, kinematics and dynamics, navigation and control technologies, viscous flow field characteristics, which in order to provide theoretical guidance and technical support for the engineering prototype manufacturing and testing. Therefore, it is conducive to the design of a new AUV through studying the latest achievements of key technologies.

3.1 Basic and applied research in thrust vector technology

Thrust vector technology is mainly used to control the flight direction and flight attitude angle at present to improve maneuverability, agility, and in high altitude and rotary ability when dynamic pressure falling in the high altitude or low speed. The AUVs mostly still use the form of propellers or rudders as the propulsion and steering system. The thrust vector technology of AUVs is not yet mature, which is usually applied with the following two methods.

The first method is vectorial water jet propulsion systems. The thrust direction is changed by changing the high-speed jet of the water jet propulsion. This method combines the advantages of water jet propulsion and thrust vector technology, which uses the mechanical deflector plate to change the high-speed jet. Currently, vectorial water jet propulsion system has been applied to surface vessels such as various types of jet propulsion unit of Hamilton Company in New Zealand and Kamewa Company in Sweden [10], whose main mode of mechanical deflection jet is deflector plate. The degrees of freedom of the vessel needing to control are less, while there are some technical difficulties to design vectorial water jet propulsion apparatus with simultaneously controlling heading and attitude for the AUVs with six degrees of freedom.

The second method is the vectorial propeller propulsion system. The thrust direction is changed by changing the direction of the propulsion system. This method can be divided into all and parts the deflection type. The former requires the entire propulsion system movable, so that the device of the driving portion is large and complex, furthermore, the movable tail part may be affected by rudder. The latter requires a complicated gear device such as the vectorial propulsion with space-based linkage and universal joint proposed by EMANUELE and RINALDO [11]. The vector propeller is driven by a “Pittman” brushless motor and three “Stepper” motors to adjust the spatial attitude of the propeller, which can be achieved around 25° angle range of the spatial movement.

A flexible wrist mechanism is proposed based on ball gear, as shown in Fig. 2. The flexible wrist mechanism is a new drive mechanism provided with 360° deflection function and the spin function, which can be used as the vectorial propulsion of the AUV, as shown in Fig. 3. The vectorial thruster achieves four functions such as wheels, legs, thrusters and course control, which has wide prospect in military applications [12].

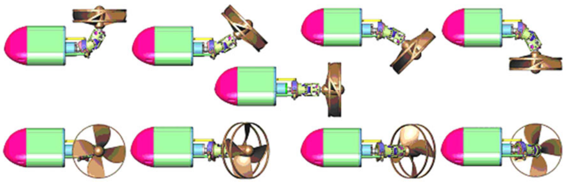

Fig. 2 Flexible wrist mechanism based on ball gear

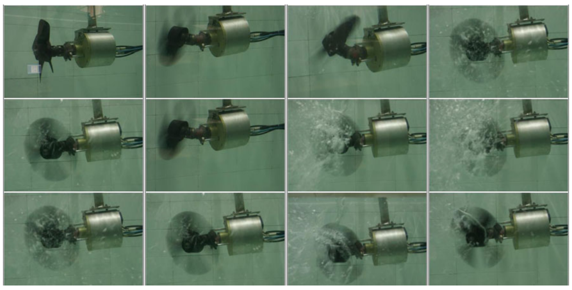

Fig. 3 Underwater test of vectorial thruster

3.2 Basic and applied research on propeller design technology

Propeller design technology has progressed continuously with the development and application of fluid mechanics. The traditional paddle-type map based on open water test of series propeller model has been unable to resolve the cavitation and vibration problems existing in design. Development of theoretical research promotes the progress of propeller design methods, which adapts the propulsion needs of various modern AUVs. Thus, the modern propeller design method based on the combination of theory and experiment has been greatly valued and widely used.

Lifting surface and panel methods in design theory of propeller calculate the hydrodynamic performance based on potential flow theory, which neglect fluid viscosity influence or only consider necessary viscosity correction. Therefore, it is difficult to give a quantitative calculation about the scale effect on the model and the real ship, nonlinear interactions between cavitation and viscous flow, the structure and mechanical mechanism of surface boundary layer and wake vortices and so on. In particular, the calculation of potential flow theory can not reveal the vortex structure of the blade's trailing edge, which affects the prediction accuracy of the propeller performance seriously. Computational fluid dynamics (CFD) based on RANS equations is an effective numerical method to solve these problems [13]. The viscous flow problems of propellers can be computed as the incompressible fluid, but one of the difficulties is how to determine the pressure field. Now the original variable method using speed and pressure as variables is usually applied to solving the problem, which has developed a variety of numerical solution methods, but the computational precision needs to be improved [14−15].

In this work, the CFD method is applied to exploring the numerical methods of the propeller open-water performance by using the RANS equation and three different turbulence models including standard k-ε, standard k-w and RSM based on sub-domains hybrid meshes. The computational results of open-water performance of the propellers including DTMB4119, DTRC3745 and D4-70 are in good agreement with the experimental data, which verifies the correctness of solid modeling and numerical methods, as shown in Fig. 4, Fig. 5 and Fig. 6, respectively. In Fig. 6, the location is at X/R=0.3281, where X is positive downstream, with its origin at the propeller reference line. The experimental data were measured with LDV (laser Doppler velocimetry) system. LDV has been demonstrated by Chesnakas to be a useful tool for flow measurements in areas related to propellers [16], as listed in Table 1, where J is the advance ratio and η is the open-water coefficient. Initially, the laser system utilized a fiber optic probe with both probes mounted on a single traverse system inside the water tunnel measuring axial and tangential velocity from the side, and a second fiber optic probe measuring the radial velocity from below. This permitted precise six-beam crossing, and coincident measurements of three- component velocity. This system is shown in Fig. 7. The maximum errors of RSM, standard k-ε and standard k-w in the computational results of DTMB4119 open-water performance comparing with the experimental data are 5.47%, 7.41% and 11.21%, which shows that the numerical method using RSM has good accuracy in the prediction of propeller open-water performance. This conclusion may guide the selection of turbulence models in viscous flow computation around complex rotating machine. A new wheel propeller (WPD4-70) with the advantages of a large thrust, high structural strength, stable hydrodynamic performance and anti-blade flutter is present through a series of propeller open-water performance computation and comparison under the guidance of the characteristic analysis of the ducted propeller and the contracted and loaded tip (CLT) propeller, which breaks the design bottleneck of the single function propeller, as shown in Fig. 8, where R_2 is the radius of D4−70 propeller. In order to ensure the security and stability of the AUV when it is moving on the ground, nonlinear buckling analysis based on finite element method is used to compute the maximum allowable load of WPD4-70, and the computational result is 3975 N, as shown in Fig. 9. Meanwhile, the natural frequencies and vibration modes are got through the modal analysis of WPD4-70. Each natural frequency indicates that the ability of its vibration insulation in the driving state is high. The final WPD4-70 has preferable open-water performance and intensity characteristics, which can realize the functional requirements of the multi-moving state AUV.

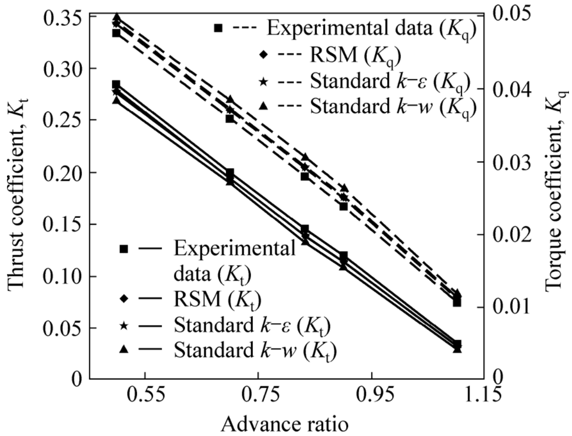

Fig. 4 Open-water performance of DTMB4119

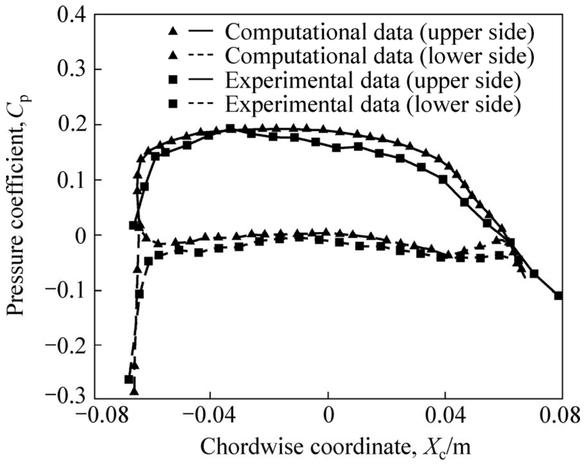

Fig. 5 Pressure distribution at r/R=0.7 of DTMB4119

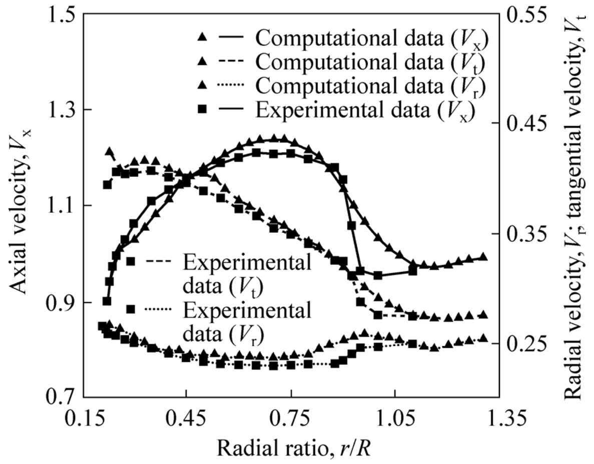

Fig. 6 Axial velocity, tangential velocity and radial velocity distribution at X/R=0.3281

Table 1 Experimental data of DTMB4119's open-water performance

J	K_t	K_q	η
0.5000	0.2850	0.0477	0.4890
0.7000	0.2000	0.0360	0.6320
0.8330	0.1460	0.0280	0.6920
0.9000	0.1200	0.0239	0.7250
1.1000	0.0340	0.0106	0.5750

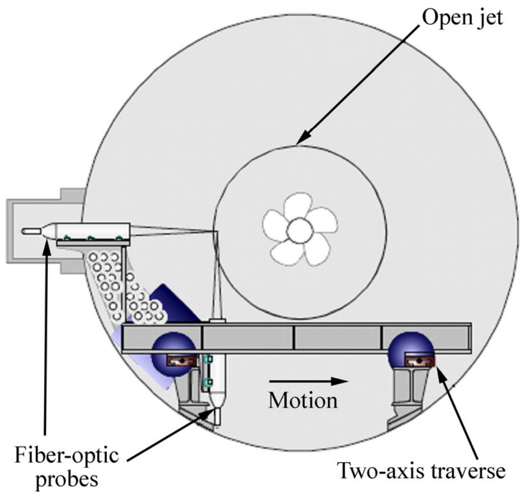

Fig. 7 LDV system used in 36" water tunnel: two probe system for coincident measurements

3.3 Basic and applied research on AUV kinematics and dynamics

Kinematics and dynamics model is the theoretical basis for the research of AUV's hydrodynamic characteristics and motion control. Mathematical modeling method is divided into two parts including mechanism modeling and non-mechanism modeling. Currently, most models are simplified according to each specific AUV and do not fully take into account all the factors of AUVs movement in complex sea environment.

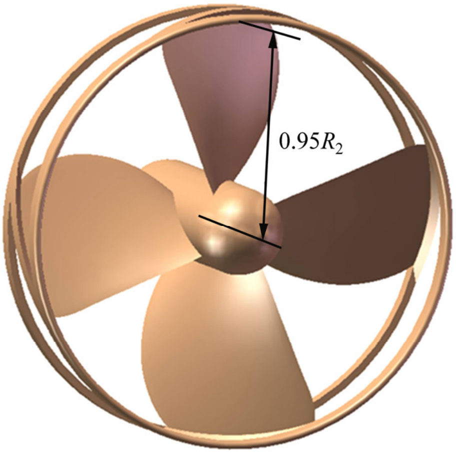

Fig. 8 Geometrical model of WPD4-70 propeller

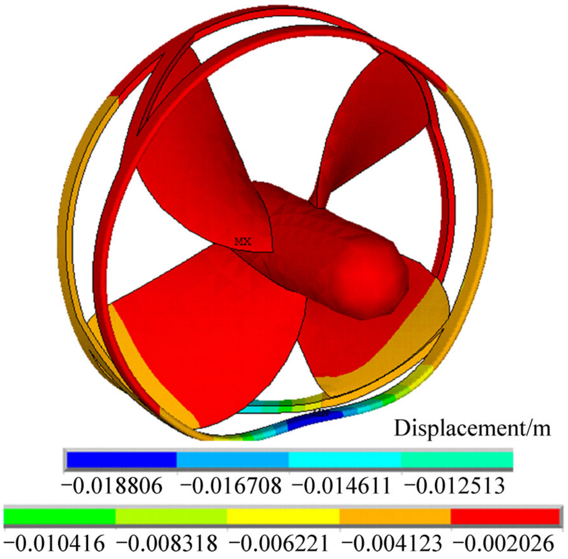

Fig. 9 Node displacement of WPD4-70 propeller in nonlinear buckling analysis (θ=45°) (m)

The mechanism modeling method mainly uses rigid body mechanics, fluid dynamics to generate a mathematical model through analyzing systems. It is perfect in theory, but a certain errors exist between the computational hydrodynamic parameters and the true parameters because of the nonlinear fluid viscous forces in the hydrodynamic model applying a similar treatment, which makes the nonlinear mechanical properties of AUVs not fully express in the kinetic model.

Non-mechanism modeling method mainly uses the properties that neural network can be arbitrary precision approximation for nonlinear systems, which simulates the nonlinear dynamics of the AUVs through online learning, but this modeling method is very complicated, which cannot consider various factors in complex sea environment.

In order to make kinematics and dynamics analysis of the AUVs near water surface, scholars usually establish the mathematical model based on the linear ship theory, but this linear theory cannot make the correct forecasts about the sharp roll of the AUVs near the surface ship and cannot also consider the coupling between its various motion forms [17−18].

In this work, Euler angles representation is applied to establishing six-DOF nonlinear kinematic model according to the structural characteristics and motion characteristics of the new AUV. Euler angles include roll (ϕ), pitch (θ) and yaw (ψ) angles, which are used to mainly express the transformation matrix between body-fixed coordinate system and inertial coordinate system. In order to achieve the satisfactory performance with arbitrary angles, the quaternion method is used to solve the especial singularities when the pitch angles are ±90°. Figure 10 shows the spiral ascending process of the vectored thruster AUV when the propeller speed n = 20 r/s, rudder angle δ_r=10° and plane angle δ_p=45°. The Newton second law and Lagrangian approach are used to deduce the vectored thruster AUV's nonlinear dynamic equations with six degrees of freedom (DOF) respectively in complex sea conditions based on the random wave theory, and the dynamic models of the two methods are same, which shows that the dynamic model of the vectored thruster AUV is accurate. On this basis, the mathematical model of the new AUV's low-frequency motion and high-frequency motion in complex sea conditions is established. The Runge−Kutta arithmetic is used to solve the dynamic equations, which not only can simulate the motions such as cruise and hover but also can describe the vehicle's low-frequency and high-frequency motion, so this method clears up the difficulties of computation and display of the coupled nonlinear motion equations in complex sea conditions. The kinematic model and dynamic model are proved to be valid through the computation and analysis of its spatial motion's performance in interference-free environment and the analysis of the integrated signals including low-frequency motion signal and high-frequency motion signal in environmental disturbance. Define the parameters including the propeller speed n=8 r/s, ocean wave grade S=4, significant wave height H_s=1.8 m, flow axis's angle of attack α_c=15° and flow axis's angle of sideslip β_c=25°. The low-frequency motion signal, high-frequency motion signal and measured motion signal of the vectored thruster AUV cruising near water surface are shown in Fig. 11, which shows that the maneuverability of the vectored thruster AUV equipped with rudders and vectored thrusters is enhanced. The six-DOF dynamic equations of motion in the inertial coordinate system can be expressed as

$$\boldsymbol{M}_{\eta}(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}}+\boldsymbol{C}_{\eta}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}}+\boldsymbol{D}_{\eta}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}}+\boldsymbol{g}_{\eta}(\boldsymbol{\eta})=\boldsymbol{f}_{\eta} \tag{1}$$

where $\boldsymbol{M}_{\eta}(\boldsymbol{\eta})=\boldsymbol{J}^{-\mathrm{T}}(\boldsymbol{\eta})\boldsymbol{M}\boldsymbol{J}^{-1}(\boldsymbol{\eta})$; $\boldsymbol{f}_{\eta}(\boldsymbol{\eta})=\boldsymbol{J}^{-\mathrm{T}}(\boldsymbol{\eta})\boldsymbol{f}$; $\boldsymbol{C}_{\eta}(\boldsymbol{v},\boldsymbol{\eta})=\boldsymbol{J}^{-\mathrm{T}}(\boldsymbol{\eta})[\boldsymbol{C}(\boldsymbol{v})-\boldsymbol{M}\boldsymbol{J}^{-1}(\boldsymbol{\eta})\dot{\boldsymbol{J}}(\boldsymbol{\eta})]\boldsymbol{J}^{-1}(\boldsymbol{\eta})$; $\boldsymbol{D}_{\eta}(\boldsymbol{v},\boldsymbol{\eta})=\boldsymbol{J}^{-\mathrm{T}}(\boldsymbol{\eta})\boldsymbol{D}(\boldsymbol{v})\boldsymbol{J}^{-1}(\boldsymbol{\eta})$; $\boldsymbol{g}_{\eta}(\boldsymbol{\eta})=\boldsymbol{J}^{-\mathrm{T}}(\boldsymbol{\eta})\boldsymbol{g}(\boldsymbol{\eta})$; $\boldsymbol{M}$ is the added mass matrix; $\boldsymbol{C}(\boldsymbol{v})$ is the Coriolis and centripetal matrix; $\boldsymbol{D}(\boldsymbol{v})$ is the damping matrix; $\boldsymbol{f}$ is the total forces and moments; $\boldsymbol{J}$ is the transformation matrix; $\boldsymbol{\eta}$ is the position and attitude vector in the inertial coordinate system; $\boldsymbol{v}$ is the linear and angular velocity vector in the body-fixed coordinate system.

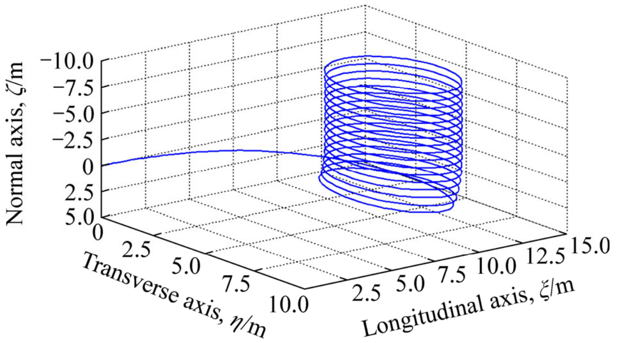

Fig. 10 Motion trajectory of spiral ascending process

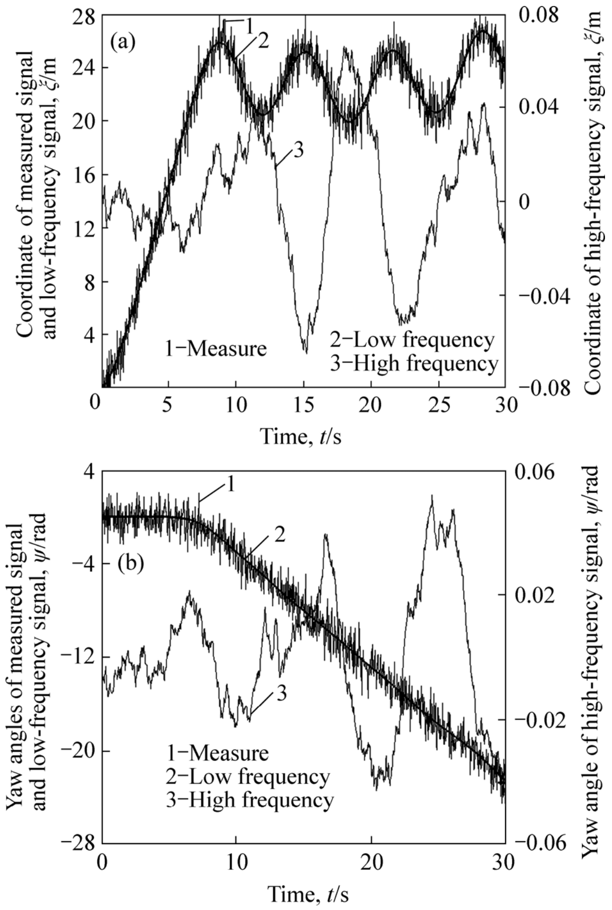

Fig. 11 Curves of position and attitude signals: (a) Longitudinal-axis coordinate ξ; (b) Yaw angle ψ

3.4 Basic and applied research on navigational control technology

AUV navigation control means that it automatically navigates with a predetermined posture along a predetermined path according to its own movement in the underwater environment through controlling the movement of the rudder or propeller. The AUV navigation control system is to make the motion state under control in complex disturbance environment. Therefore, the navigation control is essentially to study the control method of AUVs under random perturbation. The problems of AUV navigation control system design need to face problems including the highly nonlinear, time-varying and strong coupling of system model, the uncertainty of fluid dynamics parameter, stochastic perturbation of waves and currents, the center of gravity and buoyancy changing in the navigation process. Therefore, the AUV navigation control system is required to be robust enough to have the ability to self-calibration, so as to overcome the outside interference and the unmodeled uncertainty of the dynamic model. AUV navigation control system is a multi-input and multi-output system. How to improve the control precision in complex environment has been great concerned for scholars. With the development of modern control theory, scholars have put forward a number of advanced AUV navigation control methods mainly including two categories, robust control and adaptive control, but the control precision of AUVs applying these two methods in complex environment is not high [19−20].

In order to solve the nonlinear term and unmodeled dynamics existing in the new AUV's attitude control and the disturbances caused by the external marine environment in this work, a second-order sliding mode controller with double-loop structure considering the dynamic characteristics of the rudder actuators is designed. Then, Lyapunov stability theory is used to verify the stability of the controller. The impacts of system parameters, rudder actuator's constraints and boundary layer on the sliding mode controller are computed and analyzed, which verifies that the sliding mode controller based on dynamic boundary layer can effectively resolve two problems. Firstly, it can resolve sliding mode loss in the attitude control caused by the rudder actuator amplitude and rate limiting. Secondly, it can avoid the control failure caused by the design theory not matching with the actual application conditions. According to the submarine theory, six-DOF motion equations of the new AUV are decomposed into two mutually non-coupled subsystems, namely the horizontal plane subsystem and the vertical plane subsystem. As the yaw angle and yaw angle rate rather than the displacement of the new AUV can be measured directly in the horizontal plane, the sliding mode control algorithm combining cross track error method and line of sight method is used to fulfill its high-precision trajectory tracking control in different sea conditions, which ensures the robustness and accuracy of the sliding mode controller when the heading error is too large, as shown in Fig. 12, which defines the parameters including the ocean wave grade S=5, significant wave height H_s= 3.2 m, the encounter angle χ=0°. The sliding mode control algorithm combining cross track error method and line of sight method is used in this work. The control input of the vertical rudder based on cross track error method can be expressed as

$$\begin{aligned}\delta_r(t)=&[ub\cos(\tilde{\psi}(t)_{\mathrm{CTE}(i)})]^{-1}[-uar(t)\cos(\tilde{\psi}(t)_{\mathrm{CTE}(i)})+\\&ur(t)^2\sin(\tilde{\psi}(t)_{\mathrm{CTE}(i)})-\lambda_1 ur(t)\cos(\tilde{\psi}(t)_{\mathrm{CTE}(i)})-\\&\lambda_2 u\sin(\tilde{\psi}(t)_{\mathrm{CTE}(i)})-\eta_1\tanh(\sigma_1(t)/\phi_1)]\end{aligned}\tag{2}$$

where $\tilde{\psi}(t)_{\mathrm{CTE}(i)}$ is the heading error of the i-th route segment; $r(t)$ is the angular velocity of the yaw angle; a and b are heading dynamic coefficients; λ_1 and λ_2 are the sliding surface coefficients; η_1 is the reaching law coefficient.

The case that the heading error is more than 40° often occurs in the navigation process of the new AUV [21]. Especially when the new AUV converts the route, the heading change 90° suddenly is not a common case. In this case, the sliding mode controller based on the cross track error method fails and the sliding mode controller based on the line of sight method needs to be used for route guidance. The control law of the sliding mode controller based on the line of sight method is designed as

$$\delta_{\mathrm{r}}(t)=K_1 r(t)+\eta_2\tanh(\sigma_2(t)/\phi_2)\tag{3}$$

where $\eta_2\tanh(\sigma_2(t)/\phi_2)$ is the reaching law of the sliding surface; η_2 is the maximum of the reaching law; ϕ_2 determines the decay law of the sliding surface when its amplitude decreases; $\sigma_2(t)$ is the slide surface; K_1 is the control law coefficient.

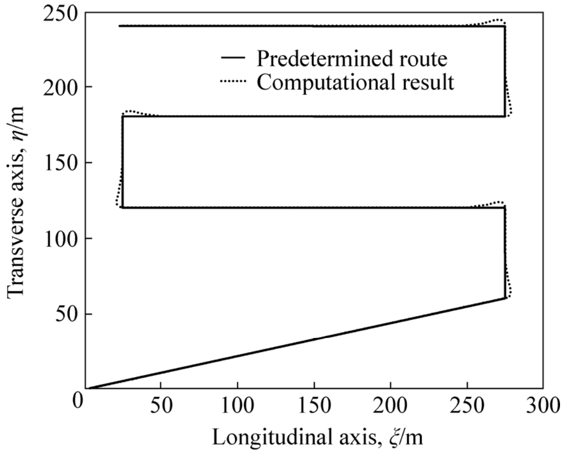

Fig. 12 Trajectory tracking result in random waves

As the vertical displacement of the new AUV can be measured by laser distance measuring sensor, a stable sliding mode controller is designed based on the single-input multi-state system, which takes into account the characteristic of the hydroplane and the amplitude and rate constraints of the hydroplane angle. Moreover, the usage of dynamic boundary layer improves the robustness and control accuracy of the system, which realizes the accurate tracking of time-varying depth signal with the desired attitude under different sea conditions, as shown in Fig. 13 and Fig. 14. The function of depth tracking sliding mode controller is to make the new AUV reach the depth command with the desired attitude and stability through controlling the multi-state variables with the hydroplane angle when the depth command is received. The sliding mode control law can be expressed as

$$u_{\mathrm{c}} = -\boldsymbol{k}^{\mathrm{T}}\boldsymbol{x} + (\boldsymbol{h}^{\mathrm{T}}\boldsymbol{b})^{-1}[\boldsymbol{h}^{\mathrm{T}}\dot{\boldsymbol{x}}_{\mathrm{d}} - \eta\,\mathrm{sat}(\sigma(\tilde{\boldsymbol{x}}))] \qquad (4)$$

where $\sigma(\tilde{\boldsymbol{x}})$ is the sliding surface; $\boldsymbol{k}$ is the feedback gain vector; $\boldsymbol{h}$ is the corresponding eigenvector; η is the reaching law coefficient; $\boldsymbol{b}$ is the coefficients matrix of the dynamic equation; $\boldsymbol{x}$ and $\boldsymbol{x}_{\mathrm{d}}$ are the state variables.

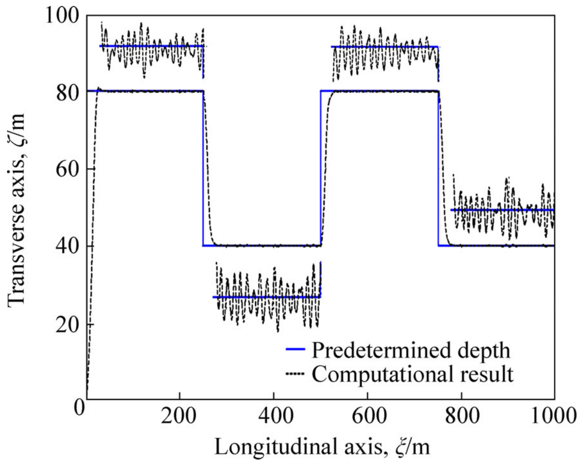

Fig. 13 Depth tracking result in random waves

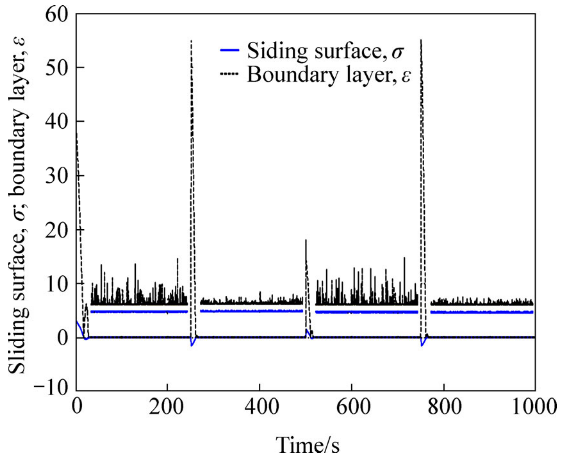

Fig. 14 Sliding surface (*σ*) and boundary layer (*ε*) in random waves

Through comparing the trajectory tracking performance of the new AUV under different sea conditions, the impacts of currents and waves on the sliding mode controller of the new AUV are analyzed qualitatively and quantitatively, which provides an effective theoretical guidance for the control system design of the new AUV in real complex environment.

3.5 Basic and applied research on viscous flow field around AUVs

The pumping action of propellers changes the pressure distribution and boundary layer thickness of AUVs' hull, while the non-uniform wake of AUVs' hull changes the inlet condition of propellers, which results in unsteady and non-uniform load distribution and causes the cavitations, noise and vibration. Therefore, the interaction between AUVs' hull and propellers is concerned by designers, which has important theoretical and practical significance to study it.

Nowadays, there are two main methods used to study the interaction between AUVs' hull and propellers including scale model experiment and numerical methods. The interaction principle study of the model experiment gets some progress through the non-contact measurement around the flow field with LDV and PIV experimental techniques. But the model experiment needs high cost and long cycle, which is also influenced by scale effect and environmental interference. So, it is difficult to reflect intuitively and accurately the real situation of the flow field. Numerical computation that used the potential theory and boundary layer cannot accurately simulate the interaction between AUVs' hull and propellers early because the flow is assumed to be irrotational and viscous effect is neglected. As the RANS equations are used to solve flow field, the computational precision is improved, which provides technical support for the study on the interaction between AUVs' hull and propellers. But it is difficult to compute the integral flow field because of the complicated geometry and the interaction between AUVs' hull and propellers. Nowadays, force field simulation is usually applied to studying the interaction by domestic and foreign scholars, which couples the computation program of AUVs' hull and the open-water performance prediction program of propellers through volume force. But the computation is only a rough approximation because only the thrust of the propeller but not its complicated geometry is taken into account by the volume force instead of the real propeller. As the capability of computers has greatly advanced, it is possible to introduce computational fluid dynamics to compute the integral flow field of the AUVs with the propellers [22−23].

In this work, the CFD method is used to simulate numerically the unsteady viscous flow around the new AUV with propellers in non-environmental interference conditions by using the RANS equations, SST *k*-*w* model and pressure implicit with splitting of operators (PISO) algorithm based on sliding mesh. The computational results have good convergence, which reflects well the real ambient flow field of the new AUV with propellers. The interaction between the AUV’s hull and wheel propellers is predicted qualitatively and quantitatively by comparing the hydrodynamic parameters, such as pressure, velocity, resistance, from integral computation and partial computation of the viscous flow around the AUV with propellers in non-environmental interference conditions, as shown in Fig. 15, Fig. 16 and Table 2, which provides an effective reference to the optimization design, vibration and noise of the AUV’s hull and propellers in real environment. The communication tasks usually require the new AUV to navigate on the sea surface in complex sea conditions. Therefore, the movement forms and flow field characteristics of the new AUV navigating against the wave at high speed are necessary to be studied. The mathematical model of the high-speed AUV in head sea is established with considering the hydrodynamic lift based on strip theory according to the motion characteristics of the new AUV in waves, which is solved to get the heave and pitch of the AUV by Gaussian elimination method. Then, the motion processes of the AUV’s heave and pitch are realized in the numerical computation of the flow field around the AUV based on the dynamic mesh driven by the UDF function source code compiled with DEFINE_CG_MOTION Macro. According to the coordinate transformation principle of AUV’s longitudinal motion theory and the technique of purely numerical wave based on the UDF function source code compiled with DEFINE Macro, the three-dimensional numerical wave of the computational field is realized through defining the unsteady inlet boundary condition. On this basis, the CFD theory is used to establish the mathematical model of the unsteady viscous flow around the AUV with considering free surface effort by using the RANS equations, SST *k*-*w* model and VOF model. The hydrodynamic parameters of the AUV, such as drag, lift, pitch torque, velocity, pressure, and wave profile, are got by numerical computation, which predicts well the real flow field around the high-speed AUV in head sea. The computational wake of the AUV is in good agreement with the experimental phenomenon of a wave-piercing surface vehicle, as shown in Fig. 17 and Fig. 18,

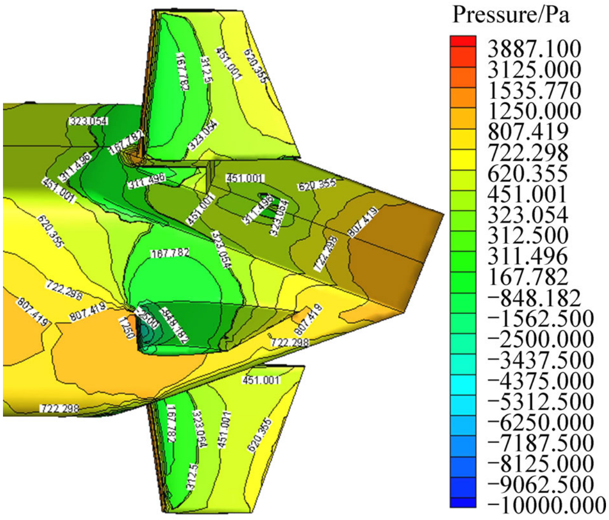

Fig.15 Relative pressure of AUV with propellers

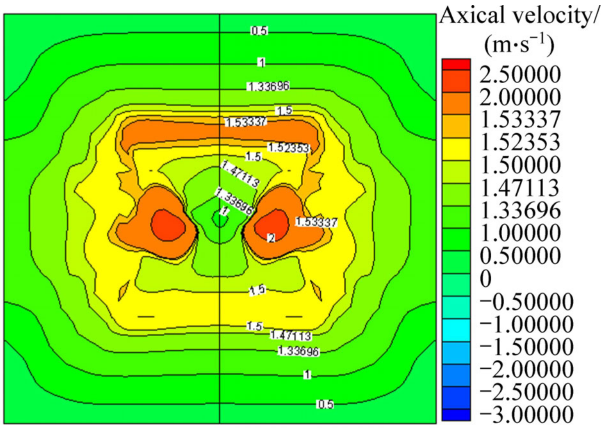

Fig.16 Axial velocity distribution of wake field of AUV with propellers

Table 2 Resistance results of integral computation and partial computation

Navigation speed, v/(m·s^{-1})	Partial computation			Integral computation			Change ratio/%		
	Total resistance, F_0/N	Pressure resistance, F_1/N	Friction resistance, F_2/N	Total Resistance, F_0/N	Pressure resistance, F_1/N	Friction resistance, F_2/N	Total resistance	Pressure resistance	Friction resistance
0.228	−762.290	−770.831	8.541	−394.960	−404.824	9.864	48.19	47.48	15.49
0.684	−660.892	−674.378	13.486	−321.881	−336.868	14.987	51.30	50.05	11.13
1.140	−545.219	−562.507	17.288	−185.402	−204.304	18.902	65.99	63.68	9.34
1.596	−410.479	−432.639	22.160	−9.388	−36.104	26.716	97.71	91.65	20.56
2.052	−257.135	−284.801	27.666	233.624	197.252	36.372	190.86	169.26	31.47
2.508	−81.164	−115.242	34.078	516.656	468.562	48.094	736.56	506.59	41.13

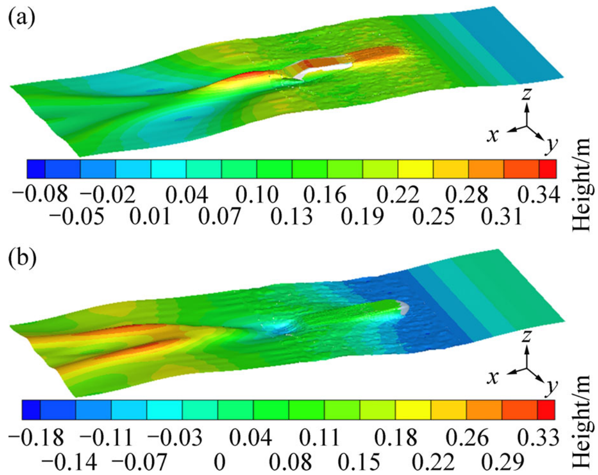

Fig. 17 Wave profiles of free surface at different time: (a) t=17.51 s; (b) t=18.11 s

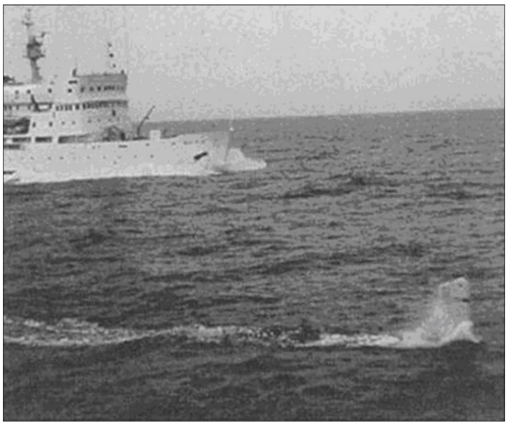

Fig. 18 Real wave profile of a wave-piercing surface vehicle

which verifies effectively the correctness of the numerical method.

4 Conclusions

1) The development of the AUVs is expatiated. The multi-functional mission needs and its key technical technologies involved in complex sea conditions are pointed out through analyzing the domestic and foreign technical program, functional characteristics and future development plans. Furthermore, the research situation and development trend of key technologies such as thrust vector, propeller design, kinematics and dynamics, navigation control, and ambient flow field characteristics are analyzed.

2) A multi-moving state AUV provided with the functions, such as the submarine vectorial thrust, landing on the sea bottom, wheel driving on the ground and crawling on the ground is developed, which is fully in accord ance with the design goals and functional requirements of international new AUV.

3) Based on the latest developments of the AUVs' key technologies and combined with the structural characteristics and motion characteristics of the new multi-moving state AUV, the innovation of a number of key technologies, such as thrust vector, propeller design, kinematics and dynamics, navigation control, and ambient flow field characteristics in complex sea conditions is illustrated individually, which verifies the good performance of the multi-moving state AUV and provides a theoretical guidance and technical support for the design of new AUVs in real complex sea conditions.

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