Numerical Calculation of Interference Force and Simulation of Navigation Motion of Underwater Vehicles Under the Influence of Ocean Currents

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Numerical Calculation of Interference Force and Simulation of Navigation Motion of Underwater Vehicles Under the Influence of Ocean Currents

Dejun Li [1,*], Chao Peng[1], Chunrong He[1], Qiaosheng Zhao[1], Houyang Zhong[2] and Wei Zhang[1]

[1] China Ship Scientific Research Center, Wuxi 214082, China
[2] PLA Navy Submarine Academy,Qingdao, 266042, China
Email: 2541086522@qq.com

Abstract. Deep sea submersible simulation has become an effective means of predicting the motion of deep-sea submersibles. The deep-sea operating environment is complex, and deep-sea submersibles are often affected by the interference of ocean currents. This article combines CFD numerical calculation method and six degree of freedom motion simulation modeling method to conduct simulation research on direct flight motion under ocean current interference. This article takes a deep-sea manned submersible as the research object, obtains the lateral ocean current interference force through numerical calculation, and applies the calculated ocean current interference force information to the motion equation of the deep-sea submersible, so as to simulate and study the motion response of the submersible to ocean currents during actual navigation. By comparing with the motion under no ocean current conditions, it can be seen that ocean current has a significant impact on heading and attitude. This study can provide reference for practical manipulation and has certain engineering significance.

Keywords: Manned submersible, Ocean currents, Numerical calculations, Simulation

1. Introduction

Deep sea manned submersible is one of the important deep-sea equipment, which has widely applications in military and civilian fields, such as marine resource exploration and development, underwater maintenance, underwater rescue, and establishment of deep-sea space stations. With further exploration of the ocean, manned submersibles are beginning to develop towards deep-sea operations. At present, countries such as China, the United States, Russia, Japan, and France are relatively mature in deep-sea manned submersible technology.

In deep-sea operational environments, manned submersibles are often affected by ocean currents, which are often unsteady and their magnitude and direction cannot be determined. Studying the motion characteristics of deep-sea submersibles under ocean current interference has certain engineering significance for practical navigation operations. The appearance of deep-sea submersible is complex, and the coupling between various degrees of freedom is strong. To describe the motion characteristics of deep-sea submersible, an accurate equation needs to be established. The dynamic equations of a submarine are a complex set of nonlinear differential equations, and the commonly used one is the motion equation for submarines proposed by the US in 1967. This standard motion equation is applicable to underwater moving objects, including submarines [1] . The US published a revised standard equation of motion for submarines in 1979. Nie (2021) [2] proposed the standard and index evaluation method for Z-shaped steering maneuverability of manned submersibles, and conducted Matlab simulation case studies on motion prediction, analyzing and elaborating on various typical characteristic parameters and motion laws of maneuvering motion. Howan Kim (2018) [3] used computational fluid dynamics (CFD) to numerically simulate the 6-DOF maneuvering of underwater vehicle and validated it with experimental data.

In the research of underwater vehicle motion prediction under the action of ocean currents, BAE J Y (2010) [4] studied the maneuvering motion of the American Manta type underwater vehicle under the action of ocean currents at high angles of attack and low speeds. The results showed that ocean currents would cause it to drift. Liu (2013) [5] established a six degree of freedom motion equation for a manned submersible and studied the rotational motion characteristics under the action of ocean currents. Zhao (2021) [6] established a model of HOV under the action of ocean currents. Hu (2022) [7] conducted simulation analysis on platform disturbance in non ocean current environment and platform disturbance in ocean current environment, and concluded that when external interference causes six degrees of freedom disturbance on the platform, the results in non ocean current environment are significantly different from those in ocean current environment.

From the above literature, it is known that scholars have conducted extensive research on underwater vehicle motion prediction, mostly using six degree of freedom motion simulation modeling methods. This article selects the lateral ocean current condition and combines CFD numerical calculation method with six degrees of freedom motion simulation modeling method to conduct research on the navigation performance of manned submersible. By comparing the motion under the condition of no ocean current, the study shows that the lateral ocean current has a significant impact on the heading and attitude.

2. Numerical calculation of disturbance force of deep-sea submersible under transverse ocean currents

At present, the main methods for solving turbulent flow problems include direct simulation method (DES), large eddy simulation method (LES), and RANSE method. The Direct Simulation Method (DES) has the highest calculation accuracy, but it requires a long calculation cycle, so it is rarely used in general; The Large Eddy Simulation (LES) method requires a relatively small number of grids, and the accuracy of flow field calculations can meet the needs of research problems, but the calculation time is still relatively long; The RANSE method requires the minimum number of grids, a short computation cycle, and computational accuracy that can meet the research needs of most problems. Taking into account the computational cost and the characteristics of the target research problem, this paper chooses the RANSE method to solve it.

The RANSE method requires additional equations to make the problem closed, which gives rise to the turbulence model. Considering the flow separation phenomenon around the cylinder under the action of incoming flow and the complex turbulent characteristics of the wake field, this paper uses the SST k - ω model [8,9] for numerical calculation and analysis. This model has good applicability in numerical prediction of near wall flow separation and wake field characteristics.

Considering that the lateral flow motion of the submersible is a high Reynolds number flow (on the order of 105), this paper selects the high Reynolds number condition ($Re=5.5\times10^5$) as the verification condition. The calculation results of this paper and MARIN&ATKINS [10] are presented below (Table 1). From Table 1, it can be seen that due to the complex flow characteristics around a cylinder, the average lateral resistance coefficient obtained from various solutions fluctuates greatly. However, overall, the solution method established in this article can meet the needs of the research problem.

The equation is as follows.

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

$$\begin{aligned}\frac{\partial(\rho u)}{\partial t}+\operatorname{div}(\rho u u)&=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xx}}{\partial z}+F_x\\ \frac{\partial(\rho v)}{\partial t}+\operatorname{div}(\rho v \mathbf{u})&=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}+F_y\\ \frac{\partial(\rho w)}{\partial t}+\operatorname{div}(\rho w \mathbf{u})&=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \tau_{zy}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+F_z\end{aligned} \tag{2}$$

In equation(2), p represents pressure, τ represents viscous shear force, and F represents other force source terms.

The turbulence model is as follows.

$$\begin{aligned}\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)&=\frac{\partial}{\partial x_j}\left[\Gamma_k\frac{\partial k}{\partial x_j}\right]+\overline{G_k}-Y_k+S_k,\\ \frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)&=\frac{\partial}{\partial x_i}\left[\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right]+\overline{G_\omega}-Y_\omega+D_\omega+S_\omega\end{aligned} \tag{3}$$

In the formula (3), k is turbulent kinetic energy, G_k is the generation term of k, G_ω is the generation term of ω,$S_{\bar{k}}$ and S_t are custom source items.

Table 1. Calculation results of average lateral resistance of cylindrical flow.

Verification method	Turbulence model	Average lateral resistance coefficient
	SST k-ω	0.620
MARIN&ATKINS[10]	RSTM	0.679
	DES	0.652
This paper	SST *k*-*ω*	0.607

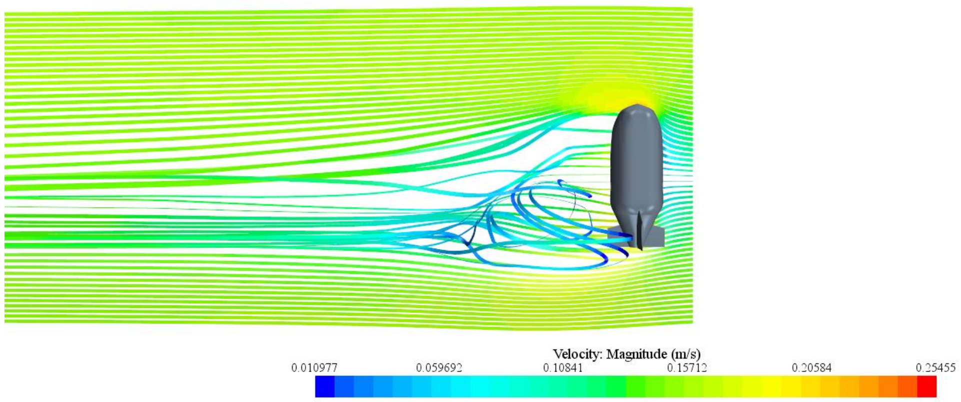

Figure 1. Flow image of the submersible under a transverse current of 0.3kn.

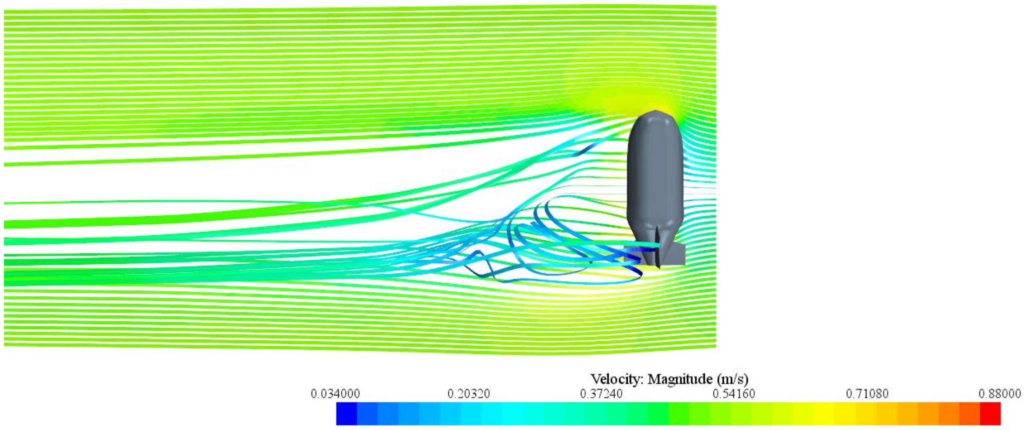

Figure 2. Flow image of the submersible under a transverse current of 1kn.

From the flow image of the submersible under the transverse ocean current, it can be seen that the transverse ocean current has an asymmetric effect on the front and rear of the submersible. As the ocean current increases, the interference with hydrodynamics also increases accordingly.

3. Simulation study on the motion of deep-sea submersible under lateral ocean currents

Computer simulation is the process of using computer tools to simulate and analyze a real system, achieving understanding and analysis of the system through simulation analysis. The process of computer simulation can generally be completed by computer high-level languages, simulation languages, and simulation software.

When studying the motion of manned submersibles, a universal coordinate system is usually used to establish two coordinate systems: one is defined as the system O-XYZ, which is known as the Earth coordinate system; Another definition is the system o-xyz, which is known as the submersible coordinate system. Both coordinate systems use the right-hand system.

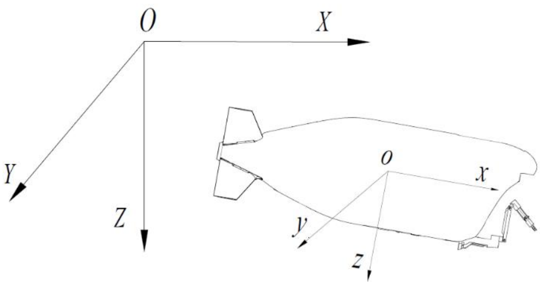

Figure 3. Reference coordinate system for manned submersible.

We can treat a manned submersible as a rigid body and conduct force analysis on it. By using the theory of rigid body motion, we can obtain equation for the submersible in space.Among them, the bow turning model is as follows.

$$\begin{aligned}\sum_{\mathrm{i}} F_{Ni} = {} & \frac{1}{2}\rho L^5\left[N'_{\dot r}\dot r + N'_{\dot p}\dot p + N'_{pq}pq + N'_{qr}qr\right] + \frac{1}{2}\rho L^5\left[N'_{r|r|}r|r| + N'_{p|p|}p|p|\right] \\ & + \frac{1}{2}\rho L^4\left[N'_{\dot v}\dot v + N'_{wr}wr + N'_{wp}wp + N'_{vq}vq + N'_{vww}vw^2 + N'_r ur + N'_p up\right] + \\ & \frac{1}{2}\rho L^4 N'_{|v|r}\left|\left(v^2+w^2\right)^{1/2}\right| r + \frac{1}{2}\rho L^3\left[N'_0 u^2 + N'_v uv + N'_{v|v|}v\left|\left(v^2+w^2\right)^{1/2}\right| + N'_{vw}vw\right] \\ & + \left(x_G W - x_C B\right)\cos\theta\sin\phi + \left(y_G W - y_C B\right)\sin\theta + N_T\end{aligned} \tag{4}$$

From (4), it can be seen that its hydrodynamic model is highly nonlinear coupled, the shape of the manned submersible is complex, and the source of hydrodynamic coefficients is the pool model test of China Ship Scientific Research Center. The dynamic equation under the action of ocean currents is as follows.

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}_{\mathrm{T}} + \boldsymbol{\tau}_{\mathrm{D}} \tag{5}$$

In the formula: $\boldsymbol{\tau}_{\mathrm{T}}$ is the thrust of the submersible's propulsion system, $\boldsymbol{\tau}_D$ is the disturbance hydrodynamic force under ocean currents, and the disturbance hydrodynamic force under transverse ocean currents is obtained through numerical calculations in Section 2.

The main thrust of the manned submersible is maintained at 600N, and a lateral ocean current condition of 1kN is selected to conduct a simulation of the submersible's direct flight motion under cross current. The simulation results are as follows.

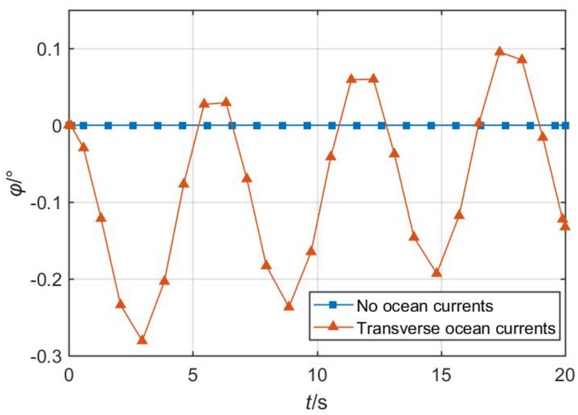

Figure 4. Curve of the transverse inclination angle.

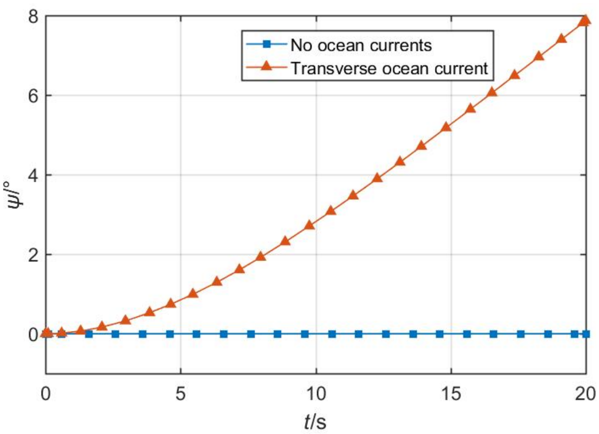

Figure 5. Curve of the heading angle.

The simulation results show that lateral ocean currents can cause changes in the vehicle's roll angle and heading angle, especially with a significant impact on the heading angle. This is due to the asymmetric front and rear shapes of the vehicle, indicating that the vehicle's motion has strong coupling and nonlinear characteristics. The simulation results in this section are consistent with the flow images of the vehicle under lateral ocean currents obtained from numerical calculations in Section 2.

4. Conclusion

A simulation of the direct flight motion of a manned submersible under transverse ocean currents was conducted. The research results indicate that compared to static water environments, lateral ocean currents can cause changes of the roll angle and heading angle of the submersible, especially with a significant impact on the heading angle. This is due to the asymmetric front and rear shapes of the submersible, indicating that its motion has strong coupling and nonlinear characteristics. This work can provide reference for the operation and control of manned submersibles under ocean currents.

Acknowledgments
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