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Characteristics and judging method of falling deep of submarine

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Abstract: [**Objectives**] In order to judge whether there is a falling deep situation on submarine, [**Methods**] a underwater motion model of submarine is established, and the motion accuracy of the model is verified by experimental data; the falling deep of submarine is simulated and the motion characteristics are analyzed; the assumption that there is a critical static load at different navigation speeds is put forward, and the assumption is verified by calculation. The method of judging falling deep of submarine is studied, and the depth rate $\partial H/\partial t$ and pitch change rate $\partial \theta/\partial t$ are used as the criteria for danger of falling deep of submarine. [**Results**] It can quickly and effectively judge whether the submarine is in danger of falling deep. [**Conclusions**] It has certain reference value for safe operation of submarine.

Key words: falling deep of submarine; safety; accident; motion control; simulation
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0 Introduction

In the course of underwater navigation, the situation that the navigation depth of a submarine increases sharply is called falling deep of submarine[1-2]. Falling deep is a sudden situation that a submarine may encounter during navigation. When the density of upper seawater is higher than that of lower seawater, a negative gradient pycnocline is formed, and the buoyancy of seawater decreases dramatically from top to bottom, resulting in sharp falling of the submarine to sea bottom. If the falling of submarine cannot be quickly controlled, the submarine will be destroyed and people in it will be killed once reaching the limit depth. Therefore, from the perspective of underwater navigation safety, it is necessary to analyze the characteristics of falling deep of submarine, make timely and accurate judgment for the phenomenon, and then take effective maneuvering measures.

Many scholars have studied the safety and maneuverability of submarine[3-7]. Wang et al. [3] summarized the safety control technology of submarine at a low underwater speed. Fu et al. [6] analyzed the factors affecting the safety of submarine underwater navigation and established a safety evaluation system for submarine underwater navigation. Yang et al. [7] analyzed the envelope quantitative evaluating indexes for submarine navigation safety and quantitatively described the envelope diagram of submarine navigation safety using Maneuvering Limitation Diagram (MLD). So far, there have been no quantitative criterion for judging the falling deep of submarine. Therefore, this paper intends to establish a motion simulation model of vertical surface of a submarine by analyzing its motion characteristics. On this basis, two aspects of research are carried out. Firstly, by simulating and analyzing falling deep, this paper tries to find out quantitative data that can accurately determine the falling deep of submarine. Secondly, based on the analysis of falling deep characteristics, a reasonable control decision is made to effectively prevent the phenomenon without affecting normal mis-

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sion.

1 Mathematical model of submarine underwater motion

1.1 Submarine motion equation

The underwater motion of submarine can be simplified as vertical plane motion [1-2], with the coupling effect between horizontal motion and vertical plane motion neglected. Under weak maneuver conditions, when the increment Δu of longitudinal velocity component, the vertical velocity component of submarine w, angular velocity q, the bow rudder angle δ_b and the stern rudder angle δ_s are small, they can be approximately neglected in the equation. The horizontal linear motion equation of submarine is as follows:

$$m\dot{u} = X \tag{1}$$

where m is the mass of the submarine; $\dot{u}$ is the longitudinal acceleration; X is the horizontal resistance. Then, the motion equation of the submarine in the vertical plane is

$$\begin{cases} m(\dot{w} - u_0 q) = Z \\ I_y \dot{q} = M \end{cases} \tag{2}$$

where I_y is the moment of inertia; $\dot{w}$ is the acceleration component of the submarine in the vertical direction; u_0 is the initial longitudinal velocity component; M and Z are the moment and force respectively; and $\dot{q}$ is the angular acceleration.

Substituting the above equation into linear hydrodynamic formula, we can obtain the linear equation of the maneuvering motion in the vertical plane, which takes into account the residual static force P, moment M_p and righting moment $M_\theta \theta$, as follows:

$$\begin{cases} (m - Z_{\dot{w}})\dot{w} - Z_w w - Z_{\dot{q}}\dot{q} - (mV + Z_q)q = \\ Z_0 + Z_{\delta_b}\delta_b + Z_{\delta_s}\delta_s + P \\ (I_y - M_{\dot{q}})\dot{q} - M_{\dot{w}}\dot{w} - M_q q - M_w w = \\ M_0 + M_{\delta_b}\delta_b + M_{\delta_s}\delta_s + X_T z_T + M_P + M_\theta \theta \end{cases} \tag{3}$$

where V is the speed of submarine; u is the longitudinal velocity component; P and M_P are the residual static force and moment; $M_\theta \theta$ is the righting moment; θ is the pitch angle; $X_T z_T$ is the moment acting on the hull by propellers; Z_0 and M_0 are the initial force and the initial moment; Z_w and M_w are the zero lift and the zero lift moment while submarine is sailing; other parameters with subscripts, such as Z_w and M_w, are the force and moment of vertical plane motion of submarine, whose detailed values are provided by the relevant design departments. The fourth-order Runge-Kutta method is used to solve Eq. (3) iteratively, and then the motion law of submarine in the vertical plane is obtained.

1.2 Model verification

Three typical speeds, 10, 14 and 18 kn, are selected respectively to conduct overtaking maneuver test and space turning motion of submarines using the established motion models. The characteristic parameters of submarines are calculated under the same working condition and compared with the data of ship test, with the results shown in Tables 1 and 2. $T_a(s)$ in Table 1 is the initial turning time; θ_{ov} is the overtaking pitch angle; H_{ov} is the overtaking

Table 1 Simulation results of submarine overtaking maneuver model and ship test results

Speed /kn	Working condition		Calculation error of characteristic parameters/%		
			T_a(s)	θ_{ov}	H_{ov}
18	Stern hydroplane	20°/−10°	−0.20	0.62	−0.29
		10°/−10°	−0.06	1.02	−0.07
	Sailplane	−20°/−5°	−0.09	−1.80	−0.47
		−10°/−3°	0	−2.78	−0.37
14	Stern hydroplane	20°/−10°	0.08	0.79	0.13
		10°/−10°	0.02	1.40	0.09
	Sailplane	−20°/−5°	−0.18	−1.22	−0.41
		−10°/−3°	−0.20	−3.85	−0.55
10	Stern hydroplane	10°/−10°	0.05	1.52	0.15
	Sailplane	−20°/−5°	0.05	0	−0.17

Table 2 Simulation results of submarine space turning motion model and ship test results

Initial condition				Data source	Motion parameters				
Speed/kn	Rudder/(°)	Sailplane/(°)	Stern hydroplane/(°)		β/(°)	D/L	U/U_0	φ/(°)	θ/(°)
18	20	8.17	16.24	Simulation	−6.643	6.124	0.724	−1.516	0.003
				Ship test	−6.640	6.120	0.725	−1.520	0
	10°	3.49°	6.64	Simulation	−4.299	9.797	0.867	−1.727	0.011
				Ship test	−4.300	9.790	0.868	−1.730	0
14	35	12.48	30.0	Simulation	−9.128	4.220	0.579	−0.748	0.596
				Ship test	−9.130	4.220	0.580	−0.750	0.600
10	35	12.89	30.0	Simulation	−9.149	4.211	0.578	−0.373	0.604
				Ship test	−9.150	4.210	0.579	−0.370	0.600

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depth; β in Table 2 is the drift angle; D/L is the tactical diameter; U/U_0 is the speed lose; and φ is heeling angle. For the detailed meaning of the above parameters, see References [1–2].

From Table 1 and Table 2, it can be seen that the maximum error of the index parameters obtained from the simulation of the overtaking maneuver model and the ship test is less than 4%. The simulation results of the space turning motion model are basically consistent with the test data, which fully meets the requirements of engineering calculation, thus verifying the accuracy and validity of the simulation model.

2 Analysis and design of the criterion for falling deep of submarine

In the course of normal maneuvering, when the depth rate $\partial H/\partial t$ suddenly increases and exceeds a certain value (recorded as $(\partial H/\partial t)$ max, it is considered that falling deep happens, and then its parameters such as depth, pitch angle and speed will change. For this reason, the characteristics of falling deep are analyzed by simulating the situation, and the feasibility of the above criterion is analyzed.

2.1 Model of falling deep

The most common reason for falling deep of submarine is that the density of seawater suddenly decreases, resulting in a sharp decline in buoyancy acting on the submarine. Therefore, given that there is a step change in the density of seawater at t_0, there is

$$\begin{cases}\rho=\rho_0, & t<t_0\\ \rho=\rho_1, & t\geqslant t_0\end{cases} \tag{4}$$

where ρ_0 is the seawater density at normal ambient temperature, and ρ_1 is the seawater density after change. Relevant studies show that [1], when the submarine which was originally in a state of steady state, constant depth and no pitch begins to fall, the force effect of the falling deep caused by the change of seawater density can be equivalent to a downward force P applied to the buoyant center position at a certain moment. It is collectively referred to as static load, as shown in Fig. 1.

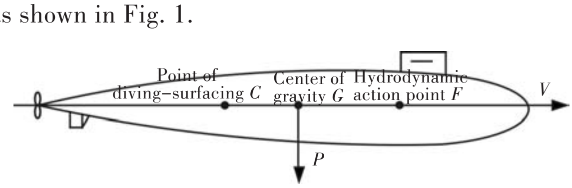

Fig.1 Force situation and main action point position of submarine in vertical plane motion with falling deep

At this time, there is not only a sharp increase of depth but also a change in submarine attitude. If the center of gravity of the submarine G is located behind its hydrodynamic action point F, there will be trim by stern during the process of falling deep, otherwise there will be trim by head. For a certain type of submarine, the relative position of G and F is kept unchanged. A type of submarine whose G is behind F is studied in this paper, namely that there will be trim by stern at the initial stage of falling deep. The relative position of point of diving–surfacing C and center of gravity G determines whether the submarine will float or submerge. If the speed is higher, the point of diving–surfacing C will be closer to the bow. When the submarine sails in a state of constant depth and no pitch, with the static load P applied at the center of gravity, if point C is behind point G, the static load P will make the submarine submerge, otherwise the submarine will float [1]. Therefore, when the submarine experiences falling deep, on the one hand, the speed should be increased immediately, which can not only improve the rudder efficiency but also make the point of diving–surfacing C move forward to restrain the falling trend. On the other hand, the floating rudder is used to control the increase of the submarine depth and balance it. In emergency circumstances, the main ballast tank is blown away by high pressure gas to drain water.

2.2 Simulation analysis of characteristics of falling deep

According to the analysis in Section 2.1, with the point of diving–surfacing backward at low speed, if the seawater density suddenly decreases, the submarine will submerge. However, the submarine may experience trim by stern in the initial stage of falling deep, while the upward hydrodynamic force on the hull will restrain the submarine from submerging. Therefore, when the submarine is subjected to downward static load due to the decrease of seawater density, it will not always cause falling deep.

In order to accurately simulate the characteristics of vertical plane motion of submarine in falling deep, without considering the influence of maneuvering (namely that the original rudder angle is maintained and balance is not carried out), this paper considers the influence of static load caused by the change of speed and density on depth and pitch angle. With 4, 6, 8 and 10 kn selected as initial speed V_s, the falling deep motion at each speed is quantitatively analyzed. The sudden change of seawater density is equalized by loading a certain amount of negative buoyancy at the buoyant center position at a certain

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moment. With the loading time set as 1 000 s of simulation time, a 10 tf static load acting at the center of gravity is simulated to analyze the change in depth and pitch angle θ of the submarine with time, with the results shown in Fig. 2 and Fig. 3.

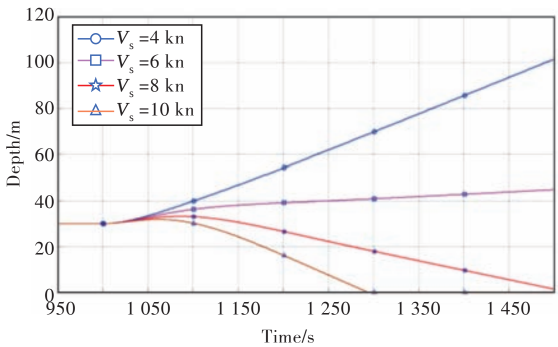

Fig.2 The relationship between submarine depth and time under 10 tf static load

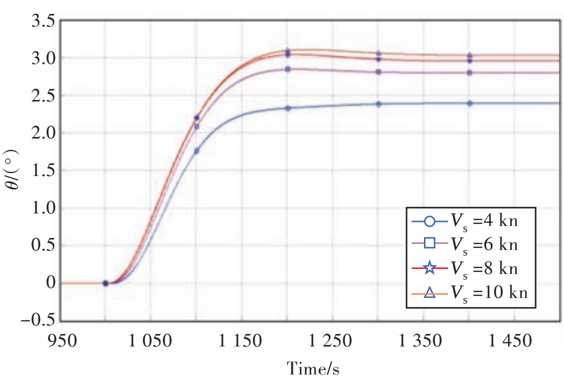

Fig.3 The relationship between the pitch angle of submarine and time under 10 tf static load

As can be seen from Fig. 2, the change trend of submarine depth varies greatly at different speeds. The lower speed (e.g., 4 kn) leads to the faster falling deep. The higher speed (e.g., 6 kn) leads to the slower falling deep. When the speed is higher (e.g., 8 kn and 10 kn), the submarine will float instead.

As can be seen from Fig. 3, the change trend of the pitch angle of submarine at different speeds is relatively consistent, all showing the trend that the trim by stern gradually increases to a stable one. This is because hydrodynamic action point F is in front of the center of gravity G, and the application of static load at the center of gravity will cause trim by stern. In addition, Fig. 3 shows that the higher speed of submarine, results in the greater pitch angle. Therefore, it is advantageous for the submarine to maintain a certain trim by stern while navigating underwater to restrain falling deep.

In the process of simulation, the size and direction of static load P remain unchanged, so the hydrodynamic force P_F produced by the hull is the key factor affecting the motion state of submarine, and P_F increases with the increase of speed. When $P > P_F$, the submarine submerges. When $P < P_F$, the submarine floats. It can be assumed on this basis that for any static load P, there is a critical speed V_C that makes the submarine maintain in a steady state of constant depth with pitch under the action of static load P. In order to verify this hypothesis, the initial submarine depth is set at 30 m, and the submarine sails at steady state and constant depth without pitch. Then the critical speed V_C corresponding to multiple static loads P can be obtained, with the calculation results shown in Table 3. The condition of submarine is reflected by the value of depth rate $\partial H/\partial t$. When $\partial H/\partial t = 0$, the depth of submarine remains unchanged, namely that the submarine sails at constant depth.

Table 3 Critical speed corresponding to different static load

P/t	V_C /kn	Depth/m		Pitch angle/(°)		$\frac{\partial H}{\partial t}$ / (m·s^{-1})
		Initial	Stable	Initial	Stable	
5	6.180	30	31.98	0	1.50	0
10	6.370	30	33.72	0	2.84	0
15	6.590	30	36.30	0	4.05	0
20	6.835	30	37.89	0	5.16	0
25	7.100	30	35.92	0	6.17	0
30	7.375	30	35.71	0	7.10	0
35	7.660	30	32.65	0	7.97	0
40	7.948	30	33.19	0	8.78	0
45	8.242	30	28.52	0	9.51	0
50	8.537	30	24.35	0	10.21	0
55	8.833	30	18.14	0	10.87	0
60	9.128	30	12.19	0	11.49	0
70	9.710	30	7.80	0	12.62	0

As can be seen from Table 3, for a given P, there is a corresponding V_C. With the increase of P, the corresponding V_C and stable pitch angle also increase gradually. Therefore, higher speed is more beneficial to eliminate falling deep. Of course, V_C cannot exceed the maximum speed of submarine, and the pitch angle of submarine in underwater motion cannot be too large. The correspondence between P and V_C can also be considered as the critical static load P_C at its corresponding speed, as shown in Fig. 4. The critical curve in Fig. 4 shows the maximum static load that a submarine can bear at different speeds during underwater motion, and it can also be considered as the safety line of falling deep without maneuvering. The lower side of the curve is the safety area of falling deep. Further analy-

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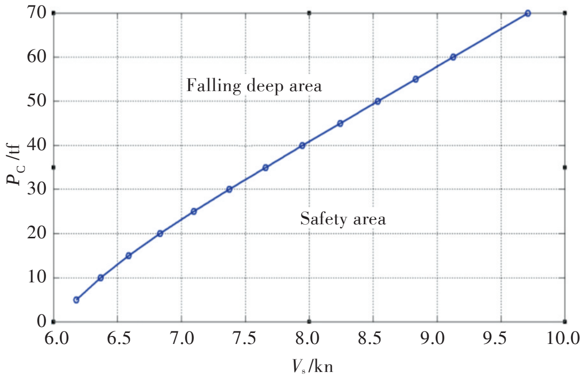

Fig.4 Corresponding relation between velocity and critical static load

sis shows that the curve inevitably passes through the coordinate origin, namely that, when the speed is 0, the static load that a submarine can bear is 0.

2.3 Determination of criterion for falling deep of submarine

According to the simulation results of Section 2.2, if the speed of a submarine is known, the maximum static load of the submarine for falling deep can be determined. However, whether the submarine can bear the static load of falling deep and the magnitude of the static load are unknown. Therefore, it is difficult to directly use the critical curve in Fig. 4 to determine whether there is a falling deep situation. On the other hand, as mentioned above, there are also drawbacks to judge falling deep of a submarine by determining whether the depth rate exceeds $(\partial H/\partial t)_{max}$, because the size and direction of $\partial H/\partial t$ vary in the initial stage of falling deep (as shown in Fig. 3). Misjudgment may occur if it is judged too early. It may take quite a long time if judgment is carried out after $\partial H/\partial t$ is stable, which will miss the optimal retrieving time. In addition, at normal speed, due to the need of rapid submergence, $\partial H/\partial t$ may also reach its maximum. If $(\partial H/\partial t)_{max}$ is used to judge, misjudgment may occur. Therefore, an appropriate criterion that is feasible and can make quick and accurate judgment needs to be designed.

The motion and attitude parameters of submarine that can be directly measured by sensors, such as submarine depth, pitch angle and speed, are preferable to be used as the criterion of falling deep. The simulation results of Section 2.2 show that when the submarine experiences falling deep due to static load, there will be trim by stern and the submarine depth will continue to increase. When it is subjected to static load but without falling deep, trim by stern will also occur, and the depth will increase first and then decrease. On the critical curve, the submarine depth will tend to be stable. Therefore, the depth rate $\partial H/\partial t$ and the change rate of pitch angle $\partial\theta/\partial t$ are selected as the criterion for falling deep of submarine. The procedure is as follows:

1) The data on the critical curve are analyzed; speed and critical static load of the 13 groups in Table 3 are simulated; and sampling calculation of $\partial H/\partial t$ and $\partial\theta/\partial t$ at a sampling interval is conducted.

2) The points taken from the safety area in Fig. 4 are analyzed and calculated with speeds as 7, 8, 9 and 9.5 kn, respectively. The static load corresponding to the grid intersection position of each speed in Fig. 4 is selected for simulation, and then $\partial H/\partial t$ and $\partial\theta/\partial t$ are sampled and calculated according to Step 1).

3) The points taken from the danger area in Fig. 4 are analyzed and calculated, with speeds as 6.5, 7, 8 and 9 kn, respectively. According to Step 2), the corresponding static loads are selected for simulation, and then $\partial H/\partial t$ and $\partial\theta/\partial t$ are sampled and calculated according to Step 1).

Sampling time is set to 10 s, and the calculated results are plotted in plane coordinates, as shown in Fig. 5.

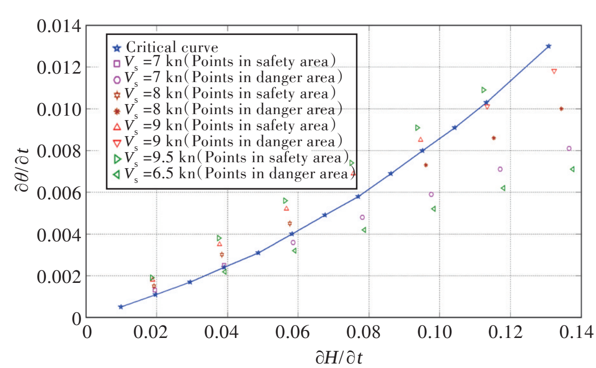

Fig.5 Judgment effect of $\partial H/\partial t$ and $\partial\theta/\partial t$ on falling deep (10 s sampling time)

The critical curve in Fig. 5 can clearly distinguish the safety area (its upper side) from the danger area (its lower side). It can be proved that falling deep of submarine can be effectively judged by $\partial H/\partial t$ and $\partial\theta/\partial t$, and the sampling time is short (only 10 s), so that timely measures can be taken against the situation.

With sampling time set to 20 s and 30 s, this paper further compares the judgment effect of different sampling time on falling deep, with the results shown in Fig. 6. It can be seen that the value intervals of $\partial H/\partial t$ and $\partial\theta/\partial t$ will change with the increase of sampling time, but the relative positions of sample points are basically the same. Therefore, the sampling time has little effect on the validity of the crite-

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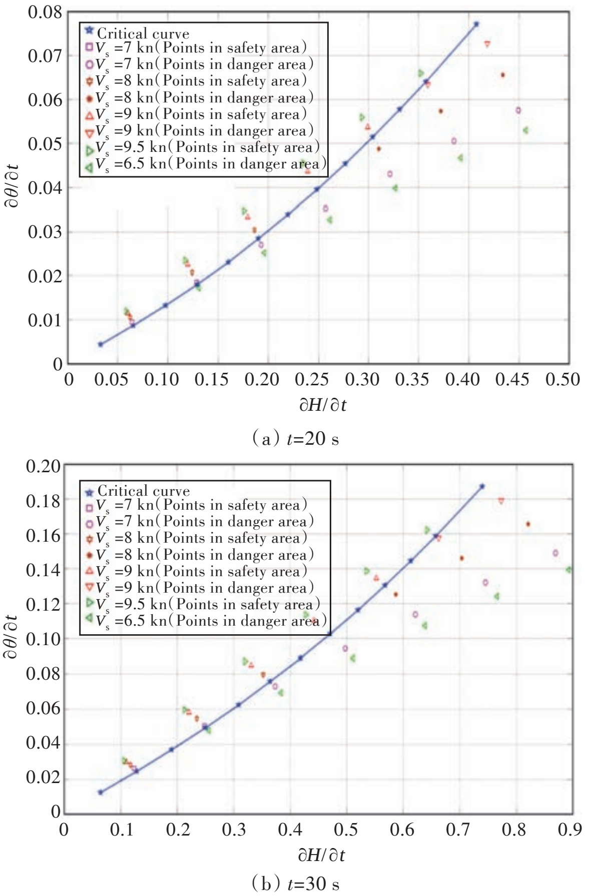

Fig.6 Judgment effect of $\partial H/\partial t$ and $\partial\theta/\partial t$ on falling deep (20 and 30 s sampling time)

rion. Based on the results above, in order to make a quick judgment on the falling deep of submarine, sampling time of 10 s is recommended.

In actual operation, the depth and pitch angle of submarine can be sampled to calculate the values of $\partial H/\partial t$ and $\partial\theta/\partial t$ in 10 s before the current time to determine whether there is falling deep according to Fig. 5. In order to obtain the data form of the criterion, the dividing line data in Fig. 5 are processed and approximated by regular curves, and the exponential function is selected according to the distribution trend of data points of the dividing line, with the results shown in Fig. 7.

Therefore, the criterion of falling deep of the submarine is obtained as follows:

$$\begin{cases} \dfrac{\partial\theta}{\partial t} > K\left(\dfrac{\partial H}{\partial t}\right)^n, & \text{safety} \\ \dfrac{\partial\theta}{\partial t} < K\left(\dfrac{\partial H}{\partial t}\right)^n, & \text{danger} \end{cases} \quad (5)$$

where K = 0.201 22; n = 1.355 4. For different types of submarines, the values of K and n may change.

2.4 Analysis of the possibility of misjudgment

The feasibility of the criterion has been analyzed.

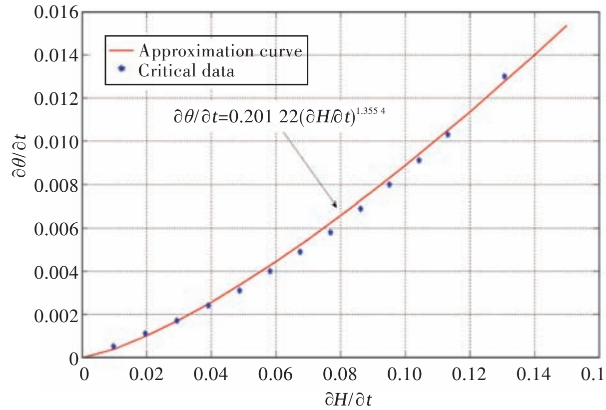

Fig.7 Curve approximation effect of sample points on the critical line

In theory, the criterion is a necessary condition for falling deep of submarine. If falling deep occurs, the submarine must meet the condition of "danger" that is judged by the criterion. Next, the sufficiency of the criterion will be analyzed, namely that whether there will be misjudgment when there is no falling deep.

2.4.1 Analysis of misjudgment caused by wind waves

Usually, the navigation depth of submarine is large and the influence of wind waves is small, so the criterion of falling deep put forward in this paper is based on still-water navigation. Although the influence of wind waves near the sea surface is great, the time of submarine sailing in vent pipe state or near sea surface is generally short, and the possibility of sudden change of seawater density near the sea surface is very small. The possibility of falling deep is very small. Therefore, the influence of wind waves on falling deep is small enough to be neglected.

2.4.2 Analysis of misjudgment caused by normal maneuvering

The calculation example of Section 2.2 shows that the criterion essentially describes a state in which both the pitch angle and the depth of submarine increase. From the maneuvering point of view, the underwater submarine navigation is at steady state and constant depth or is maneuvering with changing depths. When at steady state and constant depth, if the trim by stern occurs, it must be caused by "the weight of the hull", namely that the submarine is subjected to downward static load and falling deep may happen. In the course of maneuvering with changing depths, if the submarine submerges, the normal maneuvering condition is trim by bow, and if it floats, the normal maneuvering condition is trim by stern. Besides, trim by stern will not occur at normal

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changing depths. Therefore, from the normal maneuvering point of view, it can be concluded that the submarine is subjected to downward static load through the state of trim by stern, and there is a possibility that falling deep will occur. Hence, normal maneuvering will not lead to misjudgment.

3 Conclusions

In this paper, a certain type of submarine is taken as the research object and a simulation model of its vertical plane motion is established. The accuracy of the model is verified by the overtaking test data provided by the design department, and then the characteristics and criterion of falling deep of submarine are analyzed and studied. Through simulation, the assumption of critical static load corresponding to different speeds is put forward and verified by calculation.

The results show that there exists a relationship curve between speed and critical static load for a certain type of submarine. Based on the analysis of the characteristics of the critical curve, $\partial H/\partial t$ and $\partial \theta/\partial t$ are used as the criterion for judging falling deep. The advantage of the criterion is that it can make an effective judgment about whether the submarine will experience falling deep in a short time (10 s). In addition, the sampling data include depth and pitch angle of submarine, both of which are the most basic parameters of motion state and have high reliability and operability, and they can provide certain reference value for ensuring the safe navigation of submarine.

The criterion for falling deep of submarine proposed in this paper has a certain scope of application, namely that it is suitable for judging the falling deep caused by the static load varying with the change of seawater density, which is also the main reason for falling deep of submarine during underwater navigation. Other factors that may lead to falling deep need to be further studied.

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潜艇掉深现象的特点与判定方法

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摘　要:[**目的**]为有效判断潜艇是否存在掉深现象,[**方法**]建立潜艇水下运动模型,利用实验数据验证模型运动精度;模拟潜艇掉深现象,并进行运动特性分析;提出在不同航速下存在临界静载力的设想,通过计算验证这一设想。研究潜艇掉深的判别方法,提出将深度速率 $\partial H/\partial t$ 和纵倾变化率 $\partial\theta/\partial t$ 作为潜艇出现掉深的判据。[**结果**]能够快速有效地判断潜艇是否存在掉深危险。[**结论**]对潜艇安全操纵有一定的参考价值。

关键词:潜艇掉深;安全性;事故;运动控制;仿真

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