Research on Motion Law of Submarine Emergency Floating Under High-Pressure Blowing

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Abstract: The use of high-pressure air to blow out the ballast tank to obtain positive buoyancy and enable the submarine to quickly rise to the surface of the water is an important measure for emergency recovery of the submarine in the event of damage and water ingress accidents. However, during the emergency ascent process of submarines, especially in the later stage of recovery, attitude control is very difficult due to the rapid increase of positive buoyancy. Dangerous trim and heeling are highly likely to lead to the failure of submarine recovery. This article constructs a mathematical model for the blowing of ballast water tanks to accurately control the blowing timing, blowing position, and blowing time during the emergency recovery process of submarines. It optimizes and adjusts the motion posture of submarines in real time to ensure the safety of submarines during emergency recovery. The simulation results indicate that the constructed mathematical model can effectively predict the motion law of submarine emergency buoyancy.

1 INTRODUCTION

When submarine is navigating underwater or maneuvering in battle as a strategic weapon, if accidents such as rudder jamming, grounding and collision cause damage to the pressure hull and water ingress, damage to the sea pipeline and water ingress, sudden change of seawater density, mechanical failure and manipulation error occur, the maneuvering state of the submarine will change dramatically, which is very likely to cause accidents due to large trim and exceeding the limit depth.

In order to study the maneuver characteristics and motion laws of submarine during emergency ascent, it is necessary to calculate the force changes during emergency ascent in real time, control the space attitude of submarine during emergency recovery, and prevent the submarine from rolling and rolling due to dangerous pitch and roll. Literature (LIU H, 2013) established the mathematical model of gas parameters and drainage flow in the ballast tank during gas purging through thermodynamic analysis of the process of gas purging ballast tank. Literature (YANG S, 2009) established a mathematical model of the ballast tank purging process, and carried out a small-scale experiment on the principle of the submarine emergency gas purging system model, which effectively verified the mathematical model established. The results of literature (LIU R J, 2014) show that the process of gas release from the high-pressure gas cylinder can be considered as an adiabatic process, the gas and water in the ballast water tank have the same temperature, and the gas expansion process in the ballast water tank is considered as a constant temperature process. The above literature research methods are similar. A mathematical and physical model for purging is established by analyzing the change characteristics of the gas in the high-pressure gas purging ballast water tank. Combined with the submarine emergency operation model, the attitude change of the submarine during the floating process is studied (ZHANG J H, LIU C B).

Due to the change of the gas in the ballast tank with the submarine depth will cause the change of the force and attitude of the submarine, it is necessary to study the high pressure blow off time and the time to release the pressure in the submarine recovery process. Based on the construction of high-pressure air blowing model and pressure relief model, combined with the submarine emergency buoyancy control model developed by the research group (WU W Y, 2015), this paper studies the submarine buoyancy movement law and attitude control strategy during the emergency recovery of high-pressure air blowing ballast tank.

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2 MODELOF HIGH-PRESSURE AIR BLOWING BALLAST TANK BASED ON COMPRESSIBLE ISENTROPIC FLOW THEORY

In order to facilitate the research, the pressure cylinder used for purging on the submarine is equivalent to a high-pressure air shunt box, which is used to control high-pressure air blowing into each main ballast water tank. According to the one-dimensional isotropic compressible flow theory, the maximum flow velocity at the high-pressure gas blowing outlet is sound velocity (WU W Y, 2015). The experiment shows that when the pressure ratio on both sides of the outlet is lower than the critical value T_{lj}, the release velocity of high-pressure gas at the outlet is sound velocity.

$$T_{lj} = (\frac{2}{k+1})^{\frac{k}{k-1}} \tag{1}$$

Assuming that the high-pressure gas flow is isotropic flow during the process of high-pressure gas blowing off the ballast tank.

$$\frac{d\rho_F(t)}{dt} = C_1 \rho_F^{\frac{k+1}{2}}, C_1 = \frac{\frac{d\rho_F}{dt}|t=0}{\rho_{F0}^{\frac{k+1}{2}}} \tag{2}$$

C_1 is a negative constant, which only depends on the capacity of the high-pressure gas cylinder and the diameter of the nozzle. By integrating the above equation, the isotropic model of high-pressure gas purging can be obtained.

$$\rho_F(t) = \frac{\rho_F}{(1-\frac{k-1}{2}C_2 t)^{\frac{2}{k-1}}}, \quad C_2 = C_1 \rho_{F0}^{\frac{k-1}{2}} = \frac{\frac{d\rho_F}{dt}|t=0}{\rho_{F0}} = \frac{\frac{dm_F}{dt}|t=0}{m_{F0}} \tag{3}$$

$$P_F(t) = \frac{P_{F0}}{(1-\frac{k-1}{2}C_2 t)^{\frac{2k}{k-1}}}, \quad m_F(t) = \frac{m_{F0}}{(1-\frac{k-1}{2}C_2 t)^{\frac{2}{k-1}}} \tag{4}$$

The mass of high-pressure gas entering the simulated ballast water tank at each quasi-static calculation time point is as flowing.

$$\dot{m}_F = [\frac{m_{F0}}{[1-\frac{k-1}{2}C_2(t-1)]^{\frac{2}{k-1}}} - \frac{m_{F0}}{(1-\frac{k-1}{2}C_2 t)^{\frac{2}{k-1}}}] \times \Delta t \tag{5}$$

In the above formula, P_F, m_F and ρ_F respectively represent the gas pressure, gas mass and density in the high-pressure cylinder group. C_2 is the purging constant of high-pressure gas, which may vary from - 0.1 to -0.01, mainly depending on the nozzle diameter and the high-pressure gas storage capacity in the cylinder. $\dot{m}_F$ is the high pressure gas flow, and Δt is the calculation time step at every two calculation time points. k is the isotropic constant.

3 RELIEVING PRESSURE MODEL OF HIGH PRESSURE AIR BLOWING MAIN BALLAST TANK

3.1 The Basic Assumption of Combining Model

When stopping to blow the main ballast water tank after a period of time with high-pressure gas blowing, the gas status parameters in the high-pressure gas cylinder remain unchanged, and the gas flow of the main ballast water tank system with high-pressure gas blowing is 0. When the submarine rises to a certain depth, due to the decrease of environmental pressure, the gas in the main ballast water tank continues to expand, and the displacement of the ballast water tank continues to increase. At this time, the attitude of the submarine is difficult to control. If no measures are taken, the submarine will rush out of the water at a high speed, and form a large heel, which poses a threat to the submarine (LIU H, 2019). Therefore, in the process of emergency buoyancy of the submarine, it is necessary to choose an appropriate time to relieve the pressure in the main ballast tank. If the pressure is relieved too early, the submarine may sink again due to insufficient buoyancy. If the air pressure is released too late, the submarine may not be able to control because of the fast floating speed.

In the process of relieving the air pressure, on the one hand, the gas in the main ballast tank continues to expand. On the other hand, the gas in the main ballast tank is discharged through the vent valve. In order to establish the main ballast tank pressure relief model, the following assumptions are made (JIN T, 2010).

1) The gas expansion in the main ballast tank is adiabatic expansion.

2) The outflow process of gas from the main ballast tank through the vent valve is isentropic flow, and can be simulated as Laval nozzle.

3) The gas in the main ballast tank is in stagnation state.

4) The status parameters at the vent valve outlet are P_k , T_k , ρ_k , P_{k0} .The outlet area is A_k , and valve coefficient is C_k .

3.2 Relieving Pressure Model of Main Ballast Tank

When the high-pressure gas stops blowing to relieve the pressure, part of the high-pressure gas in the ballast water tank continues to expand and part of it flows out through the vent valve. According to the Laval nozzle model, the outlet flow $\dot{m}_B$ of the vent valve can be obtained, and the gas change law in the ballast water tank can be obtained.

1) $\frac{P_{k0}}{P_B} \le \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$, the air flow at the vent valve outlet is sonic, and the outlet gas pressure is critical pressure.

$$\dot{m}_B = \frac{A_k C_k P_B}{\sqrt{RT_B}} \cdot \sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{6}$$

2) $1 > \frac{P_{k0}}{P_B} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$, the air flow at the vent valve outlet is subsonic, and $P_k = P_{k0}$.

$$\frac{P_k}{{\rho_k}^k} = \frac{P_B}{{\rho_B}^k}, \quad \dot{m}_B = A_t C_t \frac{P_B}{\sqrt{RT_B}} \cdot \sqrt{2\frac{k}{k-1} \cdot \left(\frac{P_k}{P_B}\right)^{\frac{2}{k}} \left[1 - \left(\frac{P_k}{P_B}\right)^{\frac{k-1}{k}}\right]} \tag{7}$$

3) $P_{k0} = P_B$, the air flow is zero.

$$\dot{m}_B = 0 \tag{8}$$

For the gas in the main ballast tank, according to the gas adiabatic expansion state equation.

$$\frac{dP_B}{dt} = \frac{P_B q_B}{V_B}, \quad q_B = \frac{dV_B}{dt}, \quad \frac{dP_B}{dt} = \frac{\frac{dm_B}{dt} RT_B - P_B q_B}{V_B} \tag{9}$$

According to the isotropic flow calculation formula and equation of state

$$P_B = C \cdot {\rho_B}^k, \quad P_B V_B = m_B R T_B, \quad C = \frac{k}{k-1} \cdot \frac{P_B}{\rho_B} + \frac{{V_B}^2}{2}, \quad \frac{dT_B}{dt} = \frac{T_B}{m_B}(k-1)\dot{m}_B \tag{10}$$

3.3 Drainage Rate for the Water of Main Ballast Tank

1) $P_B - P_h - \rho_w g h > 0$

$$V_h = \sqrt{\frac{2(P_B - P_h)}{\rho_w} + 2gh}, \quad \frac{dV_B}{dt} = q_B = C_h \cdot V_h \cdot A_h = C_h A_h \sqrt{\frac{2(P_B - P_h)}{\rho_w} + 2gh} \tag{11}$$

2) $P_B - P_h - \rho_w g h < 0$

$$V_h = \sqrt{\frac{2(P_h - P_B)}{\rho_w} - 2gh}, \quad \frac{dV_B}{dt} = q_B = C_h \cdot V_h \cdot A_h = C_h A_h \sqrt{\frac{2(P_h - P_B)}{\rho_w} - 2gh} \tag{12}$$

In the above formula, P_B , T_B , V_B and ρ_B respectively represent the gas pressure, gas temperature, gas volume and density. P_h , V_h , A_h and ρ_w respectively represent submarine depth, drainage velocity, drainage valve area and water density. C_h is drainage coefficient, and equal to 0.45. k is isentropic constant, and equal to 1.4. R is gas constant.

4 THE RESULTS AND ANALYSIS OF SIMULATION EXPERIMENT

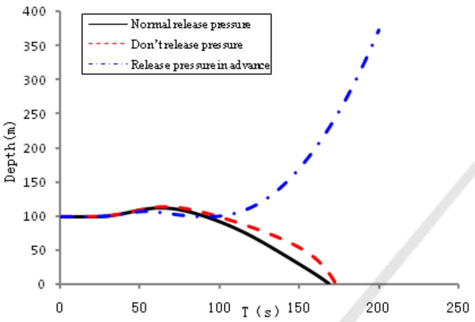
Through the mathematical model of submarine emergency manoeuvring movement established by the research group, combined with the high-pressure air blow off ballast tank and pressure relief model established in this paper, the simulation experiment was carried out for the emergency recovery of a submarine with high-pressure blow off ballast tank after the damage of the sea opening pipeline in the bow I cabin caused the cabin water ingress accident. The motion characteristics of submarine recovery process under three conditions of normal pressure relief, no pressure relief and early pressure relief during high-pressure gas blowing are compared and analyzed, which provides a theoretical basis for accurate control under accident conditions.

Table 1. Emergency recovery plan under submarine accident state.

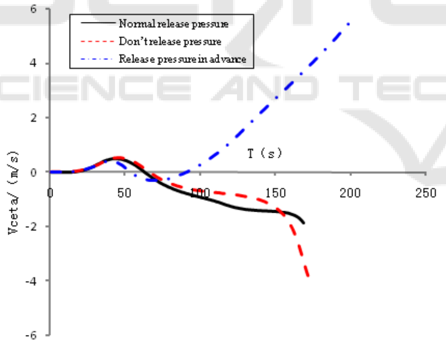
Depth	Speed	Diameter of broken hole	Recovery plan	Remarks
$100m$	4kn	$\Phi_{pk} = 150mm$	$t = 20s$, increase speed, $\delta_s = -20^\circ, \delta_b = 5^\circ$ $t = 30s$,blow head main ballast tanks $t = 60s$,stop blowing $t = 115s$, release pressure, $\delta_s = -2^\circ, \delta_b = 5^\circ$	Normal release pressure
			$t = 20s$, increase speed, $\delta_s = -20^\circ, \delta_b = 5^\circ$ $t = 30s$,blow head main ballast tanks $t = 60s$, stop blowing	Don’t release pressure

			$t=20s$, increase speed , $\delta_s=-20^\circ,\delta_b=5^\circ$ $t=30s$,blow head and middle main ballast tanks $t=60s$, stop blowing and release pressure	Release pressure in advance

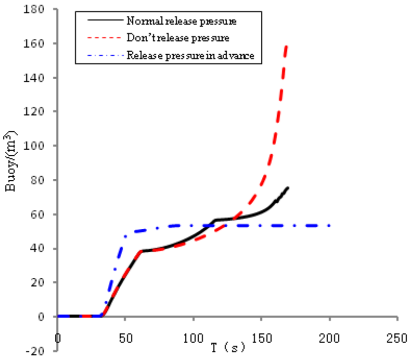
It can be seen that the motion characteristic of submarine recovery varies greatly when high-pressure air is used to blow off under the same accident conditions and the air pressure is released at different times from the simulation experiment conditions in Table 1 and the motion characteristic curve in the submarine emergency recovery process in Figure 1.



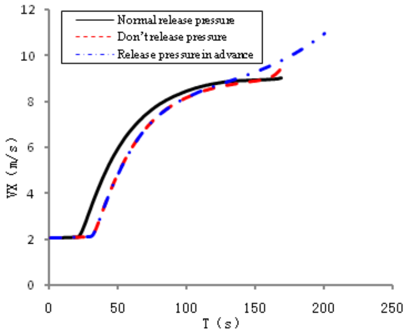
(a)Change curve of submarine depth



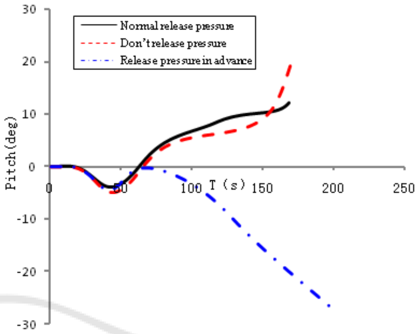
(b)Change curve of submarine vertical velocity



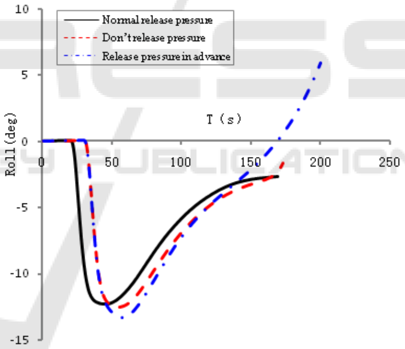
(c)Change curve of displacement under



(d)Change curve of submarine axial velocity



(e)Change curve of submarine pitch



(f)Change curve of submarine heel

Figure 1. Emergency recovery history curve of submarine high-pressure air blowing under different recovery plan.

It can be seen in Figure 1 (a) that the submarine can recover and float to the surface if the pressure is removed normally or not. If the pressure is removed too early, the submarine will fail to recover. Figure 1 (b) shows the submarine vertical floating velocity. If the air pressure is not removed, the velocities of submarine floating to surface will more than four meters per minute, which is very dangerous. According to recovery success criterion, there is failure when the floating velocity more than 3 meters per minute. But if the air pressure is removed in advance, the submarine cannot float to surface during the floating force not enough. Figure1 (c) shows the displacement of the ballast water tank. If the air pressure is not removed, the drainage of the submarine will increase rapidly due to the rapid expansion of the gas in the ballast water tank in the later recovery period, which is consistent with the result of too fast floating speed in Figure 1 (b). The displacement and floating speed can be effectively controlled when the air pressure is removed properly. Figure 1 (e) shows the trim change of the submarine. If the air pressure is not released or released in advance, a large trim will occur due to excessive and insufficient displacement. If the air pressure is not released, the trim will exceed 20 degrees. If the air pressure is released too early, the submarine will sink to the seabed with a large trim. Figure 1 (f) shows the change of the submarine's heel. At the initial stage of damage and water ingress, due to the sharp increase of the heel of the submarine under the additional force, after taking the blowing out measures, the additional torque decreases, and the heel decreases significantly, basically maintaining a normal state.

5 CONCLUSION

In view of the difficulty of attitude control in emergency recovery of submarine ballast tank by high-pressure air blowing, this paper takes the pressure gas in ballast tank as the research object, builds mathematical and physical models of high-pressure air blowing and pressure relief, and analyzes the influence of high-pressure air release timing on recovery results in the process of emergency recovery of submarine high-pressure air blowing combined with submarine accident examples.

1) When applying high-pressure air to blow out the main ballast water tank of the submarine to retrieve the submarine, the duration of high-pressure air blowing out and the time to relieve the pressure in the ballast water tank are very important, which not only seriously affect the submarine attitude in the recovery process, but also directly determine whether the submarine is successfully recovered.

2) As the recovery depth of the submarine decreases, the gas in the ballast tank expands rapidly. If the air pressure is not relieved, the submarine will appear serious heeling and rolling phenomenon during floating, and the floating speed and pitch are too large, making the submarine appear dangerous attitude.

3) If the pressure of the ballast water tank is released too early in the recovery process, the submarine will have insufficient positive buoyancy at the later stage of recovery, resulting in failure of emergency recovery.

4) It is necessary to develop a prediction system for submarine high-pressure air blowing emergency recovery movement law, evaluate submarine movement status in real time, change the time and opportunity of high-pressure air blowing off the main ballast tank and the time to release air pressure, and control submarine recovery movement posture by changing submarine speed, steering and other dynamic anti sinking measures, so as to provide decision-making support for submarine commanders to formulate emergency recovery plans.

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