Calculation on Refloating a damaged ship with salvage pontoon

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Abstract. Refloating a damaged ship with salvage pontoon can be very complicated. In the calculation process of traditional pontoon salvage for shipwrecks, the calculation of inflation time, analysis of pontoon motion and intelligent control are mainly studied. When the pontoon is inflated, the volume of gas in the pontoon will change with the change of time and temperature, which will affect the accuracy of salvage measurement. In this paper, According to the theory of heat conduction, a mathematical model of gas volume in pontoon varying with time and temperature is established, which is beneficial to getting the buoyancy and stability of ships. Through the simulation, the refloating process of a damaged ship with salvage pontoon was researched. Computation result shows that shipwreck with many pontoons sunk in the water totally of the preliminary stage, since the stability of the shipwreck is poor, the aeration rate in the pontoon should be calculated accurately to prevent the capsizing of the ship. As the draft of the wreck decreases, the stability of the hull increases gradually, which is beneficial to the process of lifting and floating. The change of pitch angle is small in the course of buoyancy, but it has obvious influence on the buoyancy distribution of ship hull. The position of pontoon has a great influence on the distribution of shear force and bending moment of ship hull. Relevant measures should be taken to reduce the damage to ship hull in the course of buoyancy.

1. Introduction

Generally, there are few major ship accidents. Because the design and construction phases of ships will be completed strictly in accordance with the relevant classification societies and international regulations.

Man-made and natural factors are the main reasons for the wreck. Man-made factors include carelessness of drivers, rule-breaking operation of management staff, low professional skills of technicians, etc., which damages the wrecked ship and causes it to sink in the water. Natural factors include bad weather (storm, typhoon, fog), underwater collision (reef, iceberg), collision of marine organisms (whale, shark, flag and other large organisms) and corrosion damage caused by marine organisms attaching to the surface of ships[1,2].

There are many ways to salvage shipwrecks. Each method can be used independently or in combination, depending on the specific needs. These methods are respectively sealed pumping salvage method, pontoon salvage method, ship lifting salvage method, foam plastic salvage method, cofferdam salvage method, inflatable drainage salvage method and so on. Among them, the pontoon salvage method
method is the one most commonly used [3-5]. The selection of a wreck removal method for a particular case involves taking into account a multitude of parameters. The most important are environmental parameters, such as prevailing weather conditions and the type of the seabed, and the weight of the shipwreck, which will determine the required lifting capacity. Pontoon salvage method was more often used in practical engineering [6].

At present, there is short of research on the pontoon salvage of shipwrecks. The research focus on the influence of pontoon on the hull, the mechanical analysis of pontoon, the analysis of pontoon motion and the motion control of pontoon.

In the salvage project of SEWOL, engineers found that pontoons of different heights could not be inflated synchronously, which resulted in low efficiency [7]. In order to reduce the lifting force of the bow, the bending moment and shear force of the hull girder and the overturn of the hull to the deck side after inflating the sunken ship cabin, it is necessary to allocate sufficient external buoyancy for the sunken ship. Pontoons were used in the bow lifting project of SEWOL, which provided 1630 tons of lifting buoyancy. According to the internal and external space and structure of the ship, additional buoyancy can be provided by installing airbags, rubber pontoons and steel salvage pontoons in the ship [8].

Ilias Zilakos and Michael Toulios studied the force of the air bag in the inflatable state and the lifting state, which provided a theoretical basis for the design of the air bag for rescue of damaged ships [9]. The mechanics changes of hull during the rescue of damaged ship by airbag are studied, but the influence of floating motion on structure is not involved [10]. In order to improve the launching speed and safety, reduce the difficulty of operation and reduce the time of launching, Lu Heng et al. put forward a novel floating structure [11].

LU et al. designed a new automatic control salvage pontoon based on Siemens, which can realize remote operation and reduce labor costs. The bottom of the pontoon is equipped with a submersible pump and a pressure sensor B, and the sensor A is installed inside the pontoon. Sensors A and B are connected to computer on the water surface. Workers on surface can use Siemens to obtain the internal pressure of the pontoon and decide whether to turn on or off the submersible pump to control the pontoon’s descent and rise [12]. In order to improve the anti-sinking performance of damaged ships, Hee et al. designed a buoyancy support system. The system uses fire fighting system as the inflatable structure of air cavity. In this paper, the ship hull with complex structure is tested, and the results are good, but it is difficult to control the water inflow [13].

A.K.D. Velayudhan designed an automatic control method for underwater lifting of airbag sediment, but the effect of air bag intake and exhaust on salvage process has not been studied in detail [14]. Chen Xiayin et al. systematically calculate buoyancy of pontoons by using multi-physical field simulation and piecewise curved-to-straight algorithm, which reduces the calculation error [15]. Yang Xin and Yebo introduced a set of automatic monitoring system with obvious advantages for pontoon salvage controlled by computer and PLC bus. The control mode of this system is mainly controlled by communication between upper computer and lower computer, which has very good stability [16].

Liu et al. introduced the application of safety analysis method of fuzzy logic to safety analysis of pontoon salvage of shipwrecks. This method is suitable for dealing with uncertainty in safety assessment [17].

At present, there are few references about the salvage pontoon. Researches mainly about the pontoon inflation calculation, hydrodynamic calculation and intelligent control, ignoring the change of temperature after air inflation of the pontoon. When the pontoon is used to lift a sunken ship, the buoyancy of the pontoon will change because of the heat dissipation after the pontoon is inflated, which will affect the accuracy of the calculation of the buoyancy. In this paper, the influence of temperature change on pressure after pontoon inflation is theoretically deduced. The process of pontoon lifting and sinking is further simulated, and the influence of different aeration rate on the state of sinking ship is analyzed.
2. Calculation of gas in pontoon

When the heat dissipation area of pontoon inflation space is $S_p$, the heat conductivity $h_p$, the constant-volume specific heat of gas $C_p$, and the volume of gas $V$, the heat conduction constant of pontoon inflation space is obtained as follows [18]:

$$H = \frac{S_p \cdot h_p}{C_p \cdot \rho_0 \cdot V}$$  \hspace{1cm} (1)

In the process of blowing up, the speed of inflation is much higher than that of temperature change, assuming that the inflation stage can be regarded as an adiabatic process. The density and temperature of cabin gases can be approximated as linear variations, which are presented as follows [19]:

$$\rho(t) = \rho_0 + \frac{\rho(t_0) - \rho_0}{t_0} \cdot t$$  \hspace{1cm} (2)

Here, $\rho_0$ is density of air; $\rho(t_0)$ is density of cabin gas after the process of blowing up; $t_0$ is time of the process of blowing up; $t$ is any time of the process of blowing up.

$$T(t) = T_0 + \frac{T(t_0) - T_0}{t_0} \cdot t$$  \hspace{1cm} (3)

Where, $T_0$ is temperature of air; $T(t_0)$ is temperature of cabin gas after the process of blowing up;

In practical engineering, when the temperature of the cabin decreases $T^\Delta(t)$ due to the heat dissipation in the pontoon, the energy conservation equation is as follows [20]:

$$H[T(t) - T^\Delta(t) - T_0] = \frac{\rho(t)}{\rho_0} \cdot \frac{dT^\Delta(t)}{dt}$$  \hspace{1cm} (4)

By the equation of (2), (3), (4), equation (4) is obtained:

$$T^\Delta(t_0) = \left\{ H \cdot t_0 - 1 + 1 \cdot \left[ \frac{P_s}{P_0} - \left( \frac{P_s}{P_0} \right)^\frac{1}{k-1} \right] - H \cdot t_0 \cdot \left( \frac{P_s}{P_0} \right)^\frac{k}{k-1} \cdot \frac{P}{P_0} - \frac{P}{P_0} \cdot \left( \frac{P_s}{P_0} \right)^\frac{k}{k-1} \cdot \frac{T_0}{T_0} \right\} \cdot \frac{1}{t_0 + P_s \cdot \frac{P}{P_0} \cdot \left( \frac{P_s}{P_0} \right)^\frac{k}{k-1}} \cdot T(t_0)$$  \hspace{1cm} (5)

At the end of inflation, the actual temperature and density of the gas in the cabin can be presented as follows:

$$T(t_{0a}) \approx T(t_0) - T^\Delta(t_0)$$  \hspace{1cm} (6)

$$\rho(t_{0a}) \approx \frac{P}{R \cdot T(t_{0a})}$$  \hspace{1cm} (7)

Here, $P$ is air pressure before the process of blowing up. $R$ is gas constant.

After inflation, the cabin temperature gradually decreases due to heat dissipation. The cabin temperature is obtained from equation (4).

$$T(t) = T_0 - [T_0 - T(t_0) + T^\Delta(t_0)] \cdot e^{\frac{-t}{\tau_{1/2}}}$$  \hspace{1cm} (8)
The pressure of the gas in the cabin can be obtained:

\[ P(t_{ta}) = \rho(t_{ta}) \cdot T(t) \cdot R \]  

(9)

The volume of gas in the cabin is:

\[ V(t_{ta}) = \frac{P \cdot V}{P(t_{ta})} \]  

(10)

According to equation (10), the inflow volume, weight and center of gravity of the pontoon and the buoyancy of the pontoon and the state of the sunken ship can be obtained.

3. Analysis of examples

Above is the theoretical analysis of the floating process of the damaged sunken ship. This example simulates and analyses the floating process of a barge by pontoon. The layout of pontoons is shown in Fig. 1, and the main dimensions of the ship are shown in Table 1. The above is the theoretical analysis on refloating a shipwreck.

![Figure 1. Arrangement plan of pontoons.](image)

Table 1. The main dimensions of the ship.

| Overall length /m | Moulded breadth /m | Moulded depth /m | Weight W/kN |
|-------------------|--------------------|------------------|-------------|
| 79.54             | 32.4               | 5.2              | 26998.48    |

The ship’s hold is broken causing ship sinking during the voyage due to an accident. Through underwater inspection of the damaged ship, it is found that the bow cabin and side cabins of the damaged ship are broken. Here, the lifting process of the shipwrecks is calculated.

The ship was sank in an accident during the voyage. Through underwater detection of the damaged ship, it is found that the bow part of the cabin and cabins on either side are broken.

Case A, liquid load rate is 0.5, draft is 5.241, local effluent of stern, tail inclination is 0.47;
Case B, liquid load rate is 0.25, draft is 4.725, local effluent of stern, tail inclination is 0.39;
Case C, liquid load rate is 0.05, draft is 4.314, local effluent of stern, tail inclination is 0.33;
Case D, liquid load rate is 0, draft is 4.198, local effluent of stern, tail inclination is 0.3.

4. Results and discussions

4.1. Ship stability

In the process of lowering and floating, we should not only pay attention to the buoyancy of the hull, but also calculate the stability of the hull to prevent accidents. Fig. 2 shows the stability of the wreck during its lowering and lifting. During the simulation process, with the decrease of hull draft, the stability of the ship increases gradually. The maximum stability arm heels of the four working conditions are 0.209 m, 1.191 m, 2.93 m and 3.391 m, respectively. The stability distances are 5.29 degrees, 102.15 degrees, 97.74 degrees and 97.26 degrees, which fully meet the requirements of lifting and floating.
engineering. The transverse metacentric radius of the hull is 10.500 m, 12.100 m, 13.203 m, 22.712 m, and the transverse metacentric height is 10.700 m, 12.167 m, 13.115 m and 22.576 m. If the angle of the hull is not properly controlled at the beginning of the floating, the hull will appear negative stability, and it is easy to tilt to one side. At this time, due to the small overall stability, if a larger overturning moment is received, the hull will overturn, which will increase the difficulty of salvage.

4.2. Weight distribution
Fig. 3 shows the weight distribution along the length direction of the hull, including the inflow into the pontoon. As the draft of the hull decreases, the inflow of damaged cabin decreases gradually.

4.3. Buoyancy distribution
As the draft of the hull decreases, the buoyancy of the hull decreases gradually. Fig. 4 shows the buoyancy distribution along the hull length, including buoyancy of pontoons. Because the hull inclines toward the stern, the buoyancy distribution gradually decreases from stern to bow.

4.4. Shear distribution
Fig. 5 shows the shear distribution along the length direction of the hull, which is similar to that of the normal hull. However, due to the effect of pontoons, the maximum/minimum shear force is located in the middle of the pontoon rather than in the first quarter of the hull. With the decrease of hull draft, the distribution of shear force under four working conditions gradually increases.

4.5. Bending moment distribution
Fig. 6 shows the bending moment distribution along the length direction of the hull, which is the same as that of the normal hull, but with with a critic condition. Measures should be taken to reduce the load in the middle cabin of the hull during lifting. The bending moment of the hull increases gradually during the lifting process, which indicates that the influence of the inflow of broken cabin on the bending moment of the hull is weaker than that of the load. It is necessary to take weight reduction measures for the successful lifting of the hull. The maximum shear force of working condition A is 42.075 m, and that of the other three working conditions is 38.25 m, which corresponds to the change of hull pitch angle.
5. Conclusion
Refloating a damaged ship with salvage pontoon is a complex engineering. When the pontoon is used to lift a sunken ship, after the inflation of pontoon, the pressure in the pontoon will change causing the change of the buoyancy of the pontoon, which will affect the accuracy of the calculation of the buoyancy. In this paper, the influence of temperature change on pressure after pontoon inflation is deduced theoretically, and the variation of gas volume along time in buoy is further obtained. According to the principle of ship statics, buoyancy of pontoon can be obtained. In the preliminary stage of shipwreck with many pontoons sunk in the water totally, since the stability of the shipwreck is poor, the aeration ratein the pontoon should be calculated accurately to prevent the capsizing of the ship. As the draft of the wreck decreases, the stability of the hull increases gradually, which is beneficial to the process of lifting and floating. The change of pitch angle is small in the course of buoyancy, but it has obvious influence on the buoyancy distribution of ship hull. The position of pontoon has a great influence on the distribution of shear force and bending moment of ship hull. Relevant measures should be taken.

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