Calculation on the Uprighting Process of a damaged-capsized ship

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Abstract. Righting a damaged-capsized ship can be very complicated. In this paper, flooding quantity and three-dimensional mathematical model of righting force are introduced in order to solve the buoyancy and stability of a capsized ship. Through the simulation, the uprighting process of a damaged-capsized ship with air cushion was researched. Computation result shows that the proportion between the maximum righting moment in the opposite direction and the maximum righting moment is 2.891. Trim decreased gradually during the uprighting process, so it reached the minimum value when the ship returned to equilibrium location. The quantity of flooding water increased slowly in the later process when the opening was beneath the water level. For each calculation, the maximum shear force was located at the same position, which does not increase with flooding quantity.

1. Introduction
Capsized ship should be righted as earlier as possible, because vessel accidents have an impact on politics, military affairs, economy, ecology and culture[1-5]. Generally, capsized ships should be righted before refloating[6]. Buoyancy and stability must be calculated before righted. In the process, the gravity center changes during adjusting load or flooding, then the buoyancy and stability is affected by the addition weight[7,8]. cabin method was proposed to lower the influence of sudden ingress of water by Vermee et al, the flooding quantity mathematical model and computer program were tested by experiments[9]. The relationship between flooding quantity and pressure of the vessel cabin and the effection of instant flooding water were identified through calculation and experiments[10]. Damaged ship may capsize under wind, wave and current circumstances because a dramatic decrease of ship dynamic stability[11]. Through the research on the causes of SS Heraklion accident, Papanikolaou found that too small freeboard result in the capsized accident[12]. Maimun studied the of roll motion damaged passenger in random transverse waves by experimental and numerical methods, the results show that wave height and loadage are the main influence factors. Must wave height a maximum of 0.2 m when the height of gravity center is 1.3 m[13].

In order to design the scheme of floating crane ship righting a capsized ship better, Hanming Liu used Analytical Hierarchy Process(AHP) to analyze the contents, principle, and conditions of project, then a total frame of the scheme was put forward as a theoretical basis[14]. According to the principle of righting a capsized ship, xiangke Huang established a mathematical model of righting fulcrums internal angle, righting force, righting force functional point and righting force point internal angle[15]. Zhao discussed the possibility of righting a capsized ship with pontoon or floating crane according to different states of the ship[16,17]. Uprighting scheme had been set up on the basis of primary data, grounding, environmental factors; then the calculate method of righting force was obtained[18]. Air
pocket is a factor which can affect reserve buoyancy and stability during righting a capsized ship. Drobyshevski solved righting force of a capsized ship with or without air pocket by theoretical method, the righting force of ship with the angle of heel at 90° was calculated [19]. To simplify the calculation, some engineers only consider the changes of heeling angle and draft. The heeling angle was found directly related to the stability and height above water surface in compartment by Xiaolu Wu, and the uprighting scheme of vertical righting force was made. Matlab software was further used to solve righting force of floating crane [20]. Take a capsized ship with the angle of heel at 90° as an example, Yaohui Tong discussed righting and refloating a sunk ship with buoy used in both side. The method is suitable for capsized ship with angle of heel less than 90° [21]. Zhiwei Dong and Peikun Cong introduced the salvage engineering of righting Liaolvdu 7 with floating crane and buoy used in both side [22]. Costa Concordia ran aground and overturned after striking an underwater rock. Divers used special anchor chain to keep it in place. 2100 tonnes of oil was drained and chimney was removed for salvage engineering. 12 Hydraulic Jacks righted the inclined ship, and 15 enormous caissons played a supplementary role in the process [23,24].

At present many Chinese salvage companies are small in scale, the economic and technical strength is relatively weak. They are lack of independent key technologies. So traditional technology methods are applied to make salvage scheme, such as empirical algorithm or semi-empirical algorithms, but the accurate datas are not obtained. For quickly and accurately calculating the distribution of cussion, flooding quantity, stress condition of a damaged and capsized ship, the paper established the flooding quantity model with cussion and righting force model. Uprighting process was simulated by GHS software, the causes and mechanism of all influencing factors were solved.

2. Analysis and calculation of damaged compartment

There are three typical classifications of damaged compartments during uprighting process according to floatation, stability, free surface, cussion [25]. Case 1: During the process, damaged compartments underwater cannot be repaired. Case 2: During the process, the damaged compartments can be repaired, but they cannot be fully drained. Free water in the slack tank can not be drained. Case 3: During the process, the damaged compartments are not repaired. The breach is not sealed, and water continues flowing inside or out the compartments. As a result, the total amount of water changes during the course, the insubmersibility of the ship must be considered. Case 3 is relatively complex. This paper researched and analyzed the uprighting process of a damaged and capsized ship.

In order to generally analyze the uprighting process of a capsized ship, mechanics model was build up in this paper [26].

\[
\begin{align*}
\Delta + F - W &= 0 \\
M_x &= M_{w_y} + M_{\Delta y} + M_{F_y} \\
&= (-z_G W + z_D \Delta + z_F F) \sin (\theta) + (x_G W - x_D \Delta - x_F F) \cos (\phi) \cos (\theta) \\
M_z &= M_{w_z} + M_{\Delta z} + M_{F_z} \\
&= (x_G W - x_D \Delta - x_F F) \sin (\phi) \cos (\theta) - (y_G W + y_F \Delta + y_F F) \sin (\theta)
\end{align*}
\]

Where, \( \phi \) is heeling angle; \( \theta \) is trim angle; \( x_G, y_G, z_G \) are the coordinates of the gravity center along the coordinate axis; \( M_{w_y}, M_{w_z}, M_{w_z} \) are the moment of the gravity along the coordinate axis; \( x_D, y_D, z_D \) are the center of buoyancy along the coordinate axis; \( M_{\Delta x}, M_{\Delta y}, M_{\Delta z} \) are the moment of the buoyancy along the coordinate axis; \( x_F, y_F, z_F \) are the of righting force along the coordinate axis; \( M_{F_x}, M_{F_y}, M_{F_z} \) are the righting force moment along the coordinate axis.

During uprighting process, if a cussion in damaged ship, flooding quantity at any time can be solved based on [27].
\[
q_i = \begin{cases}
\mu A \left\{ \frac{2}{\rho (1 - k^2)} \left[ \frac{V(t)}{S} + P_1 - P_2 \right] \right\}^{\frac{1}{2}} & \text{if } h_{i+1} < h_i \\
\mu A \left\{ \frac{2}{\rho (1 - k^2)} \left[ \frac{V(t)}{S} + P_1 - P_2 \right] \right\}^{\frac{1}{2}} & \text{if } h_{i+1} > h_i
\end{cases}
\]

Here, \( \mu \) is the flow velocity; \( A \) is the area of the opening; \( S \) is the area of free surface; \( g \) is the acceleration due to gravity; \( V(t) \) is the volume of flooding water; \( P_1 \) is air pressure of the damaged compartment; \( P_2 \) is the pressure of the opening; \( \rho \) is the density of the water; \( k \) is the function of \( \mu \), \( S \) and \( A \).

3. Analysis of examples

The above is the theoretical analysis model of a damaged and capsized ship. Take case 3 for example, this paper simulated the uprighting process of a damaged and capsized ship. Figure 1 is the hull model diagram. Table 1 is the principal dimensions of the intact ship.

\[\text{Figure 1. Hull and compartments}\]

| Overall length /m | Moulded breadth /m | Moulded depth /m | Draft /m |
|-------------------|-------------------|------------------|---------|
| 105               | 16                | 10               | 7.391   |

The ship capsized on water due to contingency. Compartment on the bow is damaged through underwater inspection. The uprighting process was simulated in this paper. The ship listed 170.48\(^\circ\) to starboard, had a −1.03\(^\circ\) trim, and an origin draft of −4.012 m. There is an air pocket in the damaged compartment during uprighting process.

4. Results and discussions

4.1. Righting moment

Stability determines the difficulty of righting a capsized ship. Negative stability values represent the ship in upright condition. Negative stability is helpful for the uprighting process without righting force sometimes. Based on calculation, the proportion between the maximum righting moment in the opposite direction and the maximum righting moment is 2.891. In later phases of the process, righting force moment in the opposite direction is also needed to avoid the ship being damaged again or capsizing again.
4.2. trim angle
Trim angle changes during uprighting process. Sometimes, free water in damaged compartment greatly intensifies the problem. In figure 3, trim angle decreases gradually during uprighting process. The variation of trim angle is 1.09, which is relatively big for salvage engineering, so the hull strength should be calculated accurately.

4.3. Flooding quantity
Flooding quantity is varies with ship body state and uprighting process. There is an air cussion in the damaged compartment, so flooding quantity is small, which is has little effect on draft.

4.4. Displacement
Reserve buoyancy ensures the insubmersibility. Floating condition changes when water is flow into or out of the damaged compartments during uprighting process. In figure 5, total displacement represents the displacement of the enclosed space of the ship, and ship’s displacement represents the displacement of the ship during uprighting process. The ship was not sink according to total displacement curve and ship’s displacement curve. Water in the damaged compartments drained automatically in the beginning of the process. The quantity of flooding water increased slowly in the
later process when the opening was beneath the water level.

![Figure 5. Displacement variations during uprighting](image)

4.5. The maximum shear force
Hull's longitudinal strength calculation is the key to salvage scheme. Serious accidents will occur when the hull's longitudinal load exceeds the approved stress. In figure 6, the changes of the maximum shear force along the longitudinal direction is obtained. For this numerical example, the position of the maximum shear force is no change, which is 88.9 m in the back of the original point. Flooding quantity is small, but the maximum shear force is very big. The flooding quantity variation tendency is not agree with the maximum shear force.

![Figure 6. Variation of the maximum shear force during uprighting](image)

5. Conclusion
Refloating a damaged ship is a complex engineering. Especially, the opening can not repaired, and there is an air pocket in the damaged compartment. The flooding quantity and righting force model were introduced based on the ship's hydrostatical theory. Uprighting process is simulated by apply GHS software. Reserve buoyancy should be calculated before engineering to ensure capsized ship floating on water. The uprighting process is composed of numerous static states. It can be concluded from the position of damaged compartment, flooding quantity, displacement, that the position of damaged compartment is more likely to affect the process when the trim angle is small. The maximum shear force appears in a fixed position which may be associated with the location of damaged compartment and flooding quantity. Then, this paper will make a comparative study on simulation results of intact capsized ship and other types of damaged ships. Simultaneously, considering that trim angle varied within a small range during process. In the future research, the influence of trim angle varied within a large range on shear force should be studied.

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