Optimal Arrangement Method of a Ship Considering the Performance Against Flooding

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Abstract. Most of the ship's accidents are accompanied by flooding. Also, water inflow due to the flooding propagates along with complex compartments of the ship, so the flooding process is very complicated. For the robust design of the ship against flooding, it is necessary to consider such a process at the stage of the arrangement design. However, at present, the arrangement design is carried out considering only the final state of the ship due to damage that generally causes the flooding. At the intermediate state, dynamic effects and various factors can lead to a more severe condition of the ship than the final state. On the other hand, the flooding process can be vary depending on the arrangement design. To improve the arrangement design in the aspect of safety, we propose an optimal arrangement method of a ship considering the flooding. For this, an optimization problem for the arrangement design is mathematically formulated. The formulation includes conventional objective functions for the arrangement design such as the operability. In terms of flooding, we add the additional objective functions such as the total time to flooding and the amount of motion during the flooding. The optimization problem includes constraints such as the requirements of damage stability. At this time, the flooding analysis, the most important part of the problem, is performed using the position based dynamics (PBD), which is a kind of mesh-free particle methods. Finally, the proposed method is applied to an example of a naval ship that the survivability is one of the important issues. The result shows the applicability of the proposed method at the arrangement design of the ship.

Keywords: Arrangement design · Ship flooding, optimization, position based dynamics · Naval ship

1 Introduction

1.1 Research Background

The arrangement design of ships is normally being made based on data of the past design and experts' experiences. When performing the arrangement design, experts refer the past design and add additional requirements such as the owner's requirements and regulations and additional information to the data for a new design based on their experiences. When performing the arrangement design, delay in design can occur due to the missing data or the absence of experts. Moreover, most of the ships are operated in the ocean so that spaces that can be filled with components for them are restricted.

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For these reasons, the demand for the optimization method for the arrangement design for ships is proposed in this study.

During the arrangement design process, there are several things to consider. Firstly, ships should satisfy the international code and regulations because they have to be operated in the ocean under the permission of related organizations or governments. Next, the ship should be designed by the ship owner's requirements. And the survivability is the most important factor in the operation of the ship. Therefore, in this study, we tried to consider the intermediate flooding during the arrangement design.

Traditionally, the rules for ships were judged whether they are satisfied with stability only by the final state of ships after accidents, so that, there was a lack of understanding of the flooding process and time to reached the final state. The most accidents in the ocean accompany flooding. And, the process progresses for quite a long time. Therefore, the accurate estimation of the flooding process for ships is very important no less than appropriate after action for accidents [1]. Moreover, the arrangement design of ships is closely related to the speed of the flooding process, so that, we tried to consider this as one of the objectives of evaluation of arrangement design.

1.2 Related Works

There are several pieces of research about the arrangement design and the flooding analysis. However, research that considers both of them at the same time is hard to find. Therefore, in this section, the researches about arrangement design and flooding analysis were reviewed separately.

Several researchers have proposed a method to find an optimal arrangement design of ships. Helvacioglu and Insel [2] proposed a multi-stage expert system to arrange the compartments on a container ship. Nick [3] proposed a method to generate, evaluate, and optimize the arrangement design of a naval surface ship. Roh et al. [4] proposed a method to layout bulkheads in the bull of a naval surface ship. And Jung et al. [5] consider the stability, operability, and survivability to optimize the arrangement design of the naval surface ship.

There are many studies that analyze the flooding process of the ships. Ruponen [6] used the quasi-static method based on a hydraulic orifice equation to perform analysis for intermediate flooding. Dankowski et al. [7] analyzed the intermediate state of flooding of a ship using the quasi-static method and considered the air compression in the compartments. Kim et al. [8] performed the intermediate flooding simulation for the barge-type damaged ship. Lee [9] has improved the hydraulic orifice equation to suggest the dynamic orifice equation and performing quasi-static flooding simulation for the passenger ship. As mentioned above, there are many studies about arrangement design and flooding analysis for ships. However, they did not consider the survivability on the side of flooding. Therefore, in this study, we proposed an optimal arrangement method of a ship considering the flooding.

2 Optimal Arrangement Method

In ships, there are various things to optimize. Thus, it is challenging to solve the problems considering all the variables at the same time. In this manner, multi-stage optimization problems and optimization algorithms for solving the problems was proposed in this study, as shown in Fig. 1.

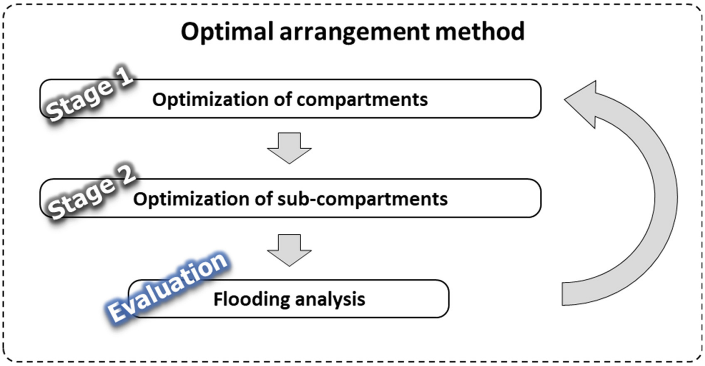

Fig. 1. The configuration of the optimal arrangement method

As shown in Fig. 1. In the first stage, the main compartments of the ship are optimized, considering the strength, and performances. In the second stage, the sub-compartments in the compartment are optimized, considering the operability and the effectiveness for crews and passengers. Finally, the alternatives derived from the two stages are evaluated using flooding analysis method.

2.1 Multi-stage Optimization

This section describes an optimization method for the arrangement of ships. As mentioned earlier, the arrangement method for the ships was formulated in two stages in this study.

First Stage-Optimization of Compartment Arrangement
The first stage is the compartment arrangement where the positions of the bulkheads and decks in the hull are determined by minimizing the maximum bending moment at the intact state, the space for liquid tanks. The bending moment can be calculated by the weight curve and the buoyancy curve of a ship. By minimizing the bending moment, the bulkhead arrangement can be safer in terms of structural safety. Also, the more cargos or passengers can be loaded by minimizing the space for liquid tanks. These two considerations were set to objective functions of the first stage as shown in (1), and (2).

$$\text{Minimize } F_1 = \max(\text{Bending moment}) \tag{1}$$

$$\text{Minimize } F_2 = V_{FOT} + V_{FWT} + V_{WBT} + V_{LOT} \tag{2}$$

When arranging the bulkheads and decks in the hull, we should obey the minimum requirements for liquid tanks and the space for engine rooms. In general, the space for the liquid tanks may have required a given volume for operation. Therefore, in this study, the upper and lower limits for each liquid tank were constrained, as shown in (3)–(10). In the equations, *FOT* is a fuel oil tank, *FWT* is a freshwater tank, *WBT* is a water ballast tank, and *LOT* is liquid oil tank.

$$g_1 = V_{FOT}^{min} - V_{FOT} \leq 0 \tag{3}$$

$$g_2 = V_{FOT} - V_{FOT}^{max} \leq 0 \tag{4}$$

$$g_3 = V_{FWT}^{min} - V_{FWT} \leq 0 \tag{5}$$

$$g_4 = V_{FWT} - V_{FWT}^{max} \leq 0 \tag{6}$$

$$g_5 = V_{WBT}^{min} - V_{WBT} \leq 0 \tag{7}$$

$$g_6 = V_{WBT} - V_{WBT}^{max} \leq 0 \tag{8}$$

$$g_7 = V_{LOT}^{min} - V_{LOT} \leq 0 \tag{9}$$

$$g_8 = V_{LOT} - V_{LOT}^{max} \leq 0 \tag{10}$$

If the length of each of the engine rooms should have a minimum length and width, such requirements can be formulated as constraints as shown in (11) and (12).

$$g_9 = l_{ER}^{min} - |x_5 - x_6| \leq 0 \tag{11}$$

$$g_{10} = l_{ER}^{min} - |x_7 - x_8| \leq 0 \tag{12}$$

Second Stage-Optimization of Sub-compartment Arrangement

After the compartment arrangement which was done in the first stage. Regarding the operability and effectiveness of a ship, the sequence of rooms and the positions of the passages in the compartments are important during the sub-compartment arrangement. To enhance the operability, the adjacency index that represents the effectiveness of the flow of crews, passengers, and supplies in the ship should be minimized. As following these reasons, the process for the sub-compartment arrangement was formulated as an optimization problem. The objective function of this stage minimize the adjacency index (*AI*) in (13). In the equation, R_i is sub-compartment to be allocated at the compartment, q_{ij} is adjacency coefficients between the room i and j, and d_{ij} is the distance between the rooms.

$$\text{Minimize} \;\; F_1 = AI = \sum_{i=1}^{N_R - 1} \sum_{j=i+1}^{N_R} \left(q_{ij} \cdot d_{ij} \right) \tag{13}$$

When arranging the sub-compartment and passages in the compartment, the area for sub-compartment and required locations of the specific sub-compartment should be satisfied. These two constraints can be formulated as (14), and (15). In the equations, a_i is an area of rooms, and R_i is sub-compartment to be allocated at the region i.

$$g_1 = a_i^{min} - a_i \leq 0 \tag{14}$$

$$g_2 = R_i - R_i^{req} \leq 0 \tag{15}$$

2.2 Flooding Analysis in the Time Domain

After the optimization, compartments, sub-compartments, and passages are determined, which means the path of the water inside the hull is determined when flooding is occurring. To evaluate the survivability in terms of flooding, flooding analysis was performed after the optimization. In this study, dynamic analysis for flooding was performed using (16).

$$\mathbf{M}\ddot{\mathbf{x}} = \mathbf{F}_{Gravitational} + \mathbf{F}_{Buotancy} + \mathbf{F}_{Hydrodynamic} \tag{16}$$

By solving (16) in each time steps, the acceleration of the ship can be obtained. Using the obtained acceleration, the velocity and position vector can be calculated by integrating the acceleration. When flooding is occurring, **M** in (16) is time variant value about ships. Depending on the inflow and outflow of water and air, the weight and center of weight can be changed from time to time. To calculate the flow of fluid in each time, we use the Position based dynamics (PBD), which is one of the Mesh-free particle method (MPM) [10].

After the first and second stage of optimization, the flooding analysis was performed for ships considering loading conditions and damage cases. By doing this, we can check accurate stability after the accident if the stability is not satisfied even in one case. The optimization is re-performed. We are changing the bulkheads or rooms considering the vulnerable compartments.

3 Application

To check the applicability of the proposed method, the prototype program was developed. Using the prototype program, optimization of arrangement was performed, and the solution was evaluated using flooding analysis of the Navy destroyer. The results of first-stage were shown in Fig. 2. As shown in Fig. 2, the bulkheads were adjusted to minimize the maximum bending moment. The objectives were to minimize approximately 20%.

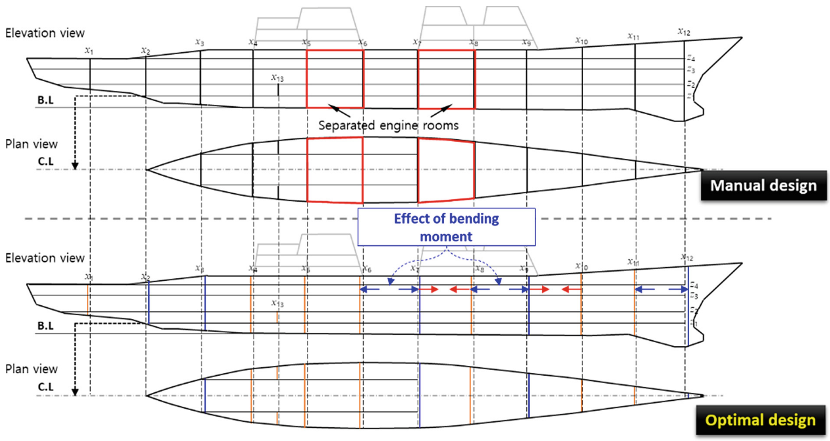

Fig. 2. Optimization results of first-stage

Using the results of first-stage, second-stage was performed. The results of the second-stage were shown in Fig. 3. As shown in Fig. 3, the room arrangement of the superstructure was optimized. By performing second-stage, the adjacency index for rooms was enhanced by about 15%.

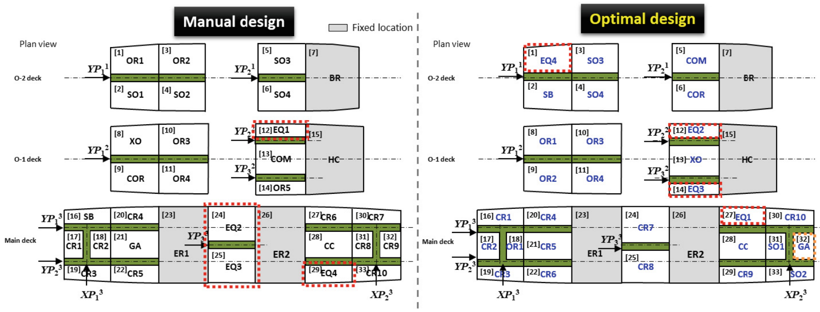

Fig. 3. Optimization results of second-stage

After two stages of optimization, intact and damage stability was checked using the prototype program. And it was confirmed that the eight criteria for stability (3 for intact and 5 for damage) were meet the criteria as shown in Fig. 4.

Moreover, we check the possibility of enhancing the survivability in an accident by optimizing the arrangement of the compartment and the sub-compartment.

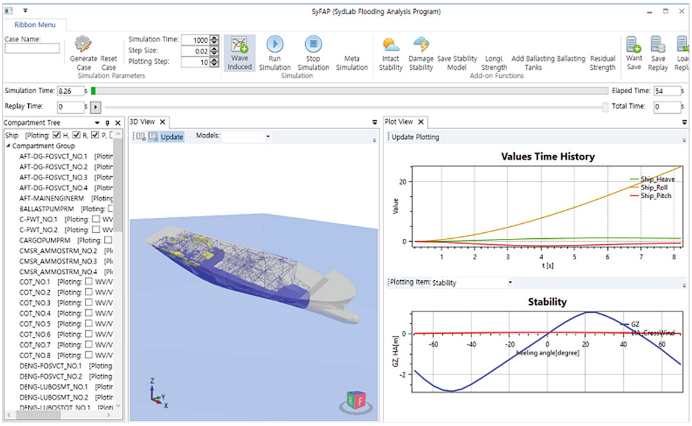

Fig. 4. The result of the flooding analysis for oil tanker

4 Conclusions

In this study, a method of optimization of arrangement considering the performance against flooding. For many variables, a multi-stage optimization was proposed. After the optimization of compartments and sub-compartments in two stages, the survivability in terms of flooding was evaluated. Dynamic flooding analysis was performed using the equations of motion, and PBD was used for calculating the amount of flow at each time steps. By applying the proposed method to the oil tanker, the applicability of the proposed method was evaluated.

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