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Kai Li
School of Naval Architecture and Ocean Engineering, Dalian University of Technology, Dalian, China., likai@dlut.edu.cn

Zhijiang Yuan
Department of Navigation, Dalian Naval Academy, Dalian, China

Xiaogang Jiang
Department of Navigation, Dalian Naval Academy, Dalian, China

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A NOVEL DAMAGED SHIP RIGHTING PLAN OPTIMIZATION METHOD BASED ON ARTIFICIAL BEE COLONY ALGORITHM

Kai Li[1], Zhijiang Yuan[2], and Xiaogang Jiang[2]

Key words: righting plan optimization, damage stability, counter-flooding, ABC.

ABSTRACT

With the increase of the sea disaster caused by ship capsizing, self-rescuing ability of damaged ship has attracted much attention among ship designers, ship owners, classification societies and authorities. Damaged ship righting optimization remains a very complicated problem due to the feasible combinations of counter-flooding approaches with different compartments and loads are numerous. The effectiveness and efficiency of the artificial bee colony (ABC) algorithm has been demonstrated on the combinatorial optimization problem. In this paper, an ABC algorithm-based righting plan optimization method for damaged ship is proposed. In this method, the objective is to minimize the inclination angle under a group of constraints regarding stability, floatation and available compartments and loads. The functions of damage stability and floatation calculation are integrated into the proposed method to evaluate the righting effect of each single counter-flooding measure. The proposed method in this paper is validated through a case study of finding optimal righting plan of a train ferry with two different damage scenarios, and provides a foundation for the adoption of emergency response technologies in ship operation

I. INTRODUCTION

With the increase of various types of sea disasters, such as grounding, collision with ship or iceberg, fire, the threat of damage and flooding of ship and offshore structures never ever decreases, how to maintain vitality effectively and handle the damage properly are still critical problems requiring exploration during operation period. In addition to the damage stability requirements of the Safety of Life at Sea (SOLAS) convention, the International Maritime Organization (IMO) has established new regulations for Safe Return to Port (SRtP).

Over the past decades, tremendous efforts of fundamental research have been made in the field of damage containment. Pekka et al. (2017) developed a new approach to the breach assessment by using time-domain simulation tool for progressive flooding and the measurement data from the flood level sensors. Hashimoto et al. (2017) proposed a numerical simulation method for predicting damaged ship's transient behavior associated with flooding, which solve equations of motion with hydrodynamic forces estimated by the semi-implicit MPS (Moving Particle Simulation) for damaged parts and by the potential flow theory for intact parts. Domeh et al. (2015) carried out experiments in a towing tank by using a segmented ship model, and studied a variety of permeabilities and internal arrangements of the damaged compartment for ship moving in waves, which show that permeability has a large effect on the pitch and heave motion responses when the ship is travelling at forward speed. Maria and Antonio (2017) built a simulation model for ship response in flooding scenario, and investigated the transient stage motions of a ship in damage, which use lumped mass method to evaluate the dynamics effects of water inside the compartment on roll motions. Evangelos et al. (2016) reviewed some active measures of damage containment and classified them into 3 categories which are design solutions, operational measures and emergency response system or measures.

Stability calculation software and hardware are commonly deployed onboard, however, in practice the damaged ship righting plan is usually a feasible solution made based on experience or simple calculation, but not the optimal solution. It is of great importance for developing new methods to determine the best righting measure for given objectives and constraints within a very short time. Many examples using ABC algorithm demonstrated the ability to find the optimal solution, and usually ABC algorithm employs fewer control parameters in contrast with the traditional optimization algorithms (Aydoğdu et al., 2016). A simple idea is to apply ABC algorithm into damaged ship righting plan optimization. For damaged ship, the righting plan optimization and optimization problem can be treated as discrete variable optimization and combinatorial optimization methods. The optimal plan should be a combination of a number of vari-

Paper submit 04/20/18; revised 06/06/18; accepted 07/10/18. Author for correspondence: Kai Li (e-mail: likai@dlut.edu.cn).
[1] School of Naval Architecture and Ocean Engineering, Dalian University of Technology, Dalian, China.
[2] Department of Navigation, Dalian Naval Academy, Dalian, China.

ous types of righting actions. The total amount of optimization parameters are dependent on a number of technical considerations.

The present work proposes a novel righting plan optimization method for damaged ship that uses artificial bee colony (ABC) algorithm to achieve optimal righting plan, which makes it possible to consider restrictions related to available counter-flooding source, righting effect and operation time and cost. The proposed approach is used to solve a righting plan optimization problem for a train ferry crossing Bohai Strait considering the combination of counter-flooding measures. The problem has a characteristic of multiple objectives including righting effect (inclination angle), the number of used compartments, minimum freeboard and constraints on stability performances including metacentric height, average draught and reserve buoyancy. Different optimizations based on individual design approaches are conducted to verify the optimization efficiency of the combined approach. In Section 2, some basic concepts in the proposed method are introduced. Based on these concepts, the proposed method of damaged ship righting plan optimization is presented in Section 3. In Section 4, a case study is provided to validate this proposed method. Finally, this paper is wrapped up with the conclusion.

II. INSTANT CALCULATION OF FLOATING CONDITION AND STABILITY OF DAMAGED SHIP

1. Calculation Principle

According to the volume of flooding water, the processing mode of flooding water, and the calculation criterion, there are several different types of calculation methods for determining damaged ship floating condition and stability.

(1) There are two methods depending on the volume of flooding water:

Linear approximation method and successive approximation method. Linear approximation method is built on two assumptions, which are the ratio of flooding water to the displacement is very small, and the hull and the bulkhead around the place with waterline changing are vertical wall. Then the draught and stability can be calculated by metacenter formula. When the flooding water increase to some extent, the draught, heel angle and trim angle change a great deal, the accuracy of using linear approximation method cannot be guaranteed then. Successive approximation method usually uses successive linearizing method, which set an arbitrary initial water plane, calculate all the factors of the hull and the flooded compartments, and substitute these factors into linearized equations to solve out the variations of floating condition parameters. If these variations cannot satisfy the specified accuracy, then the water plane should be changed and the calculation should be repeated until the requirements are met.

(2) There are also two methods according to the processing modes of flooding water:

Added weight method and lost buoyancy method. Added weight method treats the flooding water as an added liquid load on the ship, the displacement after damage equals the sum of the displacement before damage and the weight of flooding water. Lost buoyancy method treats the flooding water as a part of the outside water, hence the weight and center of gravity of the ship still remain unchanged, but the underwater hull shape is changed. Although the processing modes are different, both the two methods have definite physical meanings. Added weight method has the virtue that the volume and moment of flooding water has nothing to do with the flooding state, which is easy for calculation of multiple flooding states, however the equilibrium equation form is complicated due to all the variables are functions of floating parameters. In lost buoyancy method, the items related to floating parameters are less, and hence the equilibrium equation form is easier.

(3) According to the calculation criterion, there are also two methods:

Deterministic method and probabilistic method. Deterministic method considers the environment parameters and the ship state before damage are definite that can be used to determine the floating conditions and stability after damage. Probabilistic method considers the environment parameters and the ship state before damage are random, and uses surviving probability after being flooded to judge the safety of damaged ship. Both the two methods require determining the new balance position after being flooded and calculating the ship stability at the new position. At present the common calculation criterion among authorities still applies deterministic method.

The above methods are well known by naval architects. In this paper, deterministic method is used for damaged stability calculation, which would adopt added weight method and lost buoyancy method according to the types of flooded compartments. Calculation of damaged stability must be done in very short time to provide guide to processing emergency, and this relies on instant calculation of loading condition before damage, which should call the latest data including the liquid level of all the liquid tanks from sensors, changed solid loads and other fixed weights to calculate the weight and centroid of gravity (CoG) under the current loading condition.

2. Damaged Stability Curve Calculation at Large Angles of Heel

Damaged stability curve calculation at large angles of inclination falls into two categories: 2D method and 3D method. The righting arm solved in 2D method is the horizontal component of total righting arm. When the trim caused by heel is small, the horizontal component of the total righting arm is very close to the total righting arm. But if some large tanks in the bow or stern are damaged and flooded, the trim caused by heel would be very large so that the trim cannot be ignored and 3D method must be applied to calculate the total righting arm. The main steps of 3D method can be summarized as: (1) Set a series of heel angles; (2) For each heel angle θ, calculate the corresponding average draught T_m and trim angle ψ satisfying the work inclines the ship is the minimum; (3) Determine the in-

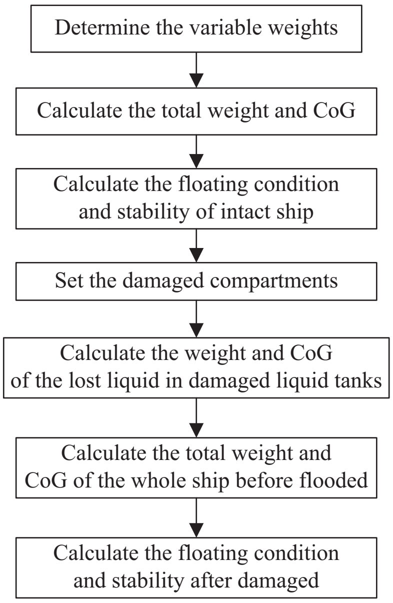


Fig. 1. Calculation process of floating condition and stability of damaged ship by using 3D method.

clining position of damaged ship and calculate the total righting arm at the inclining position. Fig. 1 shows the calculation process of floating condition and stability of damaged ship by using 3D method.

Suppose the parameters of the initial waterline with an inclination angle α_0 of the damaged ship are θ_0 and ψ_0, and the parameters of the waterline with an inclination angle α are θ and ψ, then the work of inclining ship from α_0 to α is:

$$\begin{aligned} &T(T_m, tg\theta, tg\psi) \\ &= \gamma\cos\alpha(\bar{m}_{yz} tg\psi + \bar{m}_{zx} tg\theta - \bar{m}_{xy}) - \gamma\alpha_0 V_0 \end{aligned} \tag{1}$$

The angle α_1 between the two water planes can be calculated by spherical trigonometry:

$$\cos\alpha_1 = (1 + tg\theta tg\theta_0 + tg\psi tg\psi_0)\cos\alpha\cos\alpha_0 \tag{2}$$

Then damaged stability curve calculation can be treated as the problem of seeking extreme of function $T(T_m, tg\theta, tg\psi)$ under two constraints, which can be expressed as:

$$\begin{aligned} &\min T(X) = \gamma\cos\alpha(\bar{m}_{yz} tg\psi + \bar{m}_{zx} tg\theta - \bar{m}_{xy}) - \gamma\alpha_0 V_0 \\ &G(X) = [g_1(X), g_2(X)]^T \\ &g_1(X) = V - \sum v - V_0 = 0 \\ &g_2(X) = (1 + tg\theta tg\theta_0 + tg\psi tg\psi_0)\cos\alpha\cos\alpha_0 - \cos\alpha_1 = 0 \\ &X = [T_m, tg\theta, tg\psi]^T \end{aligned}$$

$$\begin{aligned} \bar{m}_{yx} &= VX_B - \sum vx - V_0 X_G \\ \bar{m}_{xz} &= VY_B - \sum vy - V_0 Y_G \\ \bar{m}_{zy} &= VZ_B - \sum vz - V_0 Z_G \end{aligned} \tag{3}$$

where "¯" represents the geometrical elements after damaged, V_0 is the volume of displacement of damaged ship, V is the volume of displacement of intact ship, v means the flooded volumes, (x, y, z) are the coordinates of the flooded volume centroid, (X_B, Y_B, Z_B) are the coordinates of the buoyancy centroid, and (X_G, Y_G, Z_G) are the coordinates of the centroid of gravity.

By introducing the Lagrange multipliers vector $\lambda = [\lambda_1, \lambda_2]^T$, the problem of damaged stability is equivalent to solving the unconfined extreme of the following Lagrange function:

$$L(X, \lambda) = T(X) + \lambda^T G(X) = T(X) + \sum_{i=1}^{2} \lambda_i g_i(X) \tag{4}$$

The extreme point of function $T(X)$ can be determined by Eq. (5).

$$\begin{cases} \dfrac{\partial}{\partial T_m}[T(X) + \lambda_1 g_1(X) + \lambda_2 g_2(X)] = 0 \\ \dfrac{\partial}{\partial tg\theta}[T(X) + \lambda_1 g_1(X) + \lambda_2 g_2(X)] = 0 \\ \dfrac{\partial}{\partial tg\psi}[T(X) + \lambda_1 g_1(X) + \lambda_2 g_2(X)] = 0 \\ g_1(X) = 0 \\ g_2(X) = 0 \end{cases} \tag{5}$$

After eliminating λ_1 and λ_2, $g_3(X)$ is obtained, and Eq. (5) can be transformed into Eq. (6).

$$\begin{cases} g_1(T_m, tg\theta, tg\psi) = V - \sum_{1,2,3} v - V_0 = 0 \\ g_2(T_m, tg\theta, tg\psi) = (1 + tg\theta tg\theta_0 + tg\psi tg\psi_0)\cos\alpha \cdot \cos\alpha_0 - \cos\alpha_1 = 0 \\ g_3(T_m, tg\theta, tg\psi) = \bar{m}_{xz}(tg\psi - tg\psi_0) - \bar{m}_{yz}(tg\theta - tg\theta_0) - \bar{m}_{xy}(tg\theta tg\psi_0 \\ -tg\psi tg\theta_0) = 0 \end{cases} \tag{6}$$

Gradual linearization method is adopted to solve Eq. (6), the corresponding successive linearization equation (the kth) can be expressed as Eq. (7).

$$\begin{bmatrix} \dfrac{\partial g_1(X_k)}{\partial T_m} & \dfrac{\partial g_1(X_k)}{\partial tg\theta} & \dfrac{\partial g_1(X_k)}{\partial tg\psi} \\ \dfrac{\partial g_2(X_k)}{\partial T_m} & \dfrac{\partial g_2(X_k)}{\partial tg\theta} & \dfrac{\partial g_2(X_k)}{\partial tg\psi} \\ \dfrac{\partial g_3(X_k)}{\partial T_m} & \dfrac{-\partial g_3(X_k)}{\partial tg\theta} & \dfrac{\partial g_3(X_k)}{\partial tg\psi} \end{bmatrix} \cdot \begin{bmatrix} \delta T_{mk} \\ \delta tg\theta_k \\ \delta tg\psi_k \end{bmatrix} + \begin{bmatrix} g_1(X_k) \\ g_2(X_k) \\ g_3(X_k) \end{bmatrix} = 0 \tag{7}$$

Solving Eq. (7) requires iterative computation until the following accuracy conditions are satisfied simultaneously.

$$\left|\delta T_m\right| < 0.01\ \mathrm{m},\ \left|\delta tg\theta\right| < 0.005,\ \left|\delta tg\psi\right| < 0.0005 \quad (8)$$

When the average draught T_m and trim ψ are solved, the position of damaged ship water plane can be determined, and then the righting effect can be evaluated for different righting measures.

III. DAMAGED SHIP RIGHTING PLAN OPTIMIZATION PROBLEM

1. Righting Strategy of Damaged Ship

The aim of righting damaged ship is improving the stability, reducing trim and inclination, so that the floatability of ship and functioning of machinery and equipment can be guaranteed. The critical point of righting damaged ship is changing heel and trim by applying a balancing reverse moment. There are three basic approaches of righting damaged ship as follows.

(1) Moving loads: Move the loads around the damaged compartment to the diagonal compartment. The loads are usually liquid such as oil, water, some other heavy objects can be included also.
(2) Removing loads: Remove the loads around the damaged compartments, or discharge the flooded water in the plugged compartment.
(3) Ballasting diagonally: Ballast outside water into the diagonal compartment or the opposite compartment of the damaged compartment.

The righting effect, time and complexity of the three approaches are different. Moving loads can adjust floating status without loss of reserve buoyancy, but its operation process is slow. Removing loads can save reserve buoyancy, however in practice only few loads can be discharged. Ballasting diagonally can improve stability and its operation process is fast, but it would cost reserve buoyancy.

Stability and reserve buoyancy are the basic elements of a ship's floatability. In the operation of righting damaged ship, care must be taken to save reserve buoyancy while improving stability. Only when necessary reserve buoyancy can be used to improve stability. Therefore while applying the method of ballasting diagonally, those unimportant compartments should be selected, so that filling up can obtain large righting moment but with small loss of reserve buoyancy. Applying the method of moving loads also prefers the compartment far form or diagonally to the damaged compartment. As to applying the method of removing loads, those compartments near to the damaged compartment should be selected, and the bottom tanks must be avoided rom lowering stability. If the to-be removed compartments are determined, the inside liquid should be discharged completely. In other words, no matter what kind of measures are used, the operated tank should be either empty or full to diminish the free surface.

Usually, balancing the damaged ship should adjust the heel firstly. But if the heel is smaller while the trim is larger which would affect the safety, then the trim should be adjusted as a priority. If there were breaches on the hull above the water, the adjustment of the heel and trim needn't be too large to avoid new inclination. Due to the lack of real-time computer aided counter-flooding application, in practice ship crew have to make righting plan based on the above principles combining with experience. However, the righting effect cannot be guaranteed when emergency really arises.

2. Mathematical Expression of Damaged Ship Righting Plan Optimization

The key of the above counter-flooding approaches is to adjust the ship flotation condition by changing the weight distribution. With different combination of these approaches, different righting effect can be obtained by using different compartments, loads, time and energy. From the point view of optimization, the mathematical representation of damaged ship righting plan optimization problem can be expressed as:

$$\begin{aligned}
&Minimize: \alpha \\
&\cos\alpha = \frac{1}{\sqrt{1 + tg^2\theta + tg^2\psi}} \\
&F(\theta, \psi, \boldsymbol{x}) = 0 \\
&\boldsymbol{x} = [x_{m1}, x_{m2}, \ldots, x_{mp}, x_{r1}, x_{r2}, \ldots, x_{rq}, x_{b1}, x_{b2}, \ldots, x_{bs}] \quad (9) \\
&s.t.: x_{mi} = 0\ or\ 1 \\
&\quad\quad x_{rj} = 0\ or\ 1 \\
&\quad\quad x_{bk} = 0\ or\ 1
\end{aligned}$$

where p is the total count of load moving operations, q is the total count of load removing operations, s is the total count of load ballasting operations, subscript "m" means load moving, subscript "r" means load removing, subscript "b" means load ballasting, x_{mi} is the indicator of the ith load moving operation, x_{rj} is the indicator of the jth load removing operation, x_{bk} is the indicator of the kth load ballasting operation, and only the non-zero value of these indicators means applying the corresponding operation. All the three basic counter-flooding approaches require operated compartments to be either empty or full, so that the liquid volume in compartment would not be considered as optimization variable.

The complex level of this optimization problem is dependent on the number of used operations. Suppose there is no coupling among those three types of operations, and the total number of operations is N, then the total number of righting plan is 2^N-1. If N = 20, then the number of complete combination is 2^{20}-1 = 1048576, and it will be much greater if pumping from larger compartments to some smaller compartments is considered. Under this circumstance, heuristic methods have better calculation effect and efficiency than traditional methods.

3. The Artificial Bee Colony Algorithm

Artificial bee colony (ABC) algorithm is one of swarm intelligence algorithm simulating the foraging behavior of a honey bee colony, which was developed by Karaboga (2009). The main characteristic of ABC algorithm is that the application doesn't need to know the background information of optimization problem; it just needs to compare the performances of each solution through the local searching behavior of each individual artificial bee, then the global optimal value would stand out from the swarm solutions, therefore it has quick convergence speed.

Spivak (1996) firstly addressed the self-organized model of bee colony. Tereshko (2002) also proposed a simplified model according to the foraging behavior of bees. Teodorovic (2005) proposed bee colony optimization theory and fuzzy bee system, and applied it to solving numerical optimization problem. Yang (2005) presented a virtual simple bee colony algorithm with two parameters. Karaboga (2009) presented ABC algorithm and the improvement of ABC algorithm systematically, analyzed the performance of ABC algorithm, and compared ABC algorithm with DE and PSO on the optimization performance of multi dimensional functions. In recent years many researchers proposed improved ABC algorithm for optimization problems in various fields (Zhu and Kwong, 2010).

Bee colony algorithm is a novel meta-heuristic optimization algorithm, which can be classified into two ways by different biological inspiration mechanism. One is bee colony algorithm based on mating behavior of bees, which is an improved GA from its essence (Fathian et al., 2007). Another is bee colony algorithm based on foraging mechanism of bees, which is also known as ABC algorithm. In ABC algorithm, the concept "food source" represents for various possible solutions in solution space, which is measured by fitness function value. Food source is related to function value in multimodal function optimization. And there three groups of bees, which are employed bees, onlookers and scouts. Employed bees share the food source information with the other bees by dancing. Onlookers wait in the dancing area and choose food source according to the information shared by employed bees. The role of scouts is to search new position randomly.

Fig. 2 shows the foraging process of bees, and information sharing and role changing in the process can be seen from Fig. 2. Suppose there are two nectars A and B. In the beginning, the bees don't have any information about nectars near to hive, so they can only be scouts and onlookers. As indicated in Fig. 2 by "S", scouts search for nectars intuitively by following various clues. Once a nectar is found, a scout keeps the location of food source in its memory and starts foraging, then the scout becomes employed bee. As indicated in Fig. 2 by "R", onlookers search for nectars by observing the dance of employed bees. After an employed bee fly back to hive and unload honey, it has three options: it abandons the food source and becomes an onlooker (UF), it recruits other bees to fly back to the same nectar and continue foraging (EF1), and it just flies back to the same nectar and continue foraging but do not recruit other bees (EF2).

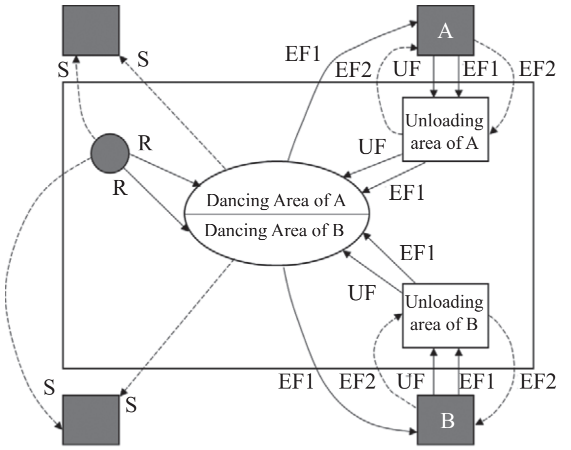


Fig. 2. The foraging process of bees.

Suppose there is an optimization problem of min $f(x)$ that the dimension of variable x is D. The basic steps of ABC algorithm are summarized as below:

Step 1. Initialization

Set FN as the population size of food source, SN as the number of scouts, $iter$ as the iteration time and C as the limitation of iteration times. An initial population of food source can be generated by using Eq. (10).

$$\mathrm{x}_i = \mathrm{x}_{low} + rand(0, 1)(\mathrm{x}_{up} - \mathrm{x}_{low}) \quad (i = 1, 2, \ldots, FN) \tag{10}$$

where x_i (i = 1, 2, …, FN) is a D-dimensional vector that represents for a potential solution of the optimization problem, x_{up} and x_{low} are upper and lower bounds on x_i, $rand(0, 1)$ is a random number between 0 and 1.

Step 2. Searching for new food source

Employed bees search for new food source by Eq. (11).

$$\text{new } \mathrm{x}_i = \mathrm{x}_i + rand(-1, 1)(\mathrm{x}_i - \mathrm{x}_k) \quad (k = 1, 2, \ldots, FN; i \neq k) \tag{11}$$

where $rand(-1, 1)$ is a random number between -1 and 1.

When the new food source is found, the fitness should be calculated. Then a greedy operator is used to select and save the food source having better fitness value. Define $search\_i$ as the times of scout searching new food source around the ith food source, and L as the limitation of $search\_i$. Set $search\_i = search\_i + 1$.

Step 3. Selecting food source

Onlookers select a food source depending on the probability calculated by Eq. (12).

$$\mathrm{p}_i = \frac{fitness_i}{\sum_{i=1}^{FN} fitness_i} \tag{12}$$

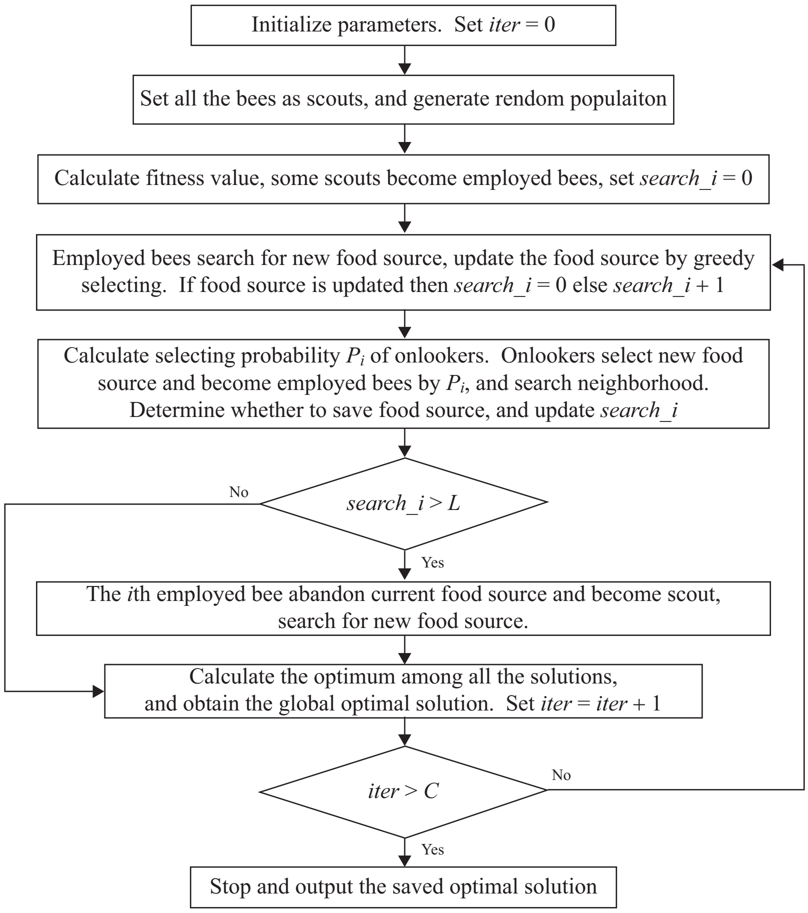


Fig. 3. The flow chart of ABC algorithm.

where $fitness_i$ is the fitness value of the ith food source.

After selecting their food source, the onlooker becomes employed bee, and then search for new food source as described in step 2.

Step 4. Determining whether there is any employed bee that has become scout

If $search\_i > L$, then it means that the ith solution cannot be improved after predefined number of trails L, the employed bee of the ith food source becomes scout, the ith solution is abandoned, and the scout starts to search for new food source by Eq. (10).

Step 5. Set iter = iter + 1

If $iter > C$, then stop the iteration and output the saved optimal solution, otherwise return to Step 2.

Fig.3 shows the flow chart of using ABC algorithm.

4. Damaged Ship Righting Plan Optimization Process Using ABC Algorithm

In this paper, a damaged ship righting plan optimization method using ABC algorithm is proposed to optimize the floatation for damaged ship. The detailed description of main steps of the proposed optimization algorithm is given as follows:

Step 1. Preparation

Collect the basic data for stability calculation, including outboard water density, displacement, floatation conditions before damaged. Locate the damaged compartments, estimate the breach size, calculate the weight of flooded water, and calculate the stability, floatation conditions and reserve buoyancy after damaged.

Step 2. Create design domain

Specify the statuses of compartments and loads onboard, calculate the available moving loads, removing loads and ballast loads. Based on the damage stability and floatation calculation, calculate the righting effects of each counter-flooding operation, such as the changes of GM, heel angle, trim, minimum freeboard, and reserve buoyancy. Set the range of moving loads, removing loads and ballast loads, which is a discrete set because the righting plan should be a combination of them. Set the sequence numbers for all counter-flooding operations. Hence an arbitrary solution that represents for a structural design plan can be expressed as:

$x = [x_{m1}, x_{m2}, \ldots, x_{mp}, x_{r1}, x_{r2}, \ldots, x_{rq}, x_{b1}, x_{b2}, \ldots, x_{bs}]$ ($x_{mi} = 0$ or 1, $x_{rj} = 0$ or 1, $x_{bk} = 0$ or 1)

where p is the total count of load moving operations, q is the total count of load removing operations, s is the total count of load ballasting operations, subscript "m" means load moving, subscript "r" means load removing, subscript "b" means load ballasting, x_{mi} is the indicator of the ith load moving operation, x_{rj} is the indicator of the jth load removing operation, x_{bk} is the indicator of the kth load ballasting operation, and only the non-zero value of these indicators means applying the corresponding operation.

Step 3. Assign optimization parameters of ABC algorithm

Set the number of employed bees (NEB), the number of onlookers (NOB), the number of maximum iterations, and the limit of searching food source. Set NEB = NOB.

Step 4. Set NS0 = NEB + NOB

Generate NS0 solutions by using Eq. (10). Perform floatation and stability calculation corresponding to each candidate solution, and check whether the calculated floatation and stability parameters can satisfy the constraints. Define penalty function to reflect the constraint violation level of candidate solution by using the following equation.

$$\begin{aligned}
&\alpha_p = \alpha \cdot f_p \\
&f_p = (1 + C_{GM})(1 + C_{MF})(1 + C_{RB}) \\
&C_{GM} = \begin{cases} \dfrac{GM_C}{GM}, \ if\ GM < GM_C \\ 0, \ if\ GM > GM_C \end{cases} \\
&C_{MF} = \begin{cases} \dfrac{MF_C}{MF}, \ if\ MF < MF_C \\ 0, \ if\ MF > MF_C \end{cases} \\
&C_{RB} = \begin{cases} \dfrac{RB_C}{RB}, \ if\ RB < RB_C \\ 0, \ if\ RB > RB_C \end{cases}
\end{aligned} \tag{13}$$

where α_p is the fitness value considering penalty effect, α is the calculated inclination angle, f_p is the composite penalty function, C_{GM}, C_{MF}, C_{RB} are the penalty functions of GM, minimum freeboard and reserve buoyancy respectively, GM_C, MF_C, RB_C are the set limit values of GM, minimum freeboard and reserve buoyancy.

Sort the solutions in NS0 by the value of α_p in ascending order, and take the first half of the solutions as the initial population x (0).

Step 5.

For the x (n) in the nth iteration, employed bees search in the vicinity of original solutions, generate an equal number of new candidate solutions *new* x (n) by using Eq. (11), evaluate these new solutions as Step 4, compare the fitness value of each solution x^i in x (n) and *new* x (n), and save the solution with better fitness value. This comparison is called greedy selection. If the new fitness value is better, than save the new solution. If the fitness value is not improved by perturbing, then set $search\_i = search\_i + 1$.

Step 6.

Calculate the selecting probability by using Eq. (12), each onlooker bee selects one solution x^i in x (n) according to the selecting probability, search for new position in the vicinity of the selected solution x^i, and evaluate the fitness value. If the new fitness value is better, than save the new solution. If the fitness value is not improved by perturbing, then set $search\_i = search\_i + 1$. Save the best solution x^{best0_n}.

Step 7.

If $search\_i > L$, abandon the old solution x^i, regenerate a solution x^i by Eq. (10). Compare the new generated solution with the best solution x^{best0_n}, replace the best solution if new x^i is better, and save the best solution.

Step 8.

Repeat Step 5 to 7 until the number of iterations exceed the predefined number C.

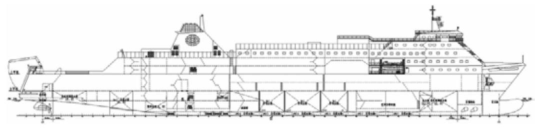


Fig. 4. General Arrangement of train ferry.

IV. APPLYING ABC ALGORITHM TO RIGHTING PLAN OPTIMIZATION PROBLEM OF A TRAIN FERRY

A train ferry is taken as an example to demonstrate the proposed optimization method. Fig. 4 shows the general arrangement plan of the ship. The ship can carry 63 crews, 480 passengers, 50 80-ton train carriages, 50 20-ton heavy trucks and 25 sedans. There are two continuous decks, the main deck is train deck and the upper deck is car deck. The ship has typical characteristics of Ro-Ro ship, and this ship type encountered several serious disasters in past 40 years (e.g., the losses of the Herald of Free Enterprise in 1987, Estonia in 1994, Express Samina in 2000, Da Shun in 1999, SEWOL in 2014, etc.). So the most critical design objective of the ship is to enhance the damage stability and self-rescue ability. The main dimensions and parameters are listed in Table 1.

To reduce the risk of capsizing caused by damage and flooding, Ro-Ro ships are usually designed to have more compartments than transport ships. The ship can sail and operate under the condition of 40 knot wind speed. The intact stability is designed for unrestricted navigation area, and the damage stability satisfies the requirement of one-compartment-damaged floata-

Table 1. Main dimensions and parameters of the train ferry.

Item	Symbol	Unit	Value
Overall length	L_{oa}	m	182.6
Length of waterline	L_{wl}	m	172.0
Length between perpendiculars	L_{pp}	m	164.6
Breadth	B	m	24.8
Depth	D	m	9.0
Designed draught	t	m	5.8
Designed displacement	$\triangle$	t	15760.7
Designed speed	v_d	kn	18

Table 2. Hull subdivision.

Location	Compartments	
	Side	Bottom
Aft - #6	Steering gear room	Aft peak
#6 - #33	Aft trim control tank (P/S)	Void space
#33 - #48	Ballast control tank (P/S)	Void space
#48 - #90	Engine room	Engine room
#90 - #116	Fin stabilizer room (P/S), No.3 anti-rolling tank (P/S)	No.6 & 5 ballast tank
#116 - #133	No. 2 anti-rolling tank (P/S)	No. 4 ballast tank
#133 - #146	No. 1 anti-rolling tank (P/S)	No. 3 ballast tank
#146 - #180	3 void spaces, AC compressor room	No. 2 & 1 ballast tank
#180 - #198	Fore trim control tank (P/S)	Void space
#198 - #211	Bow thruster room	Bow thruster room
#211 - Forward	Fore peak	Fore peak

bility. There are 3 couples of anti-rolling tanks and 2 couples of trim control tanks, for ensuring safety loading and unloading in port under 35 knot wind speed. There are 10 watertight transverse bulkheads below the main deck, located at #6, #33, #48, #90, #116, #133, #146, #180, #198, and #211. Table 2 shows the main compartments.

1. Case Study

Two typical damage scenarios are selected to examine the proposed method, which are shown in Fig. 5. In case 1, the port-side tanks between #90 and #133 are damaged that would cause heel. In case 2, the tanks from #164 to the bow are damaged that would cause trim. The damaged tanks in the both scenarios exceeded the initial designed considerations, hence special righting measures should be taken. The constraints on stability and floatation are listed as below:

$$|\theta| < 3^{\circ},\ -2 \text{ m} < t < 0,\ GM > 1 \text{ m},\ \min F > 1.5 \text{ m} \qquad (14)$$

where,

θ = heel angle

t = trim

GM = metacentric height

$\min F$ = minimum of freeboard

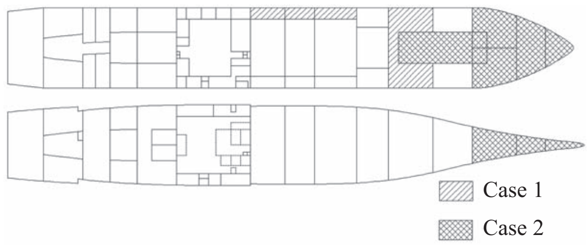


Fig. 5. Two typical damage scenarios.

By using different parameters such as colony size, initial solution, ABC algorithm is applied 25 times for each case. The computations are performed on a laptop with an Intel Core i5-6200U CPU with 2.30 GHz and 4 GB RAM. The computational time for Case 1 is 118 seconds, and that for Case 2 is 97 seconds. Table 3 and Table 4 shows the righting plans of Case 1 and Case 2. In the generated righting plan, the compartments needed to be operated and the corresponding loads are provided.

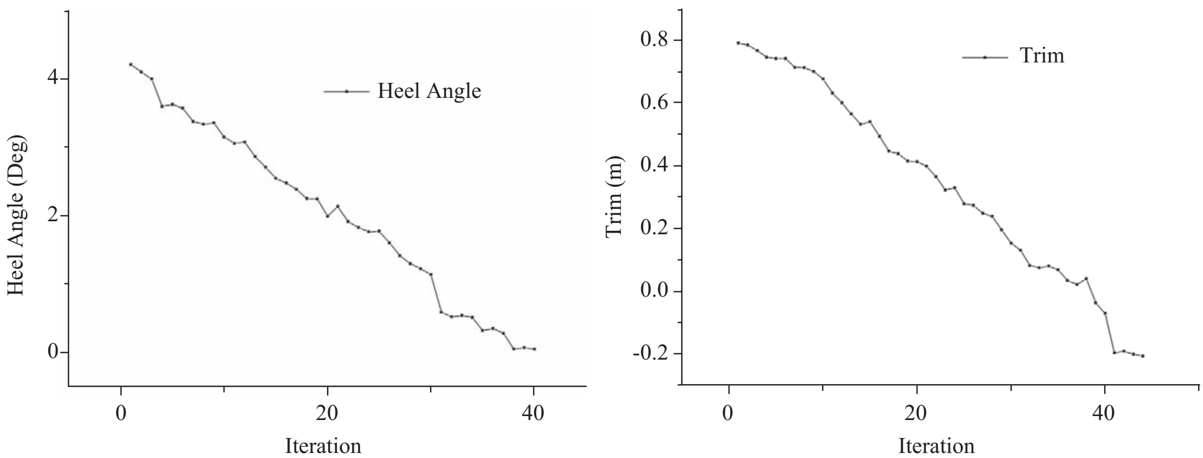
To get better insight into the problem convergence and the

Table 3. The optimal righting plan of Case 1.

	GM (m)	Heel angle (°)	Trim (m)	Minimum Freeboard (m)	Displacement (m^3)
Damaged	1.44	-4.17	-0.34	2.72	15891.81
Righted	1.53	-0.06	-0.31	2.75	15950.21
Righting plan	No.1 anti-rolling tank (P), pump out 21.99 ton water No.1 anti-rolling tank (S), pump in 21.99 ton water Void space (#164 - #180, S), pump in 10.01 ton water Aft trim control tank (S), pump in 48.39 ton water				
Damaged compartments	Fin stabilizer room (P/S) No.3 anti-rolling tank (P) No.2 anti-rolling tank (P) Void space (#146 - #164)				

Table 4. The optimal righting plan of Case 2.

	GM (m)	Heel angle (°)	Trim (m)	Minimum Freeboard (m)	Displacement (m^3)
Damaged	1.28	0	0.79	2.52	15921.35
Righted	1.56	0	-0.21	2.45	16048.83
Righting plan	Aft trim control tank (P), pump in 41.75 ton water Aft trim control tank (S), pump in 41.75 ton water No.1 anti-rolling tank (P), pump out 21.99 ton water No.1 anti-rolling tank (S), pump out 21.99 ton water				
Damaged compartments	Fore peak Bow thruster room Fore trim control tank (P/S) Void space (#180 - #198) AC compressor room				



(a) Iteration history of heel angle in Case 1 (b) Iteration history of trim in Case 2

Fig. 6. History of design attributes of ABC algorithm.

contribution of the proposed algorithm, the history of the objective function values of the righting plan optimization problem for Case 1 is given in Fig. 6 with respect to optimization cycle number n. Fig. 6(a) shows the iteration history of heel angle in Case 1. Fig. 6(b) shows the iteration history of trim in Case 2. In the whole iteration the objective value decreases quickly, in this process the algorithm has been trapped into local minimum several times, but at last the algorithm jump out of the local optimums and converged in the last several iterations. The convergence criteria is the difference between the maximum and the minimum in the vicinity of a solution is less than a predefined limit.

Table 5. Righting plan optimization performances of different methods.

Method	Optimization parameters	Total iterations	α (°)
GA-based optimization method	Population size = 3766 Crossover rate = 0.5 Mutation rate = 0.08	782/668	1.53/1.79
The proposed method	Colony size = 96 Searching limit = 20 Maximum iteration cycle = 1000	40/44	0.06/0.03

Summary on the righting plan optimization results is given as follows:

(1) Optimal solution is proposed with clear operation measures, compartments and loads.
(2) The ship is righted successfully from inclined state.
(3) Safety is ensured with saving the reserve buoyancy.
(4) The computation cost can be thought negligible with respect to numerous potential solutions.

2. Comparison of Some Existing Optimization Methods

To examine the effectiveness and computation efficiency, it is better to compare with existing methods such as GA. The used parameters and final optimized objective values of two optimiation methods for Case 1 are listed in Table 5. It is observed that the proposed ABCA (Artificial Bee Colony Algorithm)-based method produces lower value of inclination angle between the two optimization methods while it takes the smaller number of iterations.

It should be noted that the computational efficiency of both the two methods highly depends on the parameters including value range of available counter-flooding measures and compartment number, while the optimization effect highly depends on the population size and maximum iteration cycle. The more the parameters selected, the greater the amount of computation reuired. Usually, these parameters should be determined by several trails, so that they can make the optimization process stable and produce a satisfied solution.

V. CONCLUSION

This paper presents an ABCA-based optimization method for righting plan optimization of damaged ship. The main procedures of the proposed method include collecting the basic data, locating the damaged compartments, performing stability and floatation calculation before damaged, specifying the statuses of compartments and loads onboard, defining optimization parameters, setting the value ranges of optimization parameters, using the stability and floatation calculation results of each single counter-flooding operation to obtain the objective value and constraint satisfying degrees, and integrating the calculation process into performing ABC algorithm until the stop conditions are satisfied.

The proposed optimization method is applied to the righting plan optimization problem of a train ferry with two different damage scenarios. Both the two case results obtained a normal floatation state with respect to the initial heel or trim through 25 rounds of ABC algorithms with different optimization control parameters, which would justify the ability of finding the optimal solution quickly of the proposed optimization method for righting damaged ship. The results and the optimization history show that the ABCA-based optimization method can achieve better floatation state with lower calculation time cost. Thus, this study would be able to assist ship crew operating properly in very short time when emergency takes place.

In the future, this optimization method will be improved to be applied to the righting plan optimization problem of ship with more compartments or complicated hull surface. The proposed optimization method still requires a longer time to get an optimum because the stability and floatation calculation should be performed repeatedly during the optimization. Thus, a strategy to reduce the computation time of the developed program should be studied by improving the optimization algorithm further.

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