The survivability analysis and layout optimization of CODOG power system

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Abstract. The purpose of this paper is to discuss the calculation of the survivability of the CODOG power system in different layouts under the condition that the ship is hit by the simulation technology. In this paper, the impact of the weapon's hit distribution under the guidance conditions and the layout of different main power compartments on the survivability of the CODOG power system of the ship are discussed, the fuzzy evaluation method is used to evaluate its advantages and disadvantages, and the reasons for the advantages and disadvantages are analyzed.

1. introduction

As a large-scale functional platform for maritime transportation, combat, and work, ships need to face extreme situations such as typhoons, huge waves, and even weapon attacks while completing their missions. In order to ensure that all types of ships complete their missions safely and smoothly, various countries have carried out research on the survivability of all types of ships. The power system is the heart of the ship, and the survivability of the power system refers to the ability of the power system to continue to work in the case of damage[1]. This paper optimizes the damage distribution and evaluation calculation steps in the DDSA method, and calculates and evaluates the survivability of the four different layouts of the CODOG power system of the ship. Through comparison, the layout and suggestions to improve the survivability of the CODOG power system are put forward.

2. Judgment method of survivability of main power system

The DDSA method is usually used to evaluate and calculate the power system, which can provide a basis for the optimization of the ship power system. The DDSA method is divided into four basic steps: data collection (Data), damage distribution (Distribution), damage effect simulation (Simulation), and evaluation calculation (Assessment) [2].

In the data collection stage, geometric data such as the length, width and height of the main power compartment of the ship to be evaluated, the power compartment itself and the location of equipment layout, etc. need to be collected, and the main power compartment of the ship is simplified into a three-dimensional or two-dimensional model. Modern ships such as destroyers and frigates generally adopt a three-deck structure, with the main power cabin located between the bottom deck and the second deck. The survivability evaluation of the ship’s main power system requires a simulated weapon attack on the main power compartment. Therefore, the two-dimensional model is selected when the structure of the
main power cabin is simplified, and the calculation needs can be met by considering only the hit condition of the deck where the main power cabin is located. Simplify the cabins and the auxiliary equipment of the main power plant into a number of cuboids, the length, width and position of the cuboid are determined by the collected ship data [3].

With the rapid advancement of anti-ship missile technology, the threats faced by ships in modern naval battles are no longer intensive naval guns and aerial bombs, but mainly from the attacks of anti-ship missiles. Anti-ship missiles have guidance systems and strong autonomous attack capabilities. Unlike naval guns and aerial bombs, their hit distribution on ships is not a simple normal distribution or uniform distribution. The angle between the ballistic trajectory of the missile and the side plane of the ship has a greater impact on the hit rate of the missile. When the two are perpendicular, the missile will get the maximum hit rate. Studies have shown that the theoretical landing point of the missile aiming at the center of the ship is the projection center of the ship on the sea [4]. Due to a large number of random factors, a missile hitting a two-dimensional plane vertically will form a drop point distribution on the two-dimensional plane. The shape of the ship is irregular. It is planned to use a rectangular parallelepiped to simulate the ship. The length of the ship is set to $2l_x$ on the long side, the width of the ship is set to $2l_y$ on the short side, and the height above the water is set to H. Suppose that the missile shoots at the simplified cube target model of the ship. The aiming point is the center of the cube. The coordinate system is established with the theoretical landing point O after passing through the cube as the origin. The long side is the X axis and the short side is the Y axis. The coordinates of the landing point are $X = (x, y)$, and the target bottom area $v = 2l_x \times 2l_y$, as shown in the figure.

![Fig.1 Schematic diagram of missile attack](image)

The coordinate distribution of the missile's landing point obeys the $N (0, \Sigma)$ distribution, and the probability density function is:

$$\Phi(X) = \frac{1}{2\pi|\Sigma|^{\frac{1}{2}}} e^{-\frac{1}{2}x^T \Sigma^{-1}x}$$

In the formula, $X$ is the dispersion error; $\Sigma$ is the covariance matrix of the dispersion error, in the form $\Sigma = \begin{bmatrix} \sigma^2 & 0 \\ 0 & \sigma^2 \end{bmatrix}$, $\sigma = \frac{\text{CEP}}{1.1774}$, CEP is the circular probability deviation [5-6]. Then the probability distribution of a single hit of the power cabin can be obtained by integration. Calculated:
In the formula, \( l_{x1} \) is the ship's power cabin length/2; \( l_y \) is the ship's breadth/2; \( H \) is the target height; \( \sigma \) is the standard deviation of the dispersion error; \( \theta \) is the ballistic inclination; \( \alpha \) is the direction angle; \( \Phi_0(\cdot) \) is the standard positive The cumulative distribution function of the state distribution. When the ballistic inclination angle \( \theta \), target height \( H \), standard deviation \( \sigma \) of the dispersion error and other parameters are constant, the hit rate change graph with only the direction angle \( \alpha \) changing from 0° to 90° is made, as shown in the figure below:

![Fig.2 Schematic diagram of missile hit rate](image)

It can be seen that the missile gets the maximum hit rate when the direction angle is 45°. In order to perform a rigorous calculation and estimation of the ship's main power system, the situation with the highest hit rate, that is, the direction angle of 45º and the ballistic inclination level, is selected for calculation and simulation.

Damage effect simulation is an approximate simulation of the damage effect of a weapon after hitting a ship. According to previous case studies, a three-dimensional ellipsoid can be used to simulate the damage range of the weapon, and the equipment within the sphere is considered to be destroyed by the weapon. A two-dimensional model is used when estimating the power cabin, so the damage range is selected as an elliptical space simulation. According to the randomly generated explosion point coordinates in the damage distribution step, construct an elliptical damage area:

\[
\frac{(x-x_0)^2}{R_X^2} + \frac{(y-y_0)^2}{R_Y^2} \leq 1
\]

In the formula, \( R_X \) and \( R_Y \) are the damage radii in the two directions of ship length \( x \) and ship width \( y \). Whether the cabin is damaged can be judged by whether the simplified rectangular area of the cabin is in contact with the elliptical area.

The main damage modes of weapons are fragment damage, vibration damage, water ingress and fire.
For ships, the sub-cabin of the hull can greatly limit water damage and fire damage. Under the same rescue level and conditions of the crew, the watertight partition wall can better limit the spread of water and fire. In the past, when calculating the survivability of ships and using the weapon damage radius analysis method to determine damage, it was generally assumed that if the damage volume of the weapon intersects the volume of the cabin, the damage effect caused by the weapon will destroy all the equipment in the cabin. This is a relatively conservative calculation method, and the result is generally the maximum attack effect that the ship can withstand. For example, the shaft system in the main power plant is particularly important to the survivability of the main power system of a ship, and its structure has a strong ability to resist damage. When the cabin where the shafting is arranged is hit by a simulation, the ship directly loses all the power of the hit side, and the calculation result will be inconsistent with the actual situation. Therefore, the algorithm needs to be modified appropriately. When the weapon hits the cabin where the shaft system is arranged, the shaft system is considered damaged only when the damage range of the weapon overlaps with the shaft system.

The damage of the main power system is generally divided into four grades, as shown in the following table:

| Damage grade     | Grade description                          |
|------------------|--------------------------------------------|
| Class A injury   | Complete loss of survivability, power system and independent groups are destroyed |
| Class B injury   | Basically lose survivability, dynamic power rate ≤50% |
| Class C injury   | Have basic survivability, dynamic power rate >50% |
| Class D injury   | Has full survivability, dynamic power rate = 100% |

3. Algorithm simulation calculation
Perform simulation calculations on the survivability of the CODOG power plant. The system is jointly propelled by diesel and gas turbines. It consists of propulsion diesel engines, gas turbines, gearboxes, couplings, shafting (including propellers) electromechanical control rooms, as well as fuel, lubricating oil, cooling, and it is composed of auxiliary equipment such as air inlet and exhaust, sea water inlet and outlet. The picture is a two-dimensional diagram of four different CODOG power plant layouts:

![Fig.3 Simplified diagram of power cabin]
The layout of the CODOG power plant is proposed to use two high-power gas turbines and two low-power diesel engines. The diesel unit will run at lower speeds and be driven by gas turbines at higher operating conditions. In the highest operating conditions, the power of the diesel engine and the gas turbine can be combined. In order to calculate the power loss after the weapon hits, referring to the power configuration of CODOG power plants at home and abroad, the diesel engine power $W_1$ is selected as 30% of the gas turbine power $W_2$. The total power is $W = 2W_1 + 2W_2$. Fuzzy comprehensive evaluation of the survivability of four different main power system layouts is carried out, the fault trees are listed separately, and the probabilities of A, B, C, D damages in several different configurations after being attacked by weapons are calculated.

List the fault trees of four different main power system layouts respectively, and find out the logical relationship between the location of the weapon hitting the ship and the damage position and the damage of the power system. The bottom event in the fault tree represents the cause event that caused other events to occur. It is located at the bottom of the fault tree. Here, the damage of the cabin and shafting by the weapon is selected as the bottom event of the fault tree$^{[8-11]}$.

![Fault tree diagram]

Use the Monte Carlo method to calculate the survivability of different main power system layouts. Suppose that the threat weapon attacks the ship N times, of which n attacks cause the ship's power system to have different levels of failure, and the frequency of each occurrence is $p_f = \frac{n}{N}$, When N is
large enough, the frequency of occurrence of the damage approaches the probability of occurrence of damage level, here N=10000 times. Check the information and consider the actual situation, and the ship’s height H is 25 meters in the calculation.

When designing a ship, the survivability requirement of the power system is usually that the less power loss after a hit, the better, and the less likely the total power loss, the better. Therefore, the ABCD four results of the above four CODOG power plant layouts are given weights that match the survivability level, which is (1, 0.6, 0.25, 0). Then the final comprehensive survivability evaluation value is

$$S = S_a + 0.6 \times S_b + 0.25 \times S_c$$

It can be seen that the larger the $S$ value, the lower the survivability of the ship’s power system. Number the four layouts from top to bottom, and from left to right, and then draw the picture. The result is shown in the figure below:

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**Fig.5 Simulation flow chart**
4. Result analysis

1. It can be seen from the results of the graph that the missile has the highest hit rate when the directional angle of the missile is 45º and the ballistic inclination is horizontal. When the coordinate distribution of the landing point obeys the N(0, Σ) distribution, all of the four main power system layouts have good survivability. The survivability of the second arrangement is better than that of the other three ways, and the survivability of the first arrangement is the worst. Analysis of the reason is mainly because the main power system of the second arrangement has more sub-cabins, and the main power system adopts a T-shaped arrangement instead of a non-linear arrangement. Two high-power gas turbines are located at both ends of the power compartment area, and the gearboxes are also installed in the two compartments respectively, which can ensure that the ship will basically not lose all its power under a single attack. Two low-power diesel engines are installed in the same cabin, which is conducive to daily inspection and maintenance. The ship adopts this design to better ensure its ability to perform tasks.

2. From the perspective of the comprehensive survivability value, the survivability of the main power system of the layout mode 3 and 4 is not much different, and is at a medium level. Compared with other methods, the advantage of the third layout method is that it maintains survivability while having a simple structure, which is conducive to normal maintenance and lower maintenance costs.

3. As the damage radius of the weapon increases, the survivability of the main power systems of the four arrangements all decrease. Arrangement methods one, three, and four, the survivability declines first and then slow, and the second arrangement is slow first and then fast. When the weapon damage radius is more than 15 meters, the main power system of the four arrangements basically loses all survivability.

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