# A Lightweight Design Method Based on Two-Layer Topology Optimization of Limited Design Space and Parameter Optimization

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**Abstract:** This paper proposes a lightweight design method based on two-layer topology optimization of limited design space and parameter optimization to solve the lightweight problem of mechanical products better. In order to verify the effectiveness of the proposed approach, a lightweight design was carried out with the wall frame of a 70-meter ocean-going fishing boat trawl winch as an example. First, the conceptual model of the supporting structure is obtained through the two layers of topology optimization, and then the conceptual model is parameterized. After that, the optimal Latin hypercube design method is used to design the experimental structure changes to obtain multiple data points. Then, based on the obtained data points, the target performance of the supporting structure is sampled. Next, the radial basis function neural network based on the obtained sample points is established. Finally, the NLPQLP algorithm is used to solve the optimization model to obtain the optimal solution. The results show that applying the proposed method to the lightweight design of the support structure of a trawl winch can significantly reduce the quality of the support structure and get a very significant optimization effect while meeting the required target performance.

## 1. Introduction

Lightweight design technology is an effective technical tool to improve the product's overall performance and enhance the industry's competitiveness in many engineering applications. The same is true in the field of optimization of fishing boat deck machinery. With the development of FRP fishing boats in recent years, the lightweight of fishing boat deck machinery has become an important research content. The deck machinery of traditional fishing boats has many problems, like overweight, redundant performance, and high energy consumption. At the same time, FRP fishing boats have higher requirements for deck machinery's weight. These make it impossible for traditional deck machinery to be directly applied to FRP fishing boats. Therefore, it is necessary to carry out a lightweight design to realize that the existing equipment can be better adapted to FRP fishing boats after modification.

In order to find a suitable and efficient method for lightweight deck mechanical structure, a literature review of relevant lightweight methods at home and abroad is carried out. There are two main reliable methods for optimizing the structure of mechanical products. One is the shape and parameter optimization methods of improving existing structures. This method often uses approximate models and advanced optimization algorithms to reduce calculation costs and optimization cycles. Another method is topology optimization, which is a more general optimization method that can obtain the most effective structure. Topology optimization has received extensive attention and consideration due to its ability to find the optimal material layout in the product conceptual design stage. In recent years, various topology optimization methods have been developed, such as the homogenization method [1], the solid isotropic material penalty (SIMP) [2,3] method, the evolutionary structural optimization (ESO) [4] method, the level set method (LSM) [5-7].Haddouch [8] et al. used artificial neural networks (ANN) and the genetic algorithm to optimize the parameters of the pressure pipeline. Putra et al. [9] optimized the hatch cover with a

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framework that comprehensively considered material selection, structural size optimization, and layout optimization and obtained good optimization results. Xiong et al. [10] used a combination agency model to establish the relationship model between inputs and outputs. Moreover, they combined with the MOPSO algorithm to optimize the material type and structural parameters of the front-end structure of the car body. SINGH et al. [11] established the Kriging model based on the data obtained and performed multi-objective optimization of the gas cyclone. Zhu et al. [12] improved the aircraft skin stretch-forming die by topology optimization technology. Pajunen et al. [13] optimized the size of ocean structures based on a successive response surface method. Sudalaimuthu et al. [14] used topology optimization to generate a new lightweight conceptual model and finally achieved a 20% weight reduction. Assimi [15] and others combined with genetic programming and comprehensively used topology optimization and parameter optimization techniques to optimize the truss structure. Locatelli et al. [16] used an optimization framework combining topology optimization and parameter optimization to optimize the wing-box structures.

However, the existing research methods have some shortcomings: First, the existing research methods mainly focus on single parameter optimization or topology optimization, and few research methods use both. Second, the existing topology optimization methods are often based on existing models to improve the design, and the extra design space is not considered. Therefore, the optimization effect can be further improved. Besides, the direct topology optimization method has problems such as long iteration cycle time and low optimization efficiency.

In order to solve the above-mentioned existing problems, this paper proposes a new lightweight design method using two-layer topology optimization and parameter optimization while considering the additional limited design space. Through an actual engineering case of the wall frame of a trawl winch, the application steps of the proposed method are explained in detail, and the effectiveness of the proposed method is verified. The proposed method can be applied to the design stage of different mechanical products, aiming to produce a new generation of mechanical products with high efficiency, low cost, and high quality.

## 2. Lightweight Design Framework and Related Theories

### 2.1 Lightweight Design Framework

This section introduces the proposed lightweight design framework, as shown in Fig. 1. The framework mainly includes three stages: conceptual model design, intermediate processing, variable selection, and precise design. The overall idea is as follows:

Stage I: First, build the initial FEM model. Then input the Fem model to the conceptual model design layer, limit the model design space and generate filling entities. Finally, Perform double-layer topology optimization.

Stage II: The intermediate processing is carried out. This stage includes the design of experiments (DoE) program's generation and the parameterization of model variables.

Stage III: The third stage mainly completes the precise design of the conceptual model. In this stage, the establishment of an optimization model, experimental design and sampling, establishment of proxy model, and optimization problem solving based on NLPQLP algorithm are completed in sequence.

Notes: the difference between the first layer of topology optimization layer (T1) and the second layer of topology optimization layer (T2) is that T1 is a rough topology optimization design using a large grid, and T2 is a high-quality topology optimization design using a small grid.

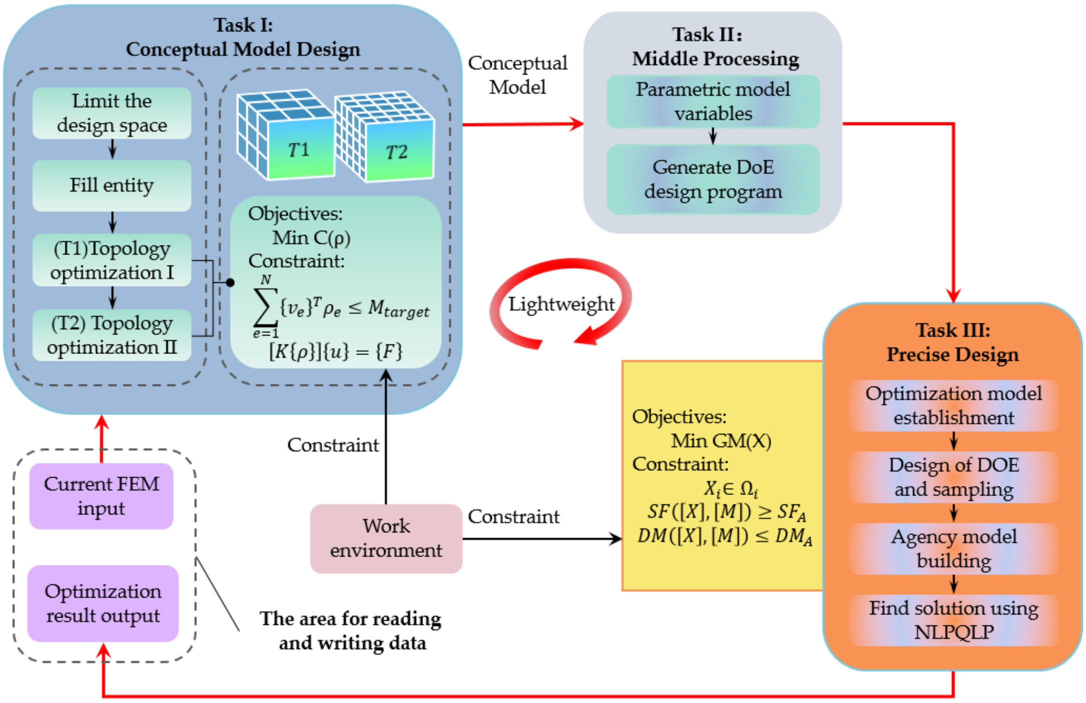



Fig.1 Lightweight Design Framework

The following subsections of this chapter will further elaborate on the related theories of the framework.

## 2.2 Topology Optimization Based on Simp

In the topology optimization stage, the SIMP [2,3] method is used. This method has good convergence, simple sensitivity, and easy calculation. Besides, it can be applied to complex nonlinear structure topologies. Therefore, this method is widely used in the field of optimization. In this study, the topology optimization aims at minimizing compliance, and finite element analysis is performed based on the actual deck operating conditions in the marine environment. The optimization model of the topology optimization stage is shown in Eq. (1):

$$\begin{cases} Min\ C(\{\rho\}) = \sum_{e=1}^{N}(\rho_e)^p[u_e]^T[K_e][u_e] \\ s.t. \quad \sum_{e=1}^{N}\{v_e\}^T\rho_e \le M_{target} \\ \qquad [K\{\rho\}]\{u\} = \{F\} \end{cases} \quad (1)$$

Where $C(\{\rho\})$ is compliance; $[u_e]$ is the nodal displacement vector of element e; $[K_e]$ is the stiffness matrix of element e; and the vector $\{\rho\}$ contains the relative density of elements $\rho_e$; $p$ is the penalty factor; $N$ is the number of elements in the design domain; $v_e$ is the element envelope; and $M_{target}$ is the optimized target quality; $[K\{\rho\}]$ is the global stiffness matrix adjusted by the relative density vector; $\{u\}$ is the displacement vector; $\{F\}$ is the external force vector.

The global stiffness expression in the SIMP method is shown in Eq. (2):

$$K_{SIMP}\{\rho\} = \sum_{e=1}^{N}\left[\rho_{min} + (1-\rho_{min})\rho_e^p\right]K_e \quad (2)$$

where $K_e$ is the element stiffness, $\rho_{min}$ is the minimum relative density, and $\rho_e$ is the element relative density.

In each iteration, the optimization algorithm will perform sensitivity analysis to evaluate the impact of material density changes on the objective function, thereby minimizing compliance. Mathematically, sensitivity analysis is expressed as the derivative of the objective function to the material density, as shown in Eq. (3):

$$\frac{dC}{d\rho_e} = -p(\rho_e)^{p-1}[u_e]^T[K_e][u_e] \quad (3)$$

## 2.3 Rbfnn Model

Radial Basis Function Neutral Network (RBFNN) is a kind of ANN. It has many advantages: the strong ability of complex nonlinear approximation, fast learning convergence, good generalization ability, and robust fault tolerance. Therefore, it is widely applied in all kinds of fields. RBFNN is a feedforward three-layer network in structure, including an input layer, a hidden layer, and an output layer, as shown in Fig. 2. The objective function expression of RBFNN is shown in Eq. 4:

$y_k = \sum_{i=1}^{h} \beta_i \varphi(\|x - c_i\|)$ (4)

where: $\beta_i$ is the connection weight coefficient, $c_i$ is the node center of the i-th hidden layer, $\|x - c_i\|$ is the Euclidean distance function, and $\varphi$ is the nonlinear basis function.

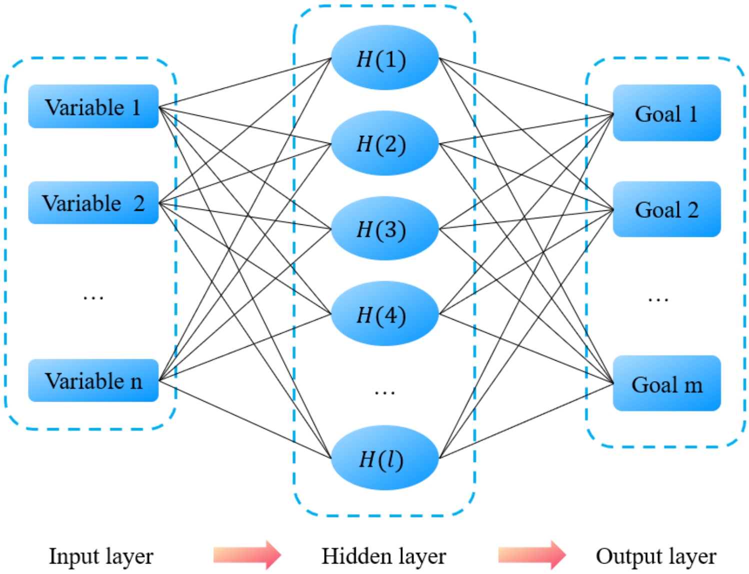



Fig.2 Rbfnn Structure

## 3. Case Study

The last chapter introduced the proposed general framework of lightweight design and related theories. In this section, taking the wall frame of the trawl winch as an example, the specific application of the proposed frame in the lightweight design is introduced.

### 3.1 Initial Performance Analysis

In this study, a wall frame was selected as an example to develop a lightweight design. The wall frame of the trawl winch is the crucial support structure of the trawl winch, whose overall mass accounts for a large proportion of the total mass of the trawl winch. Its structural model is shown in Fig. 3. The wall frame is mainly composed of the support plate (a), rib plate (b), connecting plate (c), base (d), box plate (e), and bearing seat (f). In Fig. 3, the initial material of the support plate, the rib plate, the connecting plate, the base, and the box body plate is material A, the initial material of the bearing seat is material B. The specific data of related materials are shown in Tab. 1.

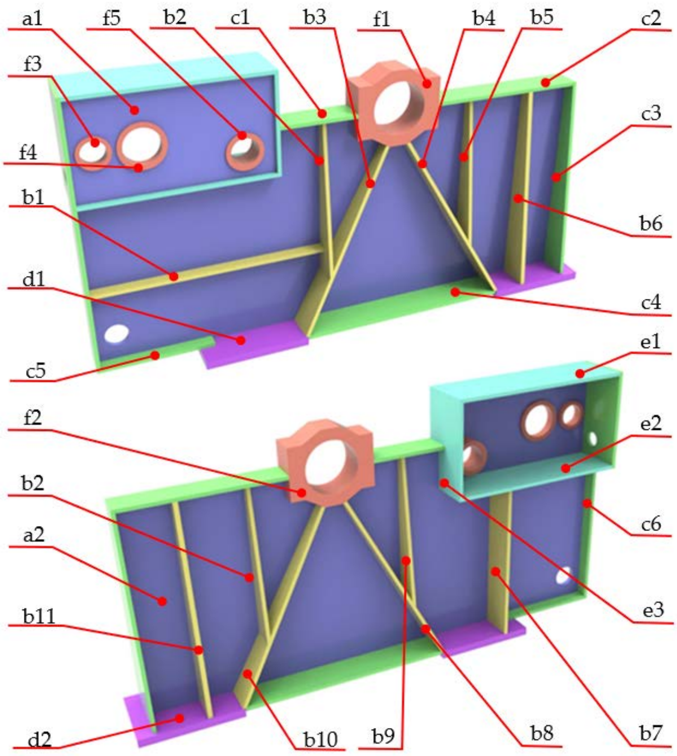



Fig.3 Structural Model of Wall Frame

Table 1 Related Material Parameters

| Material | Density | Young's Modulus | Poisson's Ratio | Tensile Yield Strength |
|---|---|---|---|---|
| A | 7860 | 2.12e+05 | 0.288 | 235 |
| B | 7850 | 2.06e+05 | 0.28 | 345 |

In the actual working environment, the load on the wall frame includes: (I) the lateral force provided by the rope arranging device to the bearing seats f3 and f4 and the support plate a2; (II) the bearing force given to the bearing seats f1 and f2; (III) The vertical pressure of the rope arranging device to the wall bracket bearing seats f3 and f4 and the support plate a2.

(I)The calculation of the lateral force provided by the rope is as shown in Eq. (5). According to Eq. (5), the side force of the two poles constraints can be calculated, respectively.

$F_C = 0.5Qsin\beta$ (5)

where $F_C$ is the lateral force; $Q$ is the working tension of the wire rope, and its value is 300KN; $\beta$ is the wire rope working angle. In general, $\beta\epsilon(-6°, 6°)$.

(II)The bearing load is decomposed into two loads in the horizontal and vertical directions, and then the maximum value of the load in both directions is calculated. The maximum value of the force in the horizontal direction can be calculated according to Eq. (6). According to Eq. (7), the maximum load value in the vertical direction can be calculated.

$Qcos\theta(l_{AC} - l_{AB}) - F_x l_{AC} = 0$ (6)

where $Q$ is the working tension of the wire rope; $\theta$ is the angle between the wire rope and the deck, which is determined to be 30° according to the actual installation conditions; $l_{AB}$ is the load spacing, which is the variable value, $l_{AB} \in (418mm, 1854mm)$; $l_{AC}$ is the total length of the supporting part, and it is 2325mm.

$Qsin\theta(l_{AC} - l_{AB}) - \text{GL} - F_z l_{AC} = 0$ (7)

where $G$ is the pressure provided by the winch drum to the wall frame, which is a non-constant value and during the working process, $G \in (49.75KN, 147KN)$.

(III)The vertical pressure value can be calculated based on the mass of the rope arranging device.

Based on the obtained load data, the wall frame of the two working conditions is subjected to finite element analysis to obtain the initial performance data. In this study, tetrahedrons grid division technology was used. Besides, add the loads and fix the part of d1 and d2 in the finite element model. Finally, get the analysis result, as shown in Tab. 2. And in Tab. 2, $DM$ is the maximum deformation, $SF$ is the minimum equivalent force coefficient, and $GM$ is the current weight of the wall frame.

Table 2 Initial Performance Data of the Wall Frame

| Group | Working condition | DM | $SF$ | $GM$ |
|---|---|---|---|---|
| 1 | $\theta = +6°$ | 1.91 | 2.99 | 1445.20 |
| 2 | $\theta = -6°$ | 1.91 | 2.99 | |

### 3.2 Conceptual Model Generation

Based on the initial model, an additional design space of the intermediate structure is added, and the entity is filled with the design space. The design space should be as ample as possible while meeting the actual environmental requirements and not affecting other components. Fig. 4 is a defined design space under the current model.

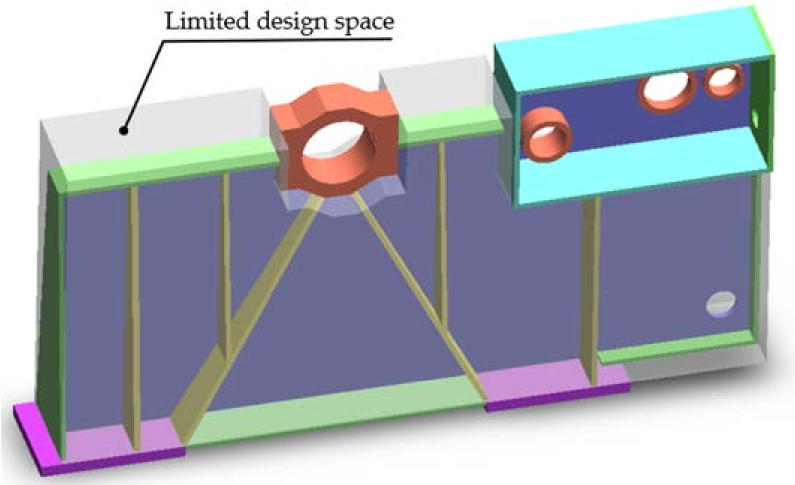



Fig.4 Limited Design Space under the Current Model

Then, the topology optimization technology based on SIMP theory is used to optimize the topology of the limited design space entities. The optimization includes two layers of topology. First, the first layer of topology optimization using a large grid can quickly reduce the limited space design range. Then, a small grid is used for topology optimization to generate a conceptual model. The topology optimization results generated based on SIMP cannot be directly applied to subsequent optimization, so software needs to be fitted. The conceptual model obtained by software fitting is shown in Fig. 5.

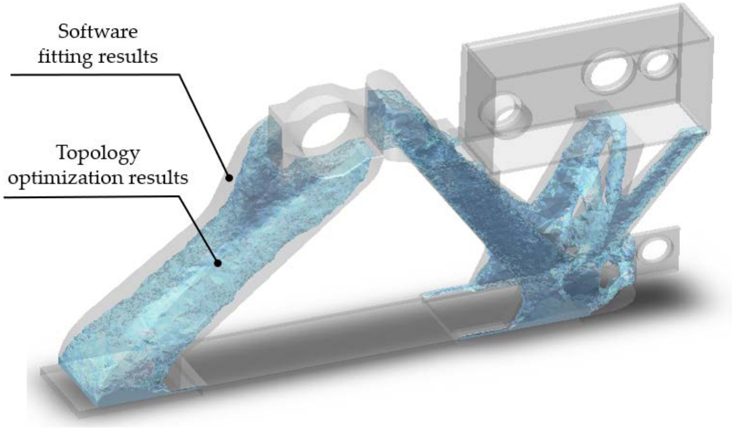



Fig.5 Conceptual Model

### 3.3 Intermediate Processing and Precise Design

Then, parameterization is performed based on the conceptual model obtained. The variable design of the wall frame is shown in Fig. 6, and the initial values of the variables and variables' upper and lower limits are shown in Tab. 3.

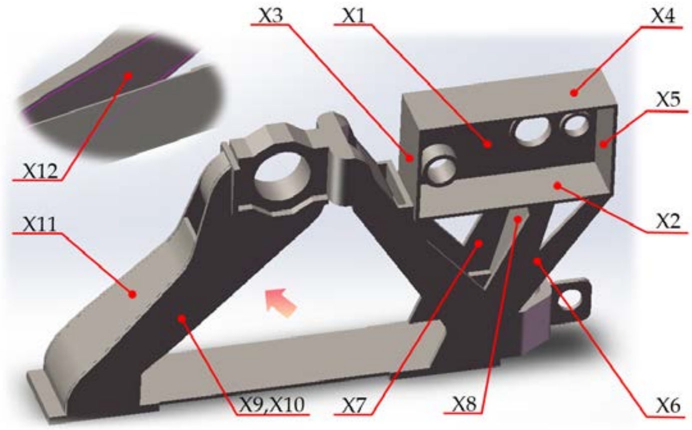



Fig.6 Structural Parameter Variable Design

Table 3 the Initial Value and Limits of the Variable

| | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $x_{11}$ | $x_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial value | 25 | 20 | 20 | 20 | 20 | 25 | 25 | 40 | 20 | 20 | 20 | 20 |
| Upper limit | 37.5 | 30 | 30 | 30 | 30 | 37.5 | 37.5 | 60 | 30 | 30 | 30 | 30 |
| Lower limit | 12.5 | 10 | 10 | 10 | 10 | 12.5 | 12.5 | 20 | 10 | 10 | 10 | 10 |

DoE is required after the variable design is completed. The DoE methods commonly include orthogonal experimental design, partial factorial design, complete factorial design, Latin hypercube design, Optimal Latin Hypercube Design (OLHD). Among the above methods, the OLHD method is used in this study. Compared with other DoE methods, the data points obtained by the OLHD method are more evenly distributed in the design space. In addition, it uses a small number of sample points to obtain higher calculation accuracy and can capture a high-order effect. Therefore, the OLHD method is used in the lightweight design of the wall frame to assist in constructing the proxy model in this paper.

Then the optimization model is established. The establishment of the optimization model requires full consideration of design variables, constraints, and objective functions. The optimization goal is to minimize the quality of the wall frame of the trawl winch. Moreover, the maximum deformation under the two operating conditions and the minimum safety factor are used as constraints. At the same time, limit the upper and lower limits of the structure variable. Based on the above, the optimization model of the wall frame's lightweight design is established, as shown in Eq. (8):

$$\begin{cases} find: X = [x_1, x_2, x_3, \dots, x_{12}] \\ min: GM(X) \\ s.t. x_i^L \leq x_i \leq x_i^U \ (i = 1, 2, 3, \dots, 12) \\ max\big(DM_1(X), DM_2(X)\big) \leq DM_a \\ min\big(SF_1(X), SF_2(X)\big) \geq SF_a \end{cases} \tag{8}$$

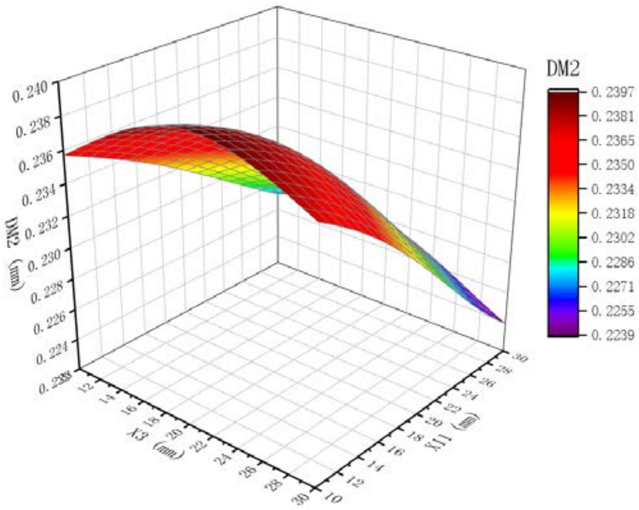
where $DM_a$ is the allowable critical value of the maximum deformation and $SF_a$ is the allowable critical value of the minimum equivalent stress safety factor

Then, each test factor's upper and lower limits are limited, and the OLHD method is used to generate the required 200 sets of design variable data points. Afterward, the maximum deformation and the minimum equivalent stress coefficient are sampled by the finite element software based on the obtained data points. Unfortunately, due to passage space limitations, Tab. 4 only shows part of the data obtained by sampling.

Table 4 Partial Data Obtained by Sampling

| Number | $x_1$ | $x_2$ | $x_3$ | ... | $x_{11}$ | $x_{12}$ | $DM_1$ | $DM_2$ | $SF_1$ | $SF_2$ | GM |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 36.75 | 22.56 | 10.30 | ... | 14.32 | 18.94 | 0.18 | 0.20 | 3.22 | 3.93 | 1540.77 |
| 2 | 22.93 | 10.70 | 26.38 | ... | 27.99 | 19.05 | 0.23 | 0.24 | 2.84 | 3.15 | 1457.70 |
| 3 | 18.91 | 14.72 | 10.20 | ... | 27.69 | 14.92 | 0.24 | 0.26 | 3.05 | 3.83 | 1409.33 |
| 4 | 17.40 | 14.12 | 25.68 | ... | 12.91 | 24.97 | 0.23 | 0.23 | 3.12 | 4.04 | 1474.00 |
| 5 | 20.67 | 22.66 | 26.48 | ... | 26.78 | 30.00 | 0.18 | 0.20 | 3.34 | 4.11 | 1557.28 |
| … | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 200 | 35.87 | 24.97 | 10.00 | ... | 27.79 | 13.92 | 0.17 | 0.20 | 3.25 | 3.96 | 1544.32 |

The RBFNN proxy model is established based on the sample points obtained. Fig. 7 shows the response effect diagram of the design variables and target performance. Due to space limitations, only some groups are given. According to the effect diagram, the relationship between the design variables and the target performance can be well observed.



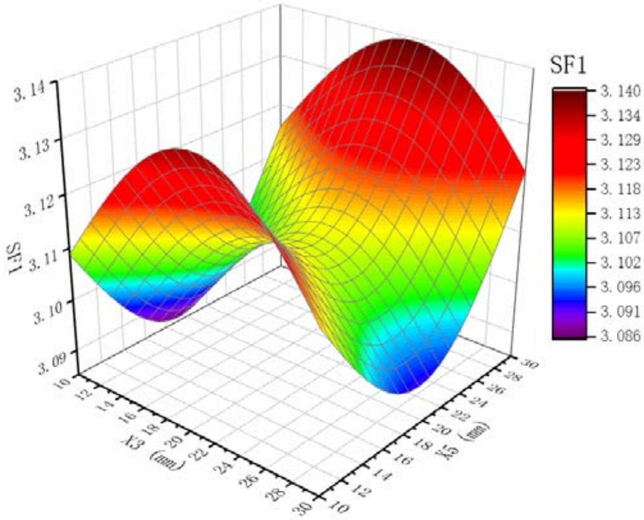



Fig.7 Design Variables and Target Performance Response

### 3.4 Optimization Results

Finally, replace the actual finite element analysis with the obtained surrogate model, and use the NLPQLP algorithm to solve the optimization model. After many iterations, the respective optimal solutions are obtained. Excessively high dimensional accuracy will significantly increase the manufacturing cost of the winch wall frame, so the dimensional accuracy should not be too high. The dimensional accuracy here is 0.1mm, and the processed solution is taken as the final solution. Because of specific errors in the approximate model, the processed solution needs to be simulated and verified by finite element analysis. Fig. 8 is the finite element cloud diagram of the final solution.

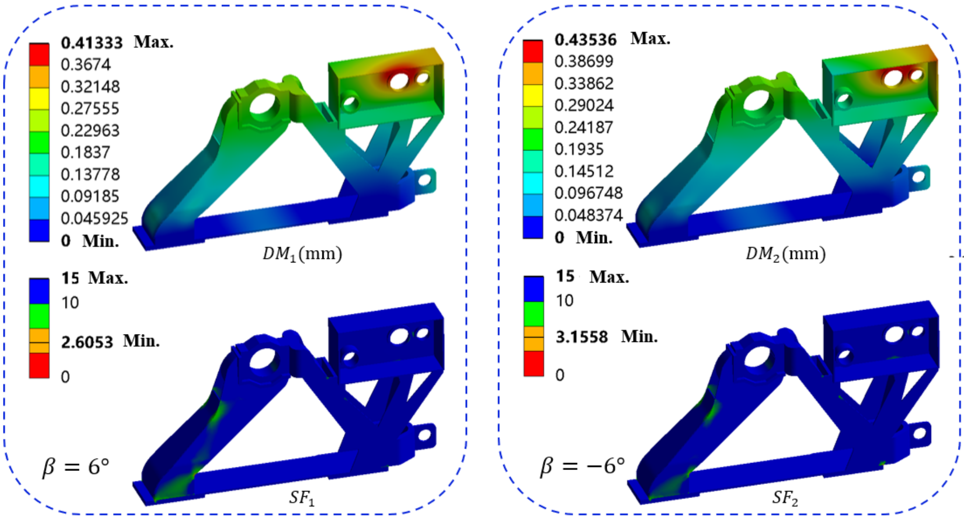



Fig.8 Finite Element Cloud Diagram of the Final Solution

Each target performance change rate of the conceptual model and the optimized model are summarized, as shown in Fig. 9. Group I is the target performance change rate of the parameterized conceptual model. Group II is the target performance change rate of the optimized model finally obtained. As for the parameterized conceptual model, the overall quality of the conceptual model has hardly changed, the maximum deformation reduction exceeds 90%, and the equivalent stress safety factor is increased by 60%. The optimization at this stage can significantly improve the performance redundancy problem of the wall frame and provided more feasible space for the precise design of the subsequent stage. As for the final model, the overall quality of the final model is reduced by 19.7%, the manufacturing stress safety factor is increased by 36.1%, and the maximum deformation is reduced by nearly 85%. In general, the proposed lightweight design method used in this paper can significantly reduce the quality of the wall frame and improve every other performance, which shows that the comprehensive optimization effect is very significant.

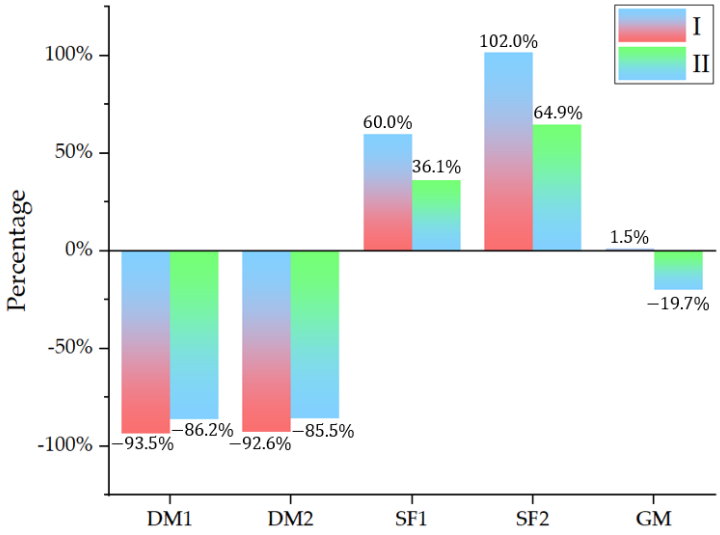



Fig.9 Optimization Percentage for Each Stage

## 4. Conclusion

This paper proposes a lightweight design method based on two-layer topology optimization and parameter optimization of limited design space to solve lightweight mechanical products better. Moreover, the proposed method is applied to the lightweight design of the wall frame, and an excellent lightweight effect is obtained. Specifically, the proposed method can significantly improve the performance redundancy problem of the deck mechanical support structure. On the one hand, it reduces the overall weight and significantly improves every other performance. In addition, this paper applies the proposed method to a lightweight design case of wall frames, which can reduce the model's overall quality by 19.7%, increase the safety factor of manufacturing stress by 36.1%, and reduce the maximum deformation by nearly 85%. In general, each performance has been dramatically improved, and the comprehensive optimization effect is very significant.

Therefore, this research can be successfully applied to the optimization and upgrading of deck mechanical support structure to reduce material expenditure and solve the problem of performance redundancy. In addition, the proposed method can provide researchers with convenient tools and a specific research foundation in the lightweight design stage of related deck machinery or similar mechanical products. This work may provide insight into breaking the current limitations of lightweight design and provide a way to enhance the lightweight effect of mechanical products further.

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