Topology Optimization Design of Boat Boom Structure Based on Level Set Method

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Abstract. The marine boom is optimized by a level set topology optimization method based on the reaction diffusion equation. In order to overcome the characteristics that the boom is difficult to be topology optimized, the periodic topology optimization theory is introduced to divide the boom into several cycles, and two typical conditions of maximum amplitude and minimum amplitude are selected respectively. Finally, the optimized boom structure is processed and remodelled and finite element analysis is performed, which still meets the original performance index.

1. Introduction

In recent years, with the rapid development of marine transportation, the loading and unloading capacity of marine deck cranes is becoming more and more demanding, and cranes with light weight and good performance are more and more popular. Based on this background, the topology optimization of the structure of the marine deck crane is carried out, so as to achieve the purpose of weight reduction on the basis of satisfying the original performance.

Peng Jingjing[1] optimized the structure of the boom by genetic algorithm. Wang Chenglin[2] used SIMP topology optimization method to optimize topology of truss arm top joint structure under single and multi-case conditions. Based on the Lagrange multiplier method and the evolutionary algorithm, Milomir[3] optimized the crane's boom section. Xiong Zhan [4] used the finite element analysis software to optimize the topology of the boom truss of the tower crane under the action of moving load.

This paper mainly optimizes the boom based on the level set topology optimization method of diffusion equation proposed by Takayuki Yamada [5-7]. In the optimization process, the periodic topology optimization theory is applied to the optimization process of the boom. The two conditions of the maximum and minimum amplitude of the crane are selected for research, which makes the optimization more convenient and effective, and the obtained results are also easy to process. Finally, the finite element analysis of the optimized structure is carried out to prove the application value of the level set topology optimization method in engineering practice.

2. Structural topology optimization design model of level set method

Based on the level set method of the reaction diffusion equation, the mathematical model of maximizing the stiffness of the boom structure is established, and the structural volume is the mathematical model of the constraint optimization problem. The structure boundary diagram is shown in the following figure:
Figure 1. Schematic diagram of the level set topology optimization structure boundary.

Where \( \Gamma_u \) is a place of displacement constraint, \( \Gamma_f \) is the external force constraint. D is the design area and \( \Omega \) is the material area. The detailed optimization model is shown in equation (1).

\[
\inf\phi J = \int_\Gamma F u_i d\Gamma, \\
s.t. G = \int_\Omega d\Omega - V_{\text{max}} \leq 0 \\
\text{div}(E_{ijkl} u_{ijkl}) = 0 \text{ on } \Omega \\
u_i = u_i \quad \text{in} \quad \Gamma_u \\
F_i = \overline{F_i} \quad \text{in} \quad \Gamma_f
\]

In the above formula, \( J \) is the objective function of the optimization model constructed by the level set topology optimization method, \( V_{\text{max}} \) is the largest volume constraint value, \( E_{ijkl} \) is the elastic modulus of the material, \( u_i \) and \( F_i \) are the corresponding displacement and external force constraints, where the displacement of the boundary \( \Gamma_u \) is zero, \( \overline{F_i} \) represents the given external load, \( \text{div}(E_{ijkl} u_{ijkl}) = 0 \) represents no additional external load on material \( \Omega \) area, and \( F_i = \sigma_j n_j = E_{ijkl} u_{ijkl} n_j \) represents tension.

The Lagrange multiplier method is used to transform the above constrained optimization problem into an unconstrained problem. The specific expression is shown in equation (2).

\[
\bar{J} = \int_\Gamma F_i u_i d\Gamma + \int_\Omega \bar{u}_i \text{div}(E_{ijkl} u_{ijkl}) d\Omega + \lambda (\int_\Omega d\Omega - V_{\text{max}})
\]

The level set function is updated by introducing a reaction diffusion equation; the specific formula is as follows:

\[
\begin{align*}
\frac{\partial \phi}{\partial t} &= -(Cd_i \bar{J} - \tau \nabla^2 \phi) \quad \text{in } D \\
\phi &= 0 \quad \text{on } D
\end{align*}
\]

\( \phi \) is a level set function, \( K \) is a proportional coefficient greater than zero, and \( \tau \) is a regularization parameter, which affects the geometric complexity of the final optimized structure in a certain extent. By reasonably determining the \( \tau \) value, an ideal objective function can be obtained, and \( \nabla^2 \phi \) is a diffusion term, it ensure the smoothness of the level set function.

3. Construction of periodic structure optimization model

The marine deck crane boom belongs to the narrow and long structure type, good optimization results can not obtain through using optimization method directly. The periodic optimization method can make the optimization more convenient and effective, and the optimization result is also convenient for
practical engineering applications. The paper uses the method of level set topology optimization of reaction diffusion equations to optimize the periodic structure, the optimization process has high efficiency, and the precision of the optimization result is high.

In order to obtain an optimal topology with a periodic structure, the whole structure is divided into an equal number of sub-domains, \( n_1 \) is the number of sub-domains in the X direction, \( n_2 \) is the number of sub-domains in the Y direction, and \( x_{n_1,n_2,j} \) represents the density value of the \( j \) unit of the \((n_1, n_2)\) subfield. For the periodic structure, each sub-domain has the same sub-structure topological configuration as any sub-domain before and after a certain direction, that is the identical unit individual.

![Figure 2. Schematic diagram of the structure dividing sub-domain unit.](image)

At this time, the mathematical model of the topology optimization of the entire periodic structure is:

\[
\inf_{\phi} J = \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j} F_i \mu_i d\Gamma
\]

\[
s.t.G = \int_{\Omega} d\Omega - \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j} V_{i,j} \leq 0
\]

\[
div\left(E_{ijkl} u_{ijkl}\right) = 0 \text{ on } \Omega
\]

\[
u_i = u_{i,j} \text{ in } \Gamma_u
\]

\[
F_i = F_{i,j} \text{ in } \Gamma_f
\]

\[
x_{i,j} = x_{2,j} = x_{3,j} = \cdots = x_{m,j}
\]

Where \( x_{i,j} \) represents the density value of the \( i \) unit of the \( a \) subdomain, \( V_{i,j} \) represents the volume of the \( j \) unit of the \( i \) subfield, and \( f \) denotes that the unit exists in the design domain.

4. Optimized design of the boom

4.1. Number Determination of boom load

The boom of the marine deck crane is a box-type boom under double-bar operation, and the movable pulley block is used to realize the lifting and lowering of heavy objects. When working, the load on the boom has variable amplitude load, rotational inertia force, lifting load and wind. Loaded. The side force and restraint state of the boom are shown in Figure 3.
Through analysis and calculation, the force of the boom can be obtained as shown in Table 1.

| Working condition  | Lifting wire rope force (t) | Luff wire rope force (t) | Hinge shaft force (t) | Rotating inertial force (kN) | Wind load (t) |
|--------------------|-----------------------------|--------------------------|----------------------|-----------------------------|---------------|
| Working condition one (\(K = 82^\circ\)) | 122.8 \(T_{b1} = 41\) \(P_x = 35.37\) | \(T_{b2} = 21.8\) \(P_y = 201\) | Weight of the hanging object 2.36 | 0.83 |
| Working condition two (\(K = 20^\circ\)) | 122.8 \(T_{b1} = 5.87\) \(P_x = 108\) | \(T_{b2} = 3.1\) \(P_y = 55\) | Weight of the hanging object 15.94 | 0.29 |

4.2. Topology optimization of the boom

The three-dimensional solid model of the boom is shown in Figure 4.

In the topology optimization of the boom, combined with the periodic topology optimization theory, the topology optimization of the boom is carried out by using the level set topology optimization method, which not only makes the optimization more convenient and effective, but also makes the obtained results easy to process, the load on the boom and the constraint situation is shown in Figure 3.

When the marine deck crane is working, the elevation angle may change at any time, so it is impossible to study all the working conditions. For the deck crane of this project, the maximum and minimum range of the crane are selected for research, the elevation angle of the boom is 82° and 20°, working condition 3 is the working condition when working condition 1 and working condition 2 correspond to different weight coefficients. In the process of optimization, the above three working conditions are studied in turn, and getting the optimal boom structure by iteration on the basis of satisfying the original performance.

The topology is optimized by the level set method. The optimized result is shown in the figure below.
Figure 6. Topology optimization results of Boom web about working condition two.

Figure 7. Topology optimization results of Boom web about working condition three.

Re-established the model according to the processed result, the new actual model of the boom is shown in Figure 8.

Figure 8. Three-dimensional model diagram of the topology optimization of the boom side panel.

After optimization, the weight of the boom was reduced from the original 7t to 5.4t, and the weight of the boom was reduced by 1.6t, achieving the goal of lightweighting the boom.

4.3. Simulation Analysis after the Topology Optimization of the Boom

Remodelling the key components of the optimized boom processed in Section 4.2. The three-dimensional model of the boom topology optimized after assembly, and it is imported into ABAQUS for finite element analysis.

By applying the calculated load and constraints, performing the finite element analysis on the boom position at 82° and 20° respectively, and the obtained stress and deformation results show in the following figure.

Figure 9. Stress distribution of the 82-angle boom

Figure 10. Deformation distribution of the 82-angle boom

Through finite element analysis, it can be obtained that the maximum deformation of the boom is about 100mm, and the stress concentration occurs in the hinge shaft. The maximum stress is 365MPa. According to the material properties selected, the position is within the safe range.

Figure 11. Stress distribution of the 20-angle boom

Figure 12. Deformation distribution of the 20-angle boom
It can be obtained from the above figure that the maximum deformation of the boom is about 63mm, and the maximum stress of 277MPa appears in the hinged shaft. The boom can meet the actual working conditions. Through the above analysis of the topology optimized boom, it can be seen that, the boom still meets the requirements of the actual working conditions on the basis of the weight reduction of the boom.

5. Conclusion
In this paper, the horizontal set topology optimization method of reaction diffusion equation is used to optimize the topology of the ship deck crane boom. Establishing the mathematical model with the maximize structural stiffness as target function and the structural volume as the constraint optimization problem. The equation updates the level set function, which realizes the topology optimization of the shape and size of the boom. At the same time, introducing the periodic theory into the topology optimization, which makes the optimization model more convenient, the obtained boom structure is clear and the engineering application is strong, the processing is easy. Finally, the optimized results are verified to meet the performance index of the boom through the finite element analysis of the optimized boom.

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