Topology Optimization of Bit Feed Device Based on SIMP Method

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Abstract. This paper explores the use of the Solid Isotropic Material with Penalization (SIMP) method for topology optimization to enhance the performance of drill feed devices. The study focuses on improving the structural stability, reducing weight, and increasing material efficiency of the feed device, all of which are critical for drilling efficiency and processing quality in modern mechanical design. Software such as Abaqus was used for model creation, stress analysis, and optimization. After optimizing the feed device, its weight was reduced by 35.6% without compromising strength, demonstrating the effectiveness of topology optimization in promoting sustainability in mechanical design.

Keywords: topology optimization; SIMP method; drill feed device; structural stability; weight reduction

1 Introduction

In modern mechanical design, the performance of drill feed devices directly affects drilling efficiency and processing quality. Topology optimization, as an innovative design approach, can significantly reduce structural weight and material consumption while meeting mechanical performance requirements. This paper explores how to enhance the overall performance of drill feed devices through topology optimization based on the Solid Isotropic Material with Penalization (SIMP) method. The research aims to provide an effective design strategy to promote the intelligence and efficiency of drilling equipment, contributing to the sustainable development of the related industries.

The feed body, as part of the feed device, provides a platform for the installation of components such as the power head, hydraulic cylinder, and gripper. Its structural stability directly impacts drilling efficiency and hole quality. To meet different practical requirements, structural optimization of the feed body has been performed.

Zhang Youzhen et al. [1] utilized ANSYS software to conduct modal and harmonic response analysis of the feed body of the ZDY4000L drilling rig, successfully optimizing the structure of this series of drilling rigs, providing a basis for subsequent design optimization. Wang Hejian [2] built a model of the feed body using Solid Edge software and analyzed the stress and strain using ANSYS. Based on the weak areas identified in the stress contour plots, structural optimization was performed, ultimately ensuring the strength and stiffness of the feed body. Zhang Rui [3] performed modal analysis using Abaqus and identified weak parts of the structure from the mode shape diagrams, laying a foundation for the optimized design of the feed body. Wang Tianlong [4] optimized the feed body according to the actual working environment, increasing the travel of the drilling rig, making the structure more compact, and adapting it to confined workspaces. Hao Yongjin [5] optimized the feed cylinder, increasing its travel from 0.95 m to 1.15 m while reducing the overall length of the machine from 2.73 m to 2.47 m. Lü Meng [6] implemented a combined design for the feed cylinder, effectively shortening the length of the feed body. In 1904, Michell [7] first proposed the theory of topology optimization, but it was only able to solve relatively simple problems and was not effectively applied to engineering. Hegerniner [8] extended Michell's theory to better address the optimization of nonlinear problems. Achtziger et al. [9] proposed the application of topology optimization to the solution of discrete systems.

Based on the above research achievements, topology optimization has gradually become an important method for improving the performance of mechanical structures. Through reasonable topology optimization design, the weight of the drill feed device can be significantly reduced while ensuring structural strength and stability under different working conditions. Therefore, integrating topology optimization with the practical requirements of complex mechanical systems to further enhance the overall performance of the device has become a key research direction today.

2 Topology Optimization Process for the Drill Feed Mechanism

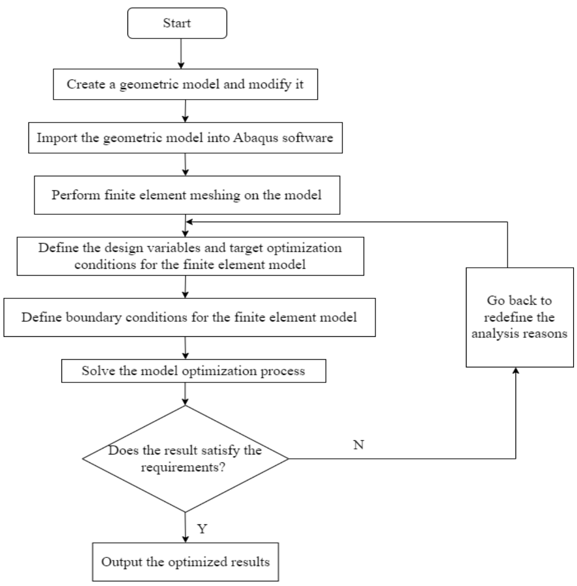

Fig. 1. Flowchart of Topology Optimization in Abaqus.

As shown in Figure 1, the topology optimization process is conducted using Abaqus software. This process includes creating the model, defining the design domain, setting topology optimization parameters, and performing the optimization calculations. The goal is to gradually enhance the structural performance of the drill feed mechanism, achieving both weight reduction and increased strength.

3 Model Creation

3.1 Preprocessing

Figure 2 shows the finite element model of the feed mechanism, which is defined using Q345 material properties. During the model creation process, the 3D model was imported into Abaqus in. step format and underwent appropriate meshing operations. The figure displays the filled model of the feed mechanism, which maintains consistency with the real mechanical structure. Details such as the transmission device and main components of the feed mechanism are clearly visible, providing a reliable foundation for subsequent topology optimization.

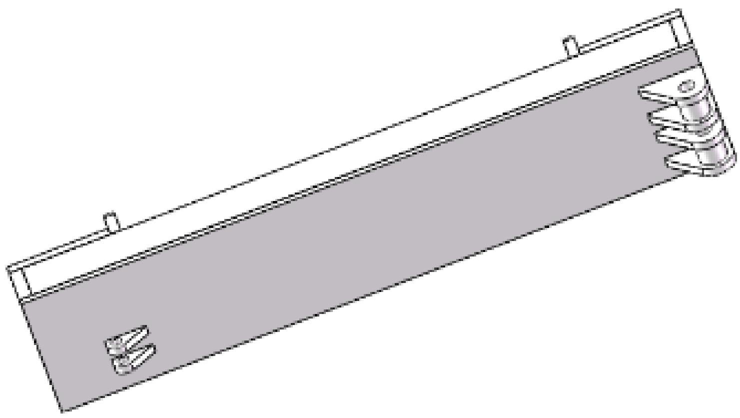

Fig. 2. Filled Model of Feed Mechanism Body.

3.2 Determination of Design Region

Based on the structure of the feed mechanism body and actual working conditions, the front and rear plates of the feed mechanism body serve to secure the double-rod double-acting hydraulic cylinder, while the clamping block and the fixed blocks connected to the base plate provide fixed constraints for the body. Apart from these, the other plates are designated as the design region. As shown in Figure 3, the blue areas of the feed mechanism body represent the design region, while the red areas represent the non-design region.

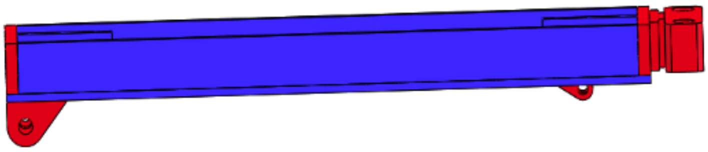

Fig. 3. Design and Non-Design Regions.

3.3 Optimization Mathematical Model

Since the feed mechanism body is entirely welded from Q345 steel, with a consistent material density, the mass-constrained strain energy minimization problem can be considered equivalent to a volume-constrained strain energy minimization problem. Based on the three key elements of optimization and the predefined volume ratio $\lambda = 0.5$, the mathematical model for topology optimization can be expressed as:

$$\begin{cases} find\,\rho = \left(\rho_1,\ldots,\rho_n\right) \\ \min C\left(\rho\right) = \mathbf{U}^T\mathbf{KU} = \sum_{s=1}^{n}\left(\rho_s\right)^p \mathbf{u}_s^T\mathbf{k}_s\mathbf{u}_s \\ subjectto\,\mathbf{K}\left(\rho\right)\mathbf{U} = \mathbf{F} \\ V\left(\rho\right) \le 0.5 \cdot V_0 \\ 0 < \rho_{\min} \le \rho_s \le 1 \end{cases} \tag{1}$$

4 Optimization Results Analysis

4.1 Topology Optimization Results of the Machine Body

The topology optimization of the feed machine body was initially set to terminate after 50 iterations. However, no optimal result was found when the optimization stopped. After adjusting the iteration count to 100, the optimization process ceased at 62 iterations, during which the strain energy decreased and stabilized, indicating that the optimal solution had been found. The optimization results are shown in Figures 4, 5, and 6.

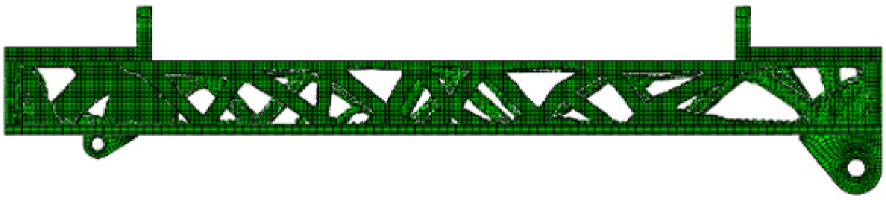

Fig. 4. Left Side Plate of the Feed Machine Body.

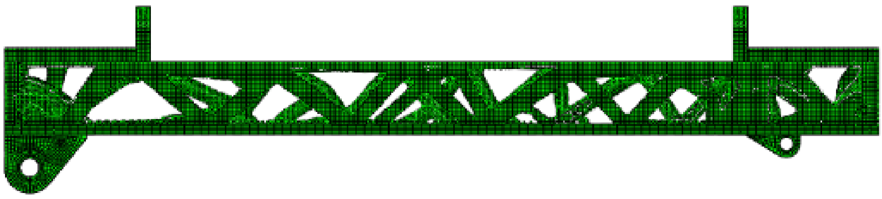

Fig. 5. Right Side Plate of the Feed Machine Body.

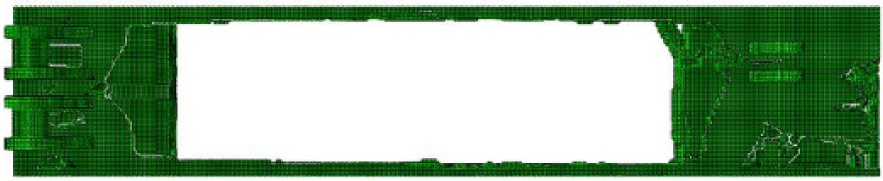

Fig. 6. Bottom Side Plate of the Feed Machine Body.

From the topology optimization results, it can be observed that the side plates of the machine body often exhibit triangular hole structures. Considering the stability of triangular structures and the issue of stress concentration, as well as the common use of rectangular structures in the optimization of lifting machinery and vehicles, two adjacent triangular structures in the topology result were approximated and merged into a single rectangular shape. Additionally, semicircular holes were added on both sides of the rectangle, connected to its edges, replacing the chamfered corners of the rectangle. A rounded rectangular structure was adopted for the bottom plate to avoid stress concentration. The 3D model is shown in Figure 7.

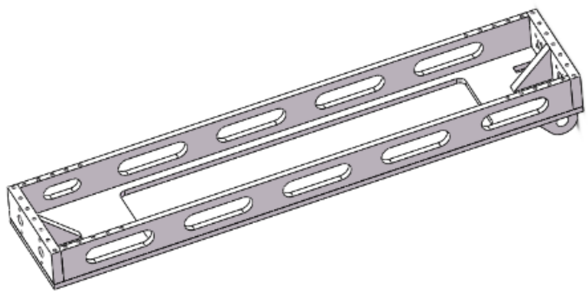

Fig. 7. Reconstructed Model After Topology Optimization.

4.2 Static Analysis of the Feed Machine Body

A static analysis was performed with the power head positioned at the front end of the feed machine body, which was tilted upwards by 20°. The constraint and boundary conditions remained consistent with the previous setup. Figure 8 shows the stress contour plot of the feed machine body, with a maximum stress of 129.7 MPa.

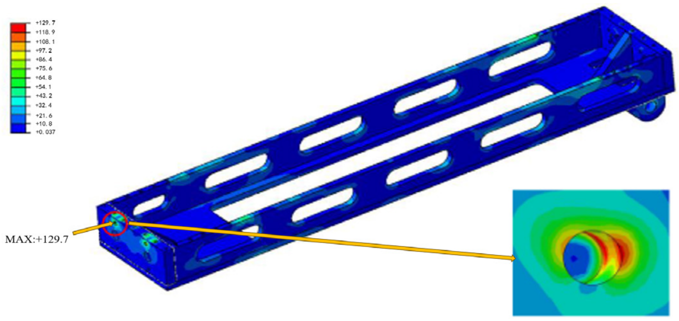

Fig. 8. Stress Contour Plot of the Feed Machine Body After Topology Optimization.

5 Conclusion

In this study, a volume-constrained mathematical model was established by integrating relevant theoretical knowledge of topology optimization. Abaqus software was used to perform topology optimization on the feed machine body after multi-objective optimization, and the model was reconstructed using SolidWorks. A static analysis of the reconstructed 3D model was then conducted using Abaqus, with results showing that the allowable stress of the material was satisfied. Through topology optimization, the feed machine body achieved a weight reduction of 55.65 kg, reducing the weight by 35.6%. Compared to the original model, the weight reduction was 70.88 kg, representing a decrease of 41.4%.

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