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Improvement of Machine Tool Ram Based on Topology Optimization

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Abstract

Taking the ram of a certain type of machine tool as the research object, the problem that the low-order natural frequency of the ram is close to the rotation frequency of the spindle is prone to resonance. Firstly, the modal analysis of the original ram is carried out, and the data of its natural frequency and mode shape are obtained; the topological optimization of the ram is carried out according to the analysis results; finally, the ram is improved and analyzed according to the topological optimization results. The results show that compared with the original ram, the low-order natural frequency of the improved ram is higher than the rotation frequency of the spindle, which avoids the resonance phenomenon during operation.

Keywords

Machine ram, Topology Optimization, Modal analysis, Optimal design.

1. Introduction

The ram is an important part of the machine tool. The electric spindle and other parts are directly installed on the ram. The dynamic performance of the ram is closely related to the accuracy of the machine tool. This paper analyzes the natural frequency of the machine tool ram and the associated information with external excitation, and optimizes the structure of the machine tool ram through the topology optimization method, and controls and adjusts the natural frequency of the structure to avoid being equal to or similar to other excitation force frequencies. , Thereby effectively reducing the dynamic response of the structure, avoiding resonance, and improving its dynamic performance. Structural topology optimization technology provides an effective solution for the structural design of the ram.

2. Analysis of the dynamic characteristics of the ram

2.1. Ram structure model

The ram studied in this paper is equipped with electric spindle, track, sheet metal decoration and other components. The external excitation source is the rotation of the electro-spindle. The maximum speed of the electro-spindle is 400r/s, that is, the rotation frequency of the electro-spindle is 400Hz. The ram material is HT250, and the material properties [1] are shown in Table 1.

Table 1. HT250 material properties

Material	Density /(kg • m^{-3})	Elastic Modulus /GPa	Poisson's ratio
HT250	7250	138	0.27

In order to improve the quality of finite element analysis, it is simplified to remove features such as positioning holes, threaded holes, fillets, and chamfers in the model. Use 3D modeling software to remove these features in the model that have little effect on the accuracy of the analysis. The simplified model is shown in Figure 1.

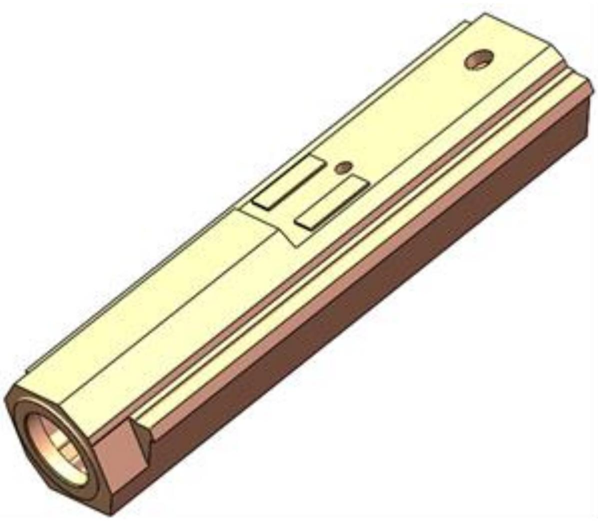

Figure 1. Simplified ram model

2.2. Ram modal analysis

The dynamic characteristics of the ram reflect its structural stability when subjected to external excitation, which has a significant impact on the accuracy of the machine tool. In the analysis of the dynamic characteristics of the structure, the weight of each mode is proportional to the inverse of the natural frequency, that is, the lower the frequency, the greater the weight, that is to say, the lower mode basically determines the dynamic performance of the ram [2]. Therefore, this paper mainly analyzes and solves the first three modes that have a greater impact on the dynamic characteristics of the ram. According to the established finite element model and loading constraints, the lower limit of the frequency is set to 0, the upper limit is unlimited, and the order is 6th. Then the dynamic characteristics of the ram are analyzed, and the rigid modal analysis is performed on the ram, and its natural frequency and mode shape are obtained. The sixth-order mode of the object is a rigid body mode, and the first three-order natural frequencies and vibration modes of the ram are shown in Figure 2.

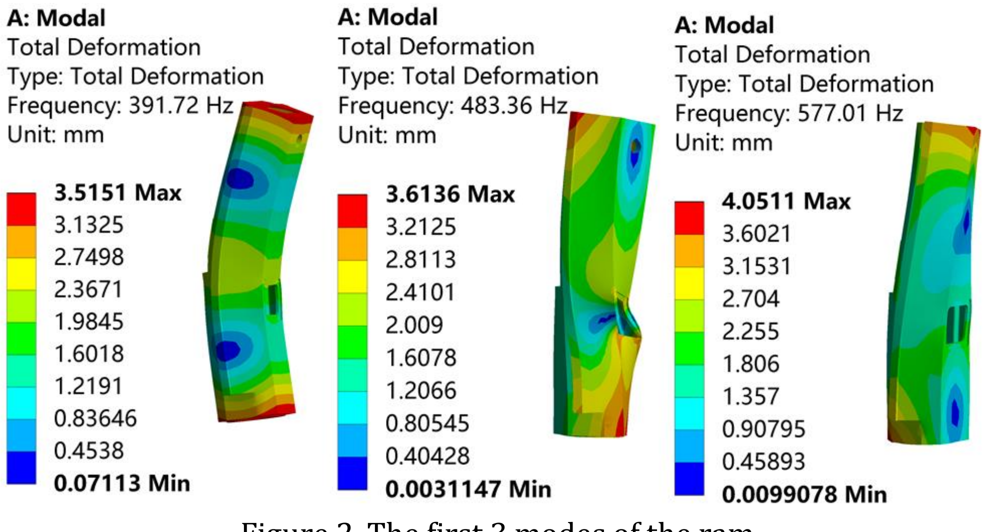

Figure 2. The first 3 modes of the ram

The modal analysis shows that the first-order natural frequency of the ram is 391.72 Hz, which is close to the highest rotational frequency of the electro-spindle. After the electro-spindle starts, the frequency changes from low to high, and resonance occurs near the first-order natural frequency of the ram. , Will have a certain impact on the high-speed machining performance and accuracy of the machine tool. From the vibration shape diagram, it can be seen that the upper and lower parts of the ram have the largest deformation during the vibration process, and the lower part is where the electric spindle is installed. Therefore, it is necessary to adjust and control the natural frequency of the ram by changing the structure, so that the first-order natural frequency that has the greatest impact on the ram is higher than the maximum rotation frequency of the electric spindle, improving the dynamic performance of the ram and improving the machining accuracy of the machine tool.

3. Topology optimization of ram

3.1. Structural design method of topology optimization

Structural optimization design is to replace traditional design with systematic and goal-oriented processes and methods. Its purpose is to find economical and applicable structural forms, and to achieve the best performance of the structure with the least amount of materials and cost. Topology optimization is a research method that uses mathematical methods to find the theoretical optimal distribution path of materials in the design space [3]. Considering the difficulty of casting and manufacturing cost of the optimized structure of the ram, the optimization of the ram structure cannot be completely optimized. Imitate the irregular shape of the topology optimization result. In this paper, the variable density method based on the SIMP (Solid Isotropic Material with Penalization) model is used to optimize the topology of the ram with the maximization of natural frequency as the optimization objective. The ram material distribution obtained by topology optimization can provide guidance for the improvement of the ram structure. The introduction of the material penalty model in the topology optimization process of the variable density method is to avoid the checkerboard format in the topology optimization results [4]. The SIMP interpolation model can force the relative density of the unit to move closer to 0 and 1 [5].

3.2. Topology optimization with natural frequency as the objective

In this topology optimization, the optimization goal is to maximize the natural frequency of the ram, and the mass percentage is retained as a constraint to optimize the ram. In the optimization software, migrate the solution data of the modal analysis to the new topology optimization module. Set the minimum normalized density to 0.001 and the penalty factor to 3. This can avoid the linear distribution of dense regions and void regions, or Avoid the phenomenon of poor iterative convergence due to excessive penalty factor [6]. Set the maximum number of iteration steps to 500 and the convergence accuracy to 0.1%. The iterative algorithm in the optimization selects the Optimality Criteria method. The topology optimization process continues until the convergence accuracy is met or the maximum number of iteration steps is reached. Because most of the boss structure of the ram except for the ribs requires other parts to be installed, these parts are set as non-optimized areas, and the rest are set as optimized areas. The optimized area setting is shown in Figure 3, and the red area is the non-optimized area. The blue area is the optimized design area. Set the maximum natural frequency as the optimization goal. After repeated experiments and 13 iterations of calculation, when the mass remaining rate is 50%, a topological optimization structure with a clear force transmission path can be obtained. The result of topology optimization with the goal of maximizing the stiffness of the ram is shown in Figure 4.

From the results of topology optimization analysis, it can be seen that in Figure 4, the red area is the removable part, and the gray area is the reserved part. On the ram model, the natural frequency and dynamic characteristics of the ram can be improved by removing the model entities in the red area. However, due to the irregular shape of the removed area in the topology optimization result, it is difficult to process in actual processing and production. Therefore, it is necessary to use chamfering, punching and other methods to remove the material in the material removal area. According to the results of topology optimization analysis, the ram

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structural materials are removed, and the comparison model of the ram before and after the structural improvement is shown in Figure 5.

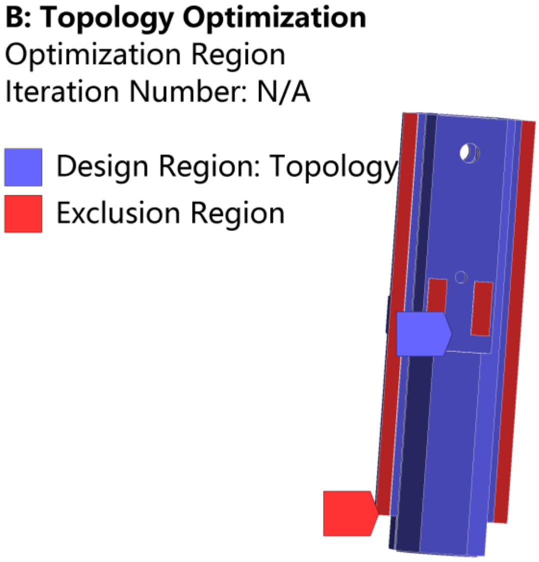

Figure 3. Optimize regional settings

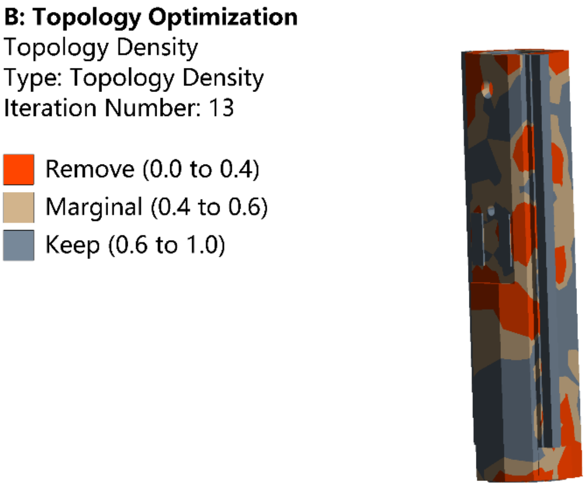

Figure 4. Ram topology optimization results

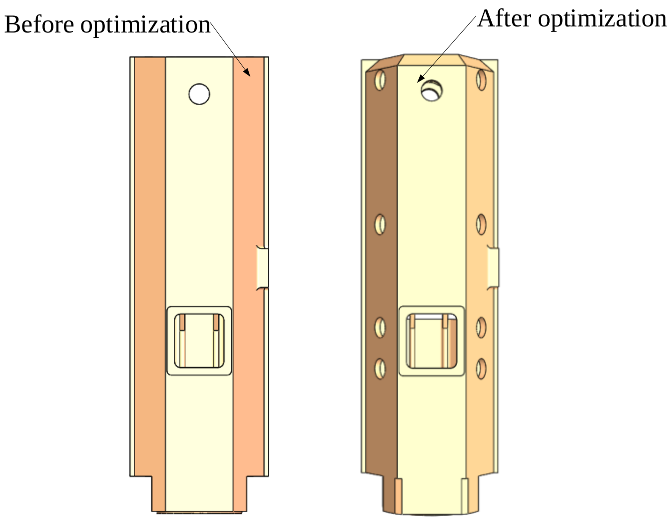

Figure 5. Comparison of ram models before and after optimization

In order to verify the rationality of the optimization and improvement, modal analysis was performed on the improved model, the finite element analysis parameters and other settings were unchanged, the improved ram was analyzed, and the dynamic characteristics of the optimized design ram were analyzed. Figure 6 shows the first 3 vibration modes of the optimized ram.

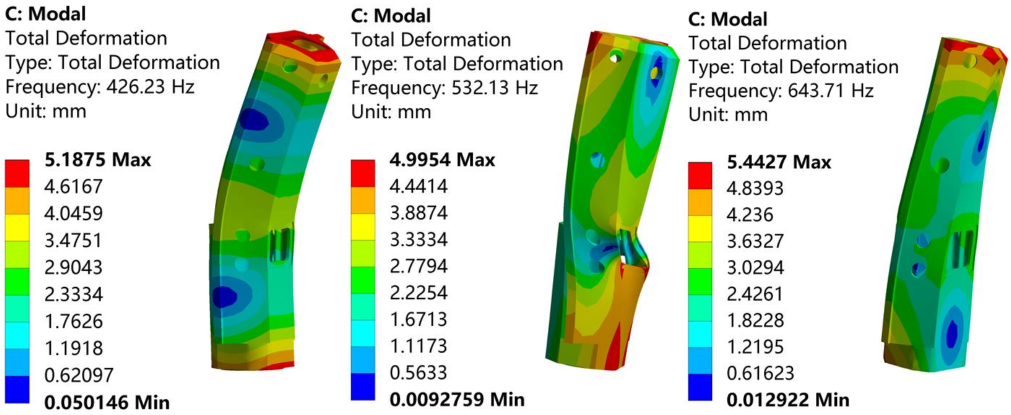

Figure 6. The first 3 modes of the ram after optimization

After the improvement and optimization, the first three natural frequencies of the ram are increased, and the weight of the ram is also reduced to a certain extent, which saves the cost of production raw materials and improves the dynamic performance of the ram. The performance parameters of the machine ram before and after optimization are shown in Table 2.

Table 2. Comparison of ram performance parameters before and after optimization

Performance parameter	Before improvement	After improvement	Rate of change
First-order natural frequency	391.72 Hz	426.23 Hz	+8.9%
Second-order natural frequency	483.36 Hz	532.13 Hz	+10.1%
Third-order natural frequency	577.01 Hz	643.71 Hz	+11.4%
Weight	145.16 Kg	140.48 Kg	-3.4%

4. Conclusion

Taking a certain type of machine tool ram as the research object, first analyze the dynamic characteristics of the original ram, and then use the SIMP-based variable density method to optimize the topology of the ram with the optimization objective of natural frequency maximization, and consider the castability of the ram structure Performance, comprehensive dynamic analysis and topology optimization results to improve the physical structure of the ram. After the improvement, the mass of the ram is reduced. The first-order natural frequency is increased from 391.72 Hz to 426.23 Hz, avoiding the maximum rotation frequency of 400 Hz of the electric spindle, improving the dynamic performance of the ram, and indirectly improving the overall processing stability of the machine tool. To achieve the purpose of optimizing the ram of the machine tool.

Acknowledgments

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