

Topology Optimization Design of the Headstock of Large Rotation Mechanism

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Abstract. Headstock is one of the most important parts of large rotation mechanism. Original design method makes the product excessively overweight. The topology optimization of headstock is taken by HyperWorks in this paper. It shows that the weight of headstock is lighter than before in the optimization result. It provides a new research way for the optimization design of large rotation mechanism by this method.

Introduction

Headstock is an important component of large rotating mechanism which has the function such as driving rotating equipment, rotary drilling, milling rotation, drilling holes and other works. Stiffness and strength of headstock can impact significantly on working properties of the entire rotating equipment and machining precision of rotating equipment.

The headstock structural design is very important for Chinese headstock manufacturers. The Chinese manufacturers design headstock structure mainly based on experiential calculation method and conventional structural design. But the structures designed by these methods are relatively bulky and its working properties cannot reach specified manufacturing requirements [1].

In the conventional design, China designers finish their work just using conventional lathe structure calculation method and existing rotating equipment that have been applicable widely. The conventional lathe structure calculation method has its theoretical bases, but the result is not accurate enough due to the complex lathe structure. According to previous experience in engineering [2], the designs are conservative to ensure the sufficient rigidity and strength of product. So the products are always overweight and difficult for installation and commissioning. This makes the static and dynamic characteristics of the product structure be assessed inaccurately and the material waste is unavoidable.

In the other countries the advanced computer technology is used to check the technical parameters of headstock structure in the design of rotation mechanism structures. This method can make the design more reliable and reasonable, and reduce the weight of headstock while ensuring the rigidity and strength of headstock. It's important to reduce cost and enhance market competitiveness of company [3].

Topology Optimization Method of Headstock

Mathematical Foundation of Topology Optimization. There are three widely used topology optimization: homogenization method, variable thickness method and variable density method. The variable density method is used here, in which the material density of each element is directly set as a design variable. The element density is related with material parameters, such as elastic modulus E, which changes continuously between 0 and 1. When the optimized element density becomes 1 or close to 1, it's proved that the material is essential in transfer process of force and cannot be removed. When

element density is 0 (or close to 0), it's proved that there is no force and the material can be removed. Through this optimization method the light-weight design is achieved and the material can be efficiently utilized [4].

Optimization design has three essential factors: design variables, objective functions and constraint condition. Design variables are a set of parameters changing in the calculation iterations. The objective functions are the optimal results that meet the solving conditions. Constraint condition is limit of variables for finding the optimal result.

For example, there is a function needed to be minimized or optimized:

$$f(X) = f(x_1, x_2, \dots, x_n) \quad (1)$$

The function is subjected to the following conditions:

$$\begin{cases} g_j(X) \leq 0 & j = 1, 2, \dots, m \\ h_k(X) = 0 & k = 1, 2, \dots, m_k \\ x_i^L \leq x_i \leq x_i^U & i = 1, 2, \dots, n \end{cases} \quad (2)$$

In the formula, $X = x_1, x_2, \dots, x_n$ are design variables, $f(X)$ is objective function, $g(X)$ are constraint inequalities, $h(X)$ are constraint equations. The footnote L means lower limit and the footnote U means upper limit.

In topology optimization, the design variable is the material density. In size optimization, the design variable is the element characteristic. In morphology optimization and shape optimization (including free-shape optimization), the design variables are limit variables that make the product shape to be stirred.

Process of Topology Optimization Design.

1) Design variables of headstock body

The density is set as topology optimization design variable of headstock body.

2) Constraint conditions of topology optimization

The aim of this paper is losing weigh by appropriately reducing the first natural frequency. So the constraint condition can be considered as that the first natural frequency is larger than $\sqrt{2}$ times of the working frequency of headstock.

3) Objective functions of headstock optimization

The weight of headstock body is needed to be reduced, so the minimized volume fraction is set as objective function.

$$f(x) = \text{volfrac} = \frac{\text{vol}_c}{\text{vol}_i} \rightarrow \min \quad (3)$$

In the formula, *volfrac* is the volume fraction of the whole headstock, range from 0 to 1;

Vol_c is the volume of optimized headstock, mm^3 ;

Vol_i is the initial volume of the whole design domain, mm^3 .

Example of Topology Optimization Analysis of Headstock

Modal Analysis of Headstock. Material of the headstock body is isotropic gray iron HT300 in this example and the parameters is shown as following:

Elasticity modulus: $E = 1.5e5 \text{ (MPa /mm}^2\text{)}$

Poisson ratio: $\nu = 0.26$

Density: $\rho = 7.4e-9 \text{ (t/mm}^3\text{)}$

Modal analysis is the basis of all the structural vibration analysis, each natural frequency of structure corresponds to a certain natural modes of vibration, natural modes of vibration reflect the relation of the substance vibrate and shock excitation. In order to keep headstock away from resonance, the frequency range of corresponding excitation force should be avoided in the design. This paper carry out constraint modal analysis of headstock and the results are shown in Table 1.

Table 1 Natural frequency, amplitude and description of vibration modes of headstock structure

Order	Natural frequency (HZ)	Maximum amplitude (mm)	Description of vibration modes of headstock system
1	157.38	9.85	vibrate along x axle
2	224.17	16.82	vibrate along y axle
3	314.31	6.30	flexural vibration occurs along y axle.
4	340.70	10.59	vibrate along z axle
5	368.20	11.20	vibrate along z axle
6	394.87	9.21	complicated deforms

The first six natural frequency and corresponding vibration modes of headstock are shown as Fig. 1.

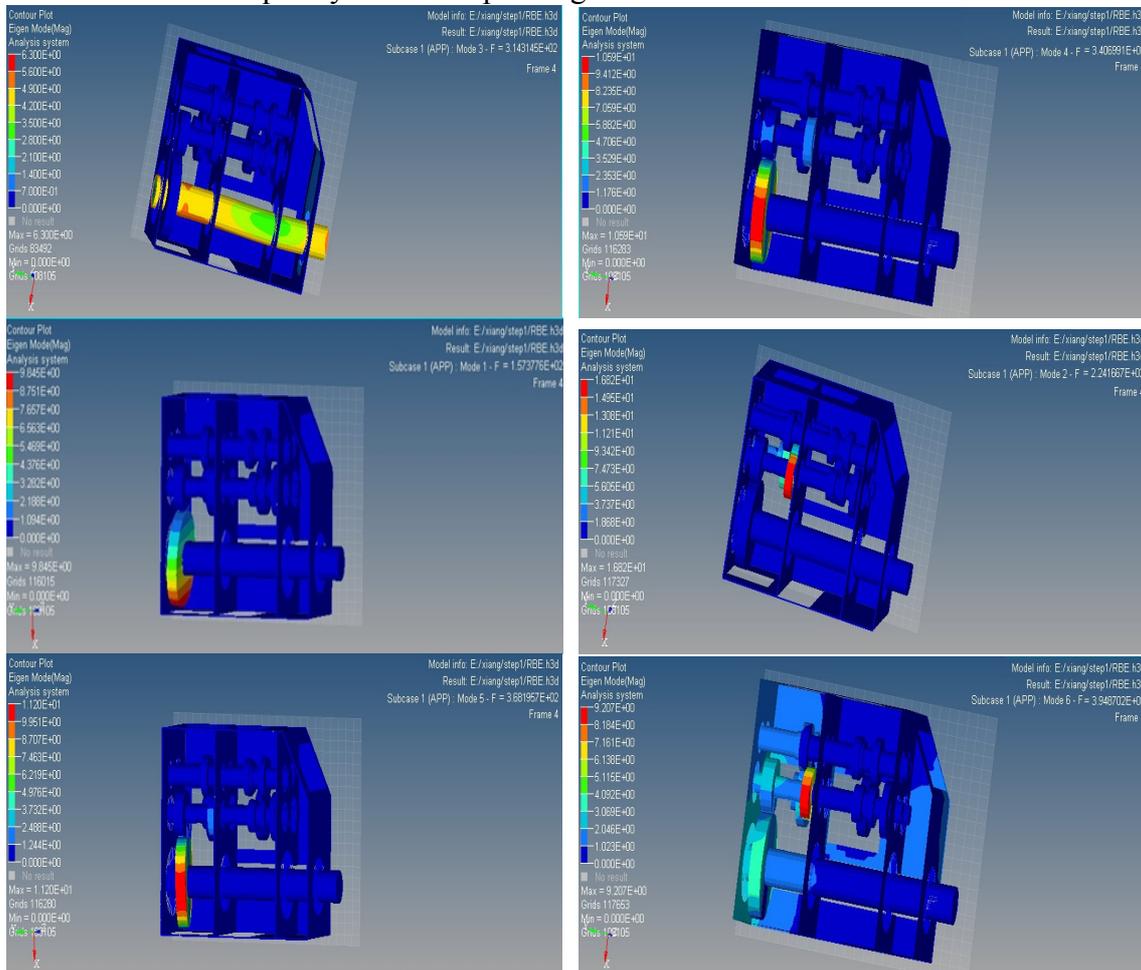


Fig. 1 The first six natural frequency and corresponding vibration modes of headstock

The external excitation frequency of principal axis is 84Hz. According to the dynamic characteristics of the lathe, the first natural frequency must be more than 120Hz ($\sqrt{2}$ times of external excitation frequency), and the first natural frequency of headstock is 157.38Hz out of the excitation frequency range. So the dynamic characteristics of headstock meet the design requirements.

Topology Optimization Design of Headstock. In this paper, the design domain of the headstock is divided into two parts. The first part is the rest of no design initial domain that is established based on boundary constraint condition; the second part (detailed design domain) is established based on optimization results. Wherein the headstock is connected with beam through the lateral slide and constrains the joint between the body and slide.

In HyperWorks software the headstock body is optimized and the topology optimization results of headstock body are obtained and shown in Fig. 2.

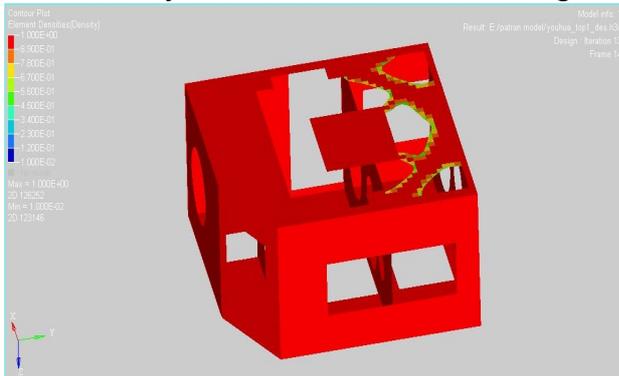


Fig. 2 The result of global topology optimization

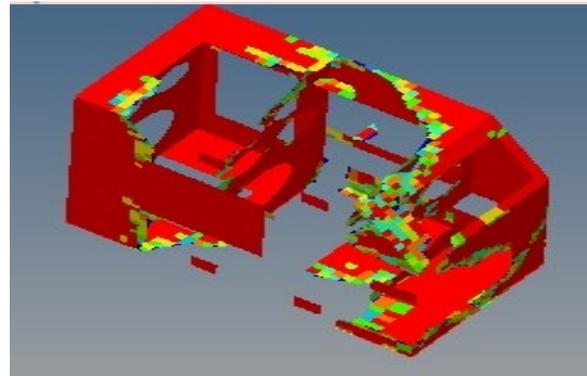


Fig. 3 The secondary topology optimization model of the body

From the results the material of the top and side of the headstock body can be cut down. Based on engineering experience and actual operating conditions, only the side of the joint between headstock and slide is suited to be lost weight. After that the secondary local design domain is established, and further topology optimization results are shown in Fig. 3.

The topology optimization results show that only the material around the joint center between headstock and slide can be appropriately reduced. The analysis above provides the optimization methods and ideas for the headstock of rotation mechanism.

Summary

The topology optimization of the headstock is carried out after the headstock dynamic analysis. The element density is set as design variables, the frequency larger than external excitation frequency is set as constraint conditions, and the minimum volume fraction is set as objective function in the method. The material optimum distribution paths and the topology optimization results are obtained by OptiStruct software which meet the engineering constraints. The analysis provides optimization methods and ideas for the headstock of rotation mechanism. The material optimum distribution paths and material optimum thickness is calculated here by software, but there are many issues to be considered in the actual project, such as the casting technology, the installation requirements and so on. So it is needed to continue on studying.

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