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The Application of Arched Structure in the Bed Ribs of Machine Tools

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Abstract

The bed is a key component of a five-axis vertical machining center. Most of the important parts of the machine tool are directly installed on the bed, and its own static and dynamic performance will directly affect the machining accuracy of the entire machine tool. In order to improve the static and dynamic performance of a certain type of five-axis vertical machining center bed, it is optimized by combining the configuration laws of multiple biological structures and using the method of structural bionics. First, the finite element analysis of the prototype bed was carried out, and the rib structure of the arched bed was determined based on the comprehensive deformation cloud map combined with the configuration characteristics of the biological structure, and the bionic optimized bed was analyzed. The results show that: compared with the original bed, the maximum deformation of the optimized bed is reduced by 25.3%, the first 4 natural frequencies are improved, and the static and dynamic performances are significantly improved.

Keywords

Five axis vertical machining center, Structure bionics, Optimal design.

1. Introduction

The various biological structures with excellent performance and exquisite structure formed by the creatures in nature after hundreds of millions of years of evolution provide a lot of design inspiration and creative improvement methods for humans to solve engineering and technical problems. Studying the similarity between biological structure and mechanical structure, extracting beneficial structural features in organisms, and applying them to the optimal design of mechanical structures have become an important content of structural bionic research. The optimization of the layout of the ribs in the bed of the machine tool is one of the research contents.

2. Finite element analysis of the bed

2.1. Introduction of bed parameters

The five-axis vertical bed studied in this paper is a box structure with a grid rib layout. The inside of the bed is a double-layer grid ribbed grid. The bottom adopts eight-point support to ensure stability. It is equipped for iron filings and cutting. Funnel-shaped inclined surface and groove structure for liquid collection and separation. The bed structure model is shown in Figure 1.

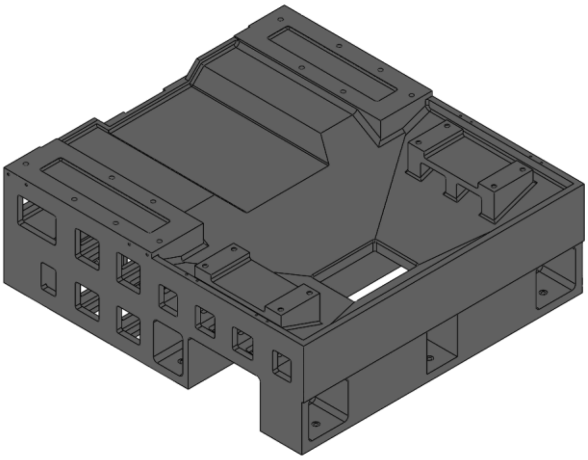

Figure 1. Bed structure model

The five-axis vertical bed is cast by HT250, refer to [1], and the material properties 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 meshing, simplify the removal of positioning holes, threaded holes, fillets, chamfers and other features in the model. Import the simplified model into the finite element analysis software for meshing. Due to the complex structure of the bed, the SOLID187 tetrahedron element, which is suitable for generating irregular grid models, is selected. At the same time, the subsequent topology optimization requires dense and uniform grids. The transition type is set to large scale, and the free meshing method is selected. The number of nodes in the finite element model is 925442 and the number of elements is 525646.

2.2. Analysis of the static characteristics of the bed

In the case of end milling, the vertical machining center has relatively large force components in all directions and complex loads. Selecting the end milling conditions to perform static analysis on the bed can more comprehensively reflect the performance of the bed [2]. The tool is a face milling cutter, the material is tool steel, and the workpiece material is carbon steel. The selected working condition parameters are milling width 30 mm, feed per tooth 0.25 mm, milling depth 2 mm, milling cutter teeth 6, cutter diameter 63 mm, the milling cutter spindle speed is 150 r/min. Substituting the data into the empirical formula, the load of milling on the bed can be calculated. The milling experience formula [3] is:

$$F_c = 9.81 \times 789.3 \times a_e^{1.1} f_z^{0.75} a_p z d^{-1.3} n^{-0.2}$$

$$F_x = \sqrt{F_c^2 - F_z^2 - F_y^2}$$

$$F_y = 0.3F_c$$

$$F_z = 0.5F_c$$

In addition, the load borne by the bed includes the weight of the bed parts, the weight of the tool magazine and the tool, the weight of the worktable and the workpiece, etc. The specific load types and sizes are shown in Table 2.

Table 2. The type of force the bed bears

Load type	Size /N
Weight of bed parts	23980
Workbench and workpiece weight	15000

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Tool magazine and tool weight	5000
Weight of electric spindle and its components	2000
Column component weight	16500
Beam assembly weight	11800
X feed force	1895
Y feed force	690
Z feed force	1164

Use quality analysis software to add mass attributes to each component of the five-axis vertical loading model, analyze and obtain the center of mass of each component. In the Z-direction view, the center of mass of each component is basically located at the geometric center of each load application surface, so it is directly applied on the contact surface Uniform load force. The above loads are correspondingly applied to the finite element model of the bed, and fixed constraints are added to the eight supporting surfaces at the bottom of the model. The comprehensive deformation cloud diagram of the bed body obtained after the solution is shown in Figure 2.

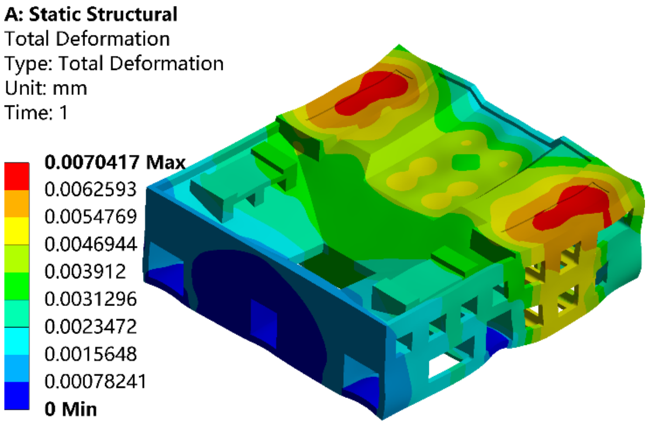

Figure 2. Comprehensive deformation cloud map of the bed

According to static analysis, under the above-mentioned end milling conditions, the maximum deformation of the bed occurs at the contact part of the bed and the column, and the maximum deformation is 7.04 μm.

2.3. Analysis of bed dynamic characteristics

The dynamic characteristics of the five-axis vertical bed 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 bed [4]. Therefore, this paper mainly analyzes and solves the first 4 modes that have a greater impact on the dynamic characteristics of the bed.

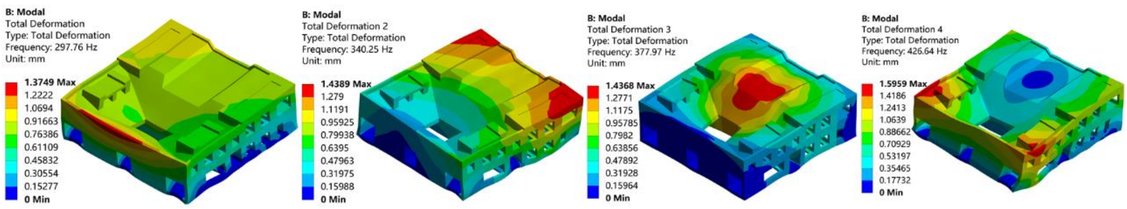

Figure 3. Vibration diagram of the 4th order in front of the bed

In the finite element software, the finite element model data of static analysis is directly transferred to the modal analysis module. The natural frequency of the bed is the dynamic characteristics of the bed itself, so the prestress is removed and the constraint method remains unchanged. The solution is The 4th order modal vibration shape in front of you is shown in Figure 3. Table 3 shows the description of the 4th order natural frequency and mode shape in front of the bed.

Table 3. Description of the 4th natural frequency and mode shape in front of the bed

No.	Natural frequency /Hz	Mode description
1	297.76	The upper part of the bed Y vibrates forward and backward
2	340.25	X swings left and right at the back of the bed
3	377.97	Breathing vibration up and down in the middle of the bed
4	426.64	The front part of the bed swings to the left and right in X

From the modal analysis, it can be seen that the modal vibration shape at the first-order natural frequency is that the upper part of the bed oscillates back and forth in the Y direction, and the modal vibration shape at the second-order natural frequency is that the back part of the bed oscillates left and right in the X direction. The deformation of the contact area between the two sides of the back of the bed under the first-order mode and the column is larger, indicating that the dynamic rigidity of this area is weak, which has a certain influence on the accuracy of the machine tool.

3. Structural bionic optimization

3.1. Biological structure feature extraction

According to static analysis, the deformation of the bed of the five-axis vertical machining center is mainly caused by the parts installed on the bed. The bed mainly bears the gravity of other parts, and the gravity is loaded on the bed in the vertical direction. In nature, biological structures such as egg shells, tortoise shells, and seashells have excellent resistance to pressure, able to withstand huge pressure without being broken, and there is no visible deformation. This is consistent with the main force of the machine bed [5]. As shown in Figure 4, egg shells, tortoise shells and shells all have a natural arched structure. This structural feature is the reason why they can withstand huge load pressure. The arched structure can decompose the pressure received into downward and outward forces, and at the same time has good seismic resistance, so the organism can ensure that its structure is not destroyed when subjected to huge external forces. Because the load on the bed is similar to that of the three organisms, according to the principle of structural bionic similarity, two arched bionic structural features are extracted and introduced into the optimization design of the bed ribs of the machine tool.

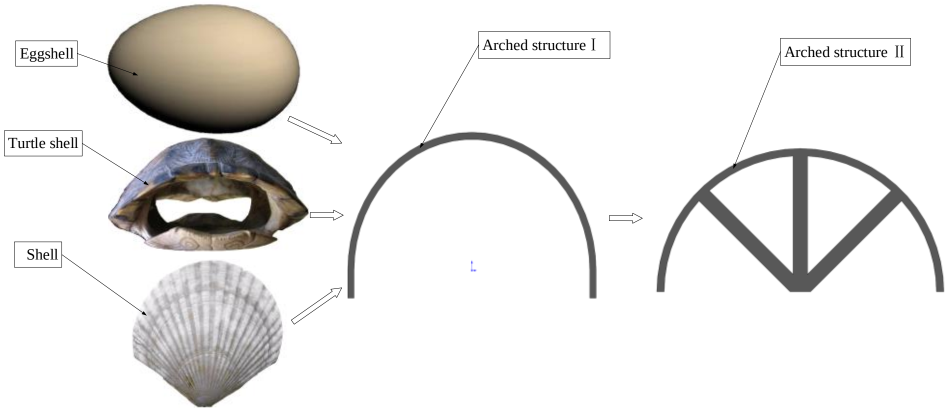

Figure 4. Bionic arch structure

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3.2. Optimization and improvement of bed structure

From the results of static analysis, it can be seen that the maximum deformation of the bed occurs at the back of the bed. It can be seen from the natural frequency mode of the bed that when the external excitation frequency is close to the second and third natural frequencies, the back of the bed will deform due to resonance. Therefore, the ribs at the back of the bed are designed to be bionic. The bed of bionic optimized design is shown in Figure 5.

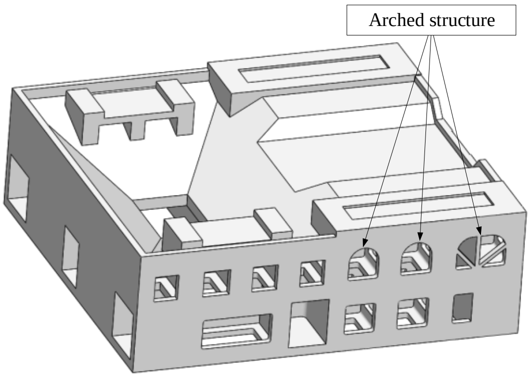

Figure 5. Bionic optimized design bed

Keep the conditions of load and fixing method unchanged, and analyze the static and dynamic characteristics of the bed after the optimized design of the ribs. The comprehensive deformation cloud diagram of the bed after the optimization design is shown in Figure 6, and the fourth-order vibration shape of the bed after the optimization is shown in Figure 7.

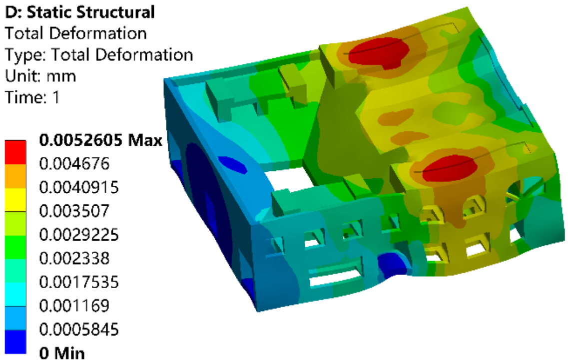

Figure 6. Comprehensive deformation cloud map of the bed after optimization

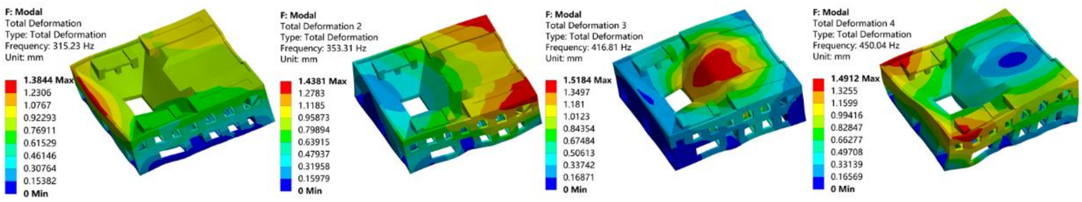

Figure 7. Optimized the front 4th order mode diagram of the bed

Table 4 shows the comparison of the performance parameters of the five-axis vertical machining center bed before and after optimization.

Table 4. Comparison of bed performance parameters before and after improvement

Performance parameter	Before improvement	After improvement	Rate of change
Maximum deformation	7.04 μm	5.26 μm	−25.3%
First-order natural frequency	297.76 Hz	315.23 Hz	+5.8%
Second-order natural frequency	340.25 Hz	353.31 Hz	+3.8%

Third-order natural frequency	377.97 Hz	416.81 Hz	+10.2%
Fourth-order natural frequency	426.64 Hz	450.04 Hz	+5.6%

4. Conclusion

This paper studies the configuration characteristics of the three organisms, extracts the arch structure features with excellent mechanical properties, analyzes the static and dynamic performance of the bed of the five-axis vertical machining center under specific conditions, and finds the largest deformation area behind the bed unit. The arch structure feature is introduced into the optimized design of the sheet metal of the bed, and the sheet metal in the most deformed area of the bed is changed to an arch structure. The results of comparative analysis found that the maximum deformation of the bed was reduced, and the first four natural frequencies were increased. The results show that the optimized design is successful, and the arch structure can be used to improve the static and dynamic performance of the bed.

Acknowledgments

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