Structural Design and Vibration Analysis of the建-in Damping Boring Bar

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Abstract. A series of related researches have been carried out in the process of deep hole machining with boring burrs, where the long diameter of the boring bar is relatively prone to chatter. Firstly, the structural design and detailed design of the damping boring bar was completed, a three-dimensional model was established, a dynamic equation was established for the damping system and using ANSYS for modal analysis and harmonic response analysis. Finally, the comparison between the solid boring bar and the analysis results of the damping boring bar is compared and the conclusion that the new type damping boring bar has good damping performance is obtained.

Introduction (Research Status)

In recent years, a great deal of research has been done at home and abroad on the research of shock absorption properties of boring bar. In foreign countries, for example, Mitsubishi improves dynamic stiffness by reducing the head weight of the boring bar [1]. Toshiba has increased the static stiffness of the boring bar by cutting away a portion of both sides of the tool bar in parallel, and then embedding the material with high stiffness and strength on both sides. The damping boring bar manufactured by Kenametal is mainly made of special materials to improve its static stiffness [2]. In China, most of the damping boring bar use the method of increasing the static stiffness. For example, a carbide-mounted boring bar is inserted in the core of the rod body [3], and most of the vibration reduction measures are in the process of improvement or in the process of the use of some techniques [4].

In this paper, in the process of designing a new type of damping boring bar, a built-in vibration-reducing structure was used to increase the dynamic stiffness of the boring bar. The damping boring bar was structurally designed and a mathematical model of the vibration-damping system was established. The modal analysis and harmonic response analysis were performed using ANSYS. Finally, the solid boring bar was compared with the analysis results of the damping boring bar, and the important parameters were corrected to obtain the optimal structural parameters.

Structure Design of Damping Boring Bar

According to the actual processing needs of the company, the designed bar length is 175mm and the diameter is 20mm. Since the damping effect of the vibration damping system is determined by the vibration amplitude of the point where the vibration damping device is located, so the vibration damping device should be installed at the far end of the bar and be placed inside the bar. The designed boring bar body structure is shown in Figure 1.
In the vibration-damping boring bar shown in the figure, the cooling pipe and the coordination block are filled with damping fluid, the same coordination block and the inner wall of the bar are also the same, and damping fluid selection methyl silicone oil. The elastic support is an important part of the vibration damping system. Rubber is selected as the elastic support material, and both ends of the coordination block are supported with rubber. The material selection of each component in the vibration damping device is a key to the vibration damping system. This paper selects the lead/hard alloy (tungsten-cobalt) as the material for the coordination block, cooling pipe, and adapter. Choose a denser material, if a better vibration reduction effect is needed, such as "heavy alloy [5]".

In order to reduce the quality of the tool bit and improve the overall damping effect of the boring bar, the GCr15 steel tool bit is used here. In the finite element analysis, the tool bit material properties are replaced with aluminum. Because the tool bit is regarded as a rigid body in the finite element analysis, the centroid of the tool bit determines the position of the tool bit. There is no direct relationship with the outer shape of the tool bit, so the outer shape of the tool bit can be arbitrarily selected. In actual engineering applications, the specific position of the tool bit can be determined by modifying the position of the centroid of the tool bit.

### Mathematical Model of Vibration-damping Boring Bar

The vibration resulting from the excitation of the initial perturbation is called free vibration, which is the vibration without external energy [6]. The designed and analyzed damping boring bar is a vibration-reducing system that uses a damping element and a rubber element to connect an additional mass to the vibration structure. According to the theory of dynamic, the dynamic equation of the system is established, and the theoretical value that can effectively reduce vibration is finally obtained.

### Simplified Model of Damping Boring Bar

The vibration-damping boring bar model can be reduced to a damped vibration system with two degrees of freedom [7], as shown in Figure 2.

![Simplified model damping boring bar](image)

**Figure 2. Simplified model damping boring bar.**

### Parameter Values of Damped Vibration System

According to the simplified model of vibration-damping boring bar, the motion equation of this vibration system can be deduced as:
\begin{align*}
    m_1x_1 + c(x_1 - x_2) + k_2(x_1 - x_2) + k_1x_1 &= P \sin \omega t \\
    m_2x_2 - c(x_2 - x_1) - k_2(x_1 - x_2) &= 0
\end{align*}

According to the motion equation of the vibration-damping boring bar, the relative amplitudes of \( m_1 \) (the concentrated mass of the damping boring bar at the research point) and \( m_2 \) (the mass of the additional mass of the damping boring bar) can be obtained as:

\begin{align*}
    \left(\frac{A_1}{\delta_n}\right)^2 &= \frac{\alpha^4 + (2\xi\alpha\lambda)^2}{(1-\lambda^2)(\alpha^2 - \lambda^2) - \mu\lambda^2\alpha^2} + (2\xi\alpha\lambda)^2(1-\lambda^2 - \mu\lambda^2) \\
    \left(\frac{A_2}{\delta_n}\right)^2 &= \frac{(\alpha - \lambda)^2 + (2\xi\alpha\lambda)^2}{(1-\lambda^2)(\alpha^2 - \lambda^2) - \mu\lambda^2\alpha^2} + (2\xi\alpha\lambda)^2(1-\lambda^2 - \mu\lambda^2)
\end{align*}

In the above formula: \( A_1 \): the amplitude of the main mass, \( A_2 \): the amplitude of the additional mass.

The static displacement produced by the main system under the static force with equal amplitude of the excitation force \( P \), as in:

\[ \delta_n = \frac{P}{k_1} \]

The ratio of the excitation frequency to the inherent frequency of the main system, as in:

\[ \lambda = \frac{\omega}{\omega_n} \]

The ratio of the damper frequency to the inherent frequency of the main system, as in:

\[ \alpha = \frac{\omega}{\omega_n} \]

The inherent frequency of the main system as in:

\[ \omega_n = \sqrt{k_1 \cdot m_1^{-1}} \]

The inherent frequency of the damper as in:

\[ \omega_n = \sqrt{k_2 \cdot m_2^{-1}} \]

The ratio of additional mass to primary mass, as in

\[ \mu = \frac{m_1}{m_2} \]

Shock absorber damping ratio, as in

\[ \xi = \frac{c}{2\sqrt{k_1 m_2}} \]

In order to make the damping boring bar have a good damping effect over the entire frequency range, so using the following two formulas [8] to choose the most reasonable damping ratio \( \xi_{op} \) and the most reasonable frequency ratio \( \alpha_{op} \).

\[ \xi_{op} = \sqrt{\frac{3\mu}{8(1 + \mu)}} \]

\[ \alpha_{op} = \frac{\omega_{op}}{\omega_n} \]

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\[
\alpha_{op} = \frac{1}{1 + \mu}
\]  \hspace{1cm} (6)

In the most reasonable range of parameters, the maximum relative amplitude of the vibration system in the frequency domain, as in

\[
\left[ \frac{A_1}{\delta_\mu} \right]_{\text{max}} = \sqrt{1 + \frac{2}{\mu}}
\]  \hspace{1cm} (7)

According to the above formula, the value of the damping system parameter can be determined [9]. From equation (7), it can be seen that when the mass ratio is increased, the amplitude of the main system will be reduced, and the system will have a higher damping effect. However, in the actual production and processing, the structure size of the vibration-damping boring bar is limited. The material with higher density should be used when selecting the internal parts of vibration-damping boring bar. At the same time, in order to meet the large radial clearance required for the damping block, it is necessary to ensure that the distance between the coordination block and the inner wall of the boring bar and between the cooling pipe and the inner wall of the coordination block is 0.02-0.1 mm. It is also possible to add damping fluid between the coordination block and the inner wall of the boring bar and between the cooling pipe and the inner wall of coordination block. The radial gap between them must be increased to meet the viscosity of the damping fluid to meet the actual working conditions.

**Dynamic Change Characteristics Analysis of Vibration-damping Boring Bar**

In this paper, the modal analysis and the harmonic response analysis of the solid boring bar and the vibration-damping boring bar are carried out using ANSYS, and the analysis results of the two boring bar structures are compared.

**Dynamic Characteristics Analysis of Solid Boring Bar**

**Modal Analysis of Solid Boring Bar.** Using SolidWorks to perform solid simplification modeling of solid boring bar, the blade and tool bit are considered as a rigid whole. Element type selects SOLID186 and MASS21 units. Define material properties and set parameters as shown in Figure 3. After the solid model is divided into meshes, corresponding finite element models can be generated and free meshes can be used to generate the meshes. In the modal analysis of a solid boring bar, the tool bit and the bar are regarded as rigid bodies. It is necessary to rigidify the tool bit and the bar. Select Block Lanczos method to extract modality. The solid boring bar has a simple structure and is only affected by the cutting force of the tool, so only the modal value of the 5th order is needed, and the constraint is added to the end of the bring bar 30mm and solved.
The results of modal analysis include: inherent frequency, expanded mode of vibration, the relative stress, and the force distribution. In this analysis, the main consideration is the mode of vibration of the solid boring bar in actual machining, so the inherent frequency value, as shown in Figure 4. The 5-th order inherent frequency and vibration mode of the boring bar are shown in Table 1. In addition, the solid boring bar corresponds to the vibration mode at the inherent frequency of the first order as shown in Figure 5.

Table 1. Inherent frequencies (Hz) and mode of vibration of solid boring bar.

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>765.88</td>
<td>766.06</td>
<td>4419.40</td>
<td>4430.80</td>
<td>5813.10</td>
</tr>
<tr>
<td>Mode of vibration</td>
<td>1-st order</td>
<td>1-st order</td>
<td>2-nd order</td>
<td>2-nd order</td>
<td>torsional</td>
</tr>
</tbody>
</table>

Figure 3. Solid boring bar finite element model, SOLID186—Three dimensional 20 node structure solid unit, Selection of material parameters.

Figure 4. The inherent frequency of solid boring bar.

Figure 5. Vibration mode with an inherent vibration frequency of 765.88 Hz.
Solid Harmonic Harmonic Response Analysis. Before the harmonic response analysis is performed on the solid of boring bar, it is also necessary to model it, allocate the cell attributes, and divide the mesh. This is consistent with the pre-processing of the modal analysis described above and will not be described here. In the harmonic response analysis of solid boring bars, the Full method is used. Add constraints and stress. When adding force, select the tool nose as the force point, the force is 300N, and the direction is the negative direction of Y. Analyze frequency and substep settings. The resonance of the machine is in the low frequency stage, and combined with the maximum tool frequency for deep hole machining in an actual project, you only need to check the frequency change in 0-2000 Hz. For this reason, set the frequency range for the analysis to 0-2000 Hz. Substep is 20. The loading method of the selected load here is stepped.

The Result of Post-Processing. You can usually observe the results with POST26 and POST1. POST1 is used to observe the entire model at a specified frequency. POST26 is used to observe processing at specified points in the model over the entire frequency range. In the post-processing of the solid boring bar, the corresponding frequency of the radial displacement value of the solid boring bar joint is obtained through analysis as shown in Figure 6. The harmonic response curve of the solid boring bar is shown in Figure 7.

**Figure 6.** The solid boring bar point node radial displacement value corresponding frequency diagram.

**Figure 7.** The solid boring bar nose joint radial displacement corresponding frequency curve.

Dynamic Characteristics Analysis of Damping Boring Bar

Modal Analysis of Vibration Damping Boring Bar. Using SolidWorks to perform simplified modeling of damping boring bar, as shown in Figure VIII. Selecting COMBIN14 and MASS21 unit.COMBIN14-Spring-damper unit. The properties of the two materials were added separately. During the analysis, the density of each part of the vibration damping device was initially set to 1400, and the density of the tool bit and the bar was set to 7650. In the analysis of vibration damping boring bar, a sweep grid method was used to divide the vibration damping devices into grids. In addition, in order to facilitate the establishment of a spring-damper (COMBIN14 unit), the coordination block and the cooling pipe are specifically cut. The tool bar, bar and adapters are freely divided and the grid accuracy is 4 levels. A spring-damper (COMBIN14) was set up to simulate the damping fluid in the damping boring bar. In order not to influence the force transmission, a line unit is established in four directions between the cooling pipe and the gap at...
both ends of the coordination block. Choose the XY plane nodes at both ends of the cooling pipe and the coordination block respectively. The selection range is 0.0205 and 0.0185. A key point is established on the node. The key points are established in the four directions between the cooling pipe and the gap at both ends of the coordination block. And connect the key points of symmetry, establish the line unit and divide the mesh. In this analysis, the tool bit and the bar are regarded as rigid bodies and rigidified. The rigid region is mainly constructed using the GUI method.

Results of Dynamic Characteristics Analysis. The method used here is the same as the solid of boring bar mentioned above. It is also the extraction of the modal value of the 5th order. The main consideration here is the vibration mode of the vibration boring bar in actual processing, so the inherent frequency value of the damping boring bar is read, as shown in Figure 9. Figure 10 shows the vibration mode of the damping boring bar with the frequency of 485.68Hz. Table 2 shows the vibration mode of the damping boring bar in each stage.

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>485.68</td>
<td>485.93</td>
<td>2963.70</td>
<td>2967.60</td>
<td>4529.20</td>
</tr>
<tr>
<td>Mode of vibration</td>
<td>1-st order</td>
<td>1-st order</td>
<td>2-nd order</td>
<td>2-nd order</td>
<td>torsion al</td>
</tr>
</tbody>
</table>

Table 2. Inherent frequency (Hz) and mode of various stages of damping boring bar.

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Harmonic Response Analysis of Damping Boring Bar

In the analysis of the harmonic response of the damping boring bar, the analysis method and the loading method used are the same as those described above for the analysis of the harmonic response of the solid boring bar. Damping boring bar resonance analysis results post-processing. The analysis of the 138-node radial displacement value of the damping boring bar corresponds to the frequency and the harmonic response curve of the damping boring bar, as shown in Figure 11.

![Image](image)

**Figure 11.** The 138-node radial displacement value of the damping boring bar corresponds to the frequency, Radial displacement corresponding to frequency curve of tool nose joint of the damping boring bar.

Comparative Analysis

According to the dynamic characteristics of the solid boring bar and the damping boring bar, the results from the analysis can be obtained as shown in Table 3. The maximum response amplitude of the different types of boring bar models over the entire frequency domain and the corresponding frequency at this time.

<table>
<thead>
<tr>
<th>Model</th>
<th>Maximum response amplitude(dB)</th>
<th>Corresponding frequency(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid boring bar</td>
<td>$3.65 \times 10^{-3}$</td>
<td>500</td>
</tr>
<tr>
<td>Damping boring bar</td>
<td>$2.12 \times 10^{-3}$</td>
<td>600</td>
</tr>
</tbody>
</table>

From the simulation analysis of the data and the comparison of the amplitude response curves of the various models in the entire frequency domain can be concluded as follows. Due to the action of the vibration damping device, the vibration damping device increases the inherent frequency of the boring bar in the harmonic response process, and the maximum vibration amplitude of the damping boring bar in the entire frequency domain is greatly reduced when the vibration damping device is added. This shows that the vibration damping system of the built-in damping boring bar improves the dynamic stiffness of the boring bar and has good damping performance.

Result

From the analysis of the design research, the influence of various parameters of the boring bar system on the vibration reduction system was obtained.

The modal analysis and harmonic response analysis of the solid and damping boring bar were conducted, and the following conclusions were obtained:

- Due to the action of the vibration damping device, the vibration damping device increases the inherent frequency of the boring bar in the harmonic response process, and the maximum vibration amplitude of the damping boring bar in the entire frequency domain is greatly reduced when the vibration damping device is added. This shows that the vibration damping system of the built-in damping boring bar improves the dynamic stiffness of the boring bar and has good damping performance.
- Since the analysis of the rubber spring support has the same method as the analysis of the damping fluid, it can be seen from this paper that the reasonable selection of the rubber spring
support also determines the damping performance of the vibration damping system. Selecting the appropriate spring support can also achieve better damping effect.

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