Optimal design of high-speed loading spindle based on ABAQUS

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Abstract. The three-dimensional model of high-speed loading spindle is established by using ABAQUS's modeling module. A finite element analysis model of high-speed loading spindle was established by using spring element to simulate bearing boundary condition. The static and dynamic performance of the spindle structure with different specifications of the rectangular spline and the different diameter neck of axle are studied in depth, and the influence of different spindle span on the static and dynamic performance of the high-speed loading spindle is studied. Finally, the optimal structure of the high-speed loading spindle is obtained. The results provide a theoretical basis for improving the overall performance of the test-bed.

1. Introduce
High-power hydraulic transmission is mainly used in oil and gas field mining equipment, military trucks and civilian use high-end commercial vehicles, highway and construction machinery and other fields, is one of the important components of the transmission system, its performance directly affects the performance of the transmission system, related to the power of the machine, fuel economy and other aspects of performance. In order to improve the quality of transmission products, ensure the outgoing quality and shorten the development cycle, it is necessary to test the performance of the various aspects of the transmission. The high-speed loading spindle is an important part of the front and back loading ends of the test-bed. The structure of the test-bed directly affects the test performance of the test-bed. The test-bed of this project has the characteristics of high power, high torque and high speed, which puts forward the higher requirements of the static and dynamic performance of the test-bed. Therefore, it is very important to use the finite element analysis and parametric discussion method to optimize the structure of the high-speed loading spindle.
2. Design of high-speed loading spindle

The test-bed uses AC variable frequency motor to simulate the actual working condition, driving motor to simulate the engine power input, and loading motor to simulate the size of the load. The main function of the high-speed loading spindle is to pass the load applied by the loading motor to the output of the transmission. The loading end of the transmission test-bed has high rotating speed in actual conditions and is subjected to greater torque or load. If the stiffness is not enough, it is easy to produce larger deformation in the case of torsion, and may break even when severe, which will affect the overall performance of the test-bed. Considering the error of machining and assembly process, in the actual conditions there will be inevitable misalignment vibration, and for installation on the transmission of the advanced bench vibration monitoring system, the vibration is absolutely not allowed. Fig. 2 shows the transmission test-bed high-speed loading spindle system structure, the structure as a whole on the front and back symmetry, and the circumferential mass uniformity, making the spindle dynamic balance is easy to be guaranteed. As the spindle in the actual working conditions mainly by the torque, the axial load is very small, so the high-speed loading spindle directly through the deep groove ball bearings support in the bearing house, and axially through the shaft shoulder, flange limit plate, bearing house end cap and support locating ring positioning. The shaft ends pass the rectangular spline to convey the circumferential motion. Rectangular splines with the advantages of easy processing, high precision centering, and good centering stability and so on, can reduce the difficulty of processing and assembly difficulties. In summary, the spindle system has a simple structure, low cost, easy maintenance, long service life and other characteristics.

![Figure 1. Assembly drawing of high-power hydraulic transmission test-bed](image1)

![Figure 2. Structural diagram of high-speed loading spindle system of transmission test-bed](image2)
Spline width), The length of Rectangular spline is 120mm; The diameter of the transition shaft is 100mm; The length of the transition shaft is 20mm, Bearing type is 6024(d is 120mm; D is 180mm; B is 28mm; Ball diameter $D_w$ is 19; The number of balls is 14), The length of neck of axle is 70mm, The diameter of axle body is 135mm, The length of axle body is 200mm.

3. Static analysis and modal analysis of high-speed loading spindle

3.1. Model Preprocessing and Meshing
High-speed loading spindle consists of spindle, bearing and bearing house and so on. As the bearing house for the fasteners, so the bearing house on the static and dynamic performance of the study can be ignored, here only consider the spindle and bearing. ABAQUS finite element analysis software is one of the most widely used static and dynamic analysis software, it has a friendly three-dimensional modeling interface. In the modeling process, the features of the spindle such as chamfer, fillet and screwed hole are multiplied the time of calculation and the difficulty of convergence is merged and simplified. The simplified finite element model is shown in Fig. 3.

Meshing is the largest part of the workload in the establishment of finite element models. The number of units determines the level of analysis costs, and the quality of the unit determines the correctness of the analysis. ABAQUS can only be divided into tetrahedral units by default, but it is possible to use its dividing technique and distributed seed technique. In order to obtain accurate and reliable calculation results, the model is fine meshed, and 104640 C3D6 entity units and 57089 nodes are generated, as shown in Fig. 4.

3.2. Create Material Property, Interaction, and Load
The choice of spindle material is mainly based on stiffness, strength, wear-resistance and other factors to choose. The high-speed loading spindle selection material is 40Cr, the specific material properties shown in Table 1.

| Table 1. 40Cr material properties |
|-----------------------------------|
| Young's modulus/Gpa | Poisson's ratio | Density/(kg/m³) |
| 211 | 0.277 | 7870 |
Spindle is the step-shaped shaft, only consider the spindle and bearing two parts. The spindle and bearing as a whole, the spindle is mainly subjected to torque and bearing support force, which is a complex statically indeterminate beam structure. According to the actual situation, it can be seen that the support of the spindle is not rigid, and the support stiffness of the bearing has a great influence on the static and dynamic performance of the spindle. Therefore, the elastic effect of the bearing must be taken into account in the analysis. Consider the actual situation to simplify the bearing into a radial spring unit with only radial stiffness and constant stiffness. At each bearing support position, the four uniform spring units shown in Fig. 5 are used to simulate the bearing support boundary conditions. B1, B2, B3, B4 are located at the section surface of the bearing support position simulates the joint of the bearing inner ring and the spindle. A1, A2, A3, A4 are located at the section outside of the bearing support position simulates the bearing outer ring. The stiffness of the spring is the bearing stiffness. According to the actual working condition of spindle, imposed the boundary conditions on the spring. B1, B2, B3, B4 nodes are subjected to axial constraints, and the four nodes of the other end of the spring are complete constraints.

**Figure 5.** Elastic support boundary conditions

On the basis of the Hertz theory, Garguilo derives a series of formulas for calculating the stiffness of different types of bearings. For deep groove ball bearings:

$$K_r = 3.18 \times 10^6 \sqrt{D^2 Z \cos \beta}$$  \hspace{1cm} (1)

In the formula: $K_r$ is the bearing support stiffness, $D$ is the ball diameter, $Z$ is the number of balls, $\beta$ is the contact angle [1].

According to the formula (1), the support stiffness of the bearing is 194058181 N / mm. Create two analysis steps. The first analysis step is modal analysis step, and the load in modal analysis cannot make any effect. The block Lanczos method is used to extract the first eight order vibration modes. The second analysis step is the static analysis step. Since the solid element does not have the degree of freedom of rotation, a reference point is created at the center of the two ends of the spindle and the reference point is coupled with the end face. Then apply the torque to the reference point indirectly to apply the torque to the spindle, two opposite torques of equal magnitude are applied to the two ends of the spindle. According to the actual working condition, the maximum torque of the high-speed loading spindle is 9683N.m.

4. **Submit analysis and result processing**

Spindle modal analysis can determine the vibration characteristics of the spindle system, that is, the spindle frequency and vibration mode, to solve its critical speed, to find out its shortcomings, preparing for the next step to optimize. Static analysis of the node displacement data can be used for structural stiffness analysis, stress, strain and other data can be used for structural strength analysis. Based on the analysis result, whether the stiffness and strength of structure meet the design requirements is studied to help improve the design of the structure [2]. In the Job module, the analysis work is created and
submitted, and after the calculation is completed, the post-processing module is applied to analyze and process the analysis results.

4.1. Statics Solving Results
Spindle material 40Cr is a plastic material, the ultimate stress is the yield limit of the material \( \sigma_y = 785 \text{MPa} \). For plastic materials, according to the yield stress specified by the safety factor \( n_s \), usually take 1.5 to 2.0, select the maximum safety factor \( n_s = 2 \). From the formula (2) to obtain the allowable stress value.

\[
[\sigma] = \frac{\sigma_y}{n} = 392.5 \text{MPa}
\]  

(2)

Figure 6. Maximum stress and displacement nephogram of static

As shown in Fig. 6. In the static analysis step, the maximum displacement Magnitude of the high-speed loading spindle under the torsion load is 0.1746mm, which is located at the torque action. The maximum stress Mises is 101.6Mpa, located in the transition shaft section, far less than the yield force, and can fully meet the static stress requirements.

4.2. Modal Analysis Solving Results
High speed spindle unit is formed by spindle, bearing and so on, each individual degree of freedom corresponds to the unique natural frequency of the system. If the spindle unit excitation force frequency is located in the natural frequency around, will cause the spindle resonance speed called the critical speed [3]. The following formula for the critical speed of the spindle in the test-bed:

\[
n = 60f
\]

(3)

In the formula: \( n \)--speed (r/min), \( f \)--frequency (Hz).

Figure 7. The vibration mode nephogram of high-speed loading spindle
Table 2. High-speed loading spindle modal frequency and critical speed

| Order | Frequency/Hz | Critical speed /(r/min) |
|-------|--------------|-------------------------|
| 1     | 0            | 0                       |
| 2     | 598.54       | 35912                   |
| 3     | 598.57       | 35914                   |
| 4     | 680.57       | 40834                   |
| 5     | 680.6        | 40836                   |
| 6     | 3117.7       | 187062                  |
| 7     | 3124.6       | 187476                  |
| 8     | 3585.5       | 215130                  |

According to Table 2 and Fig. 7, we can see that the first-order natural frequency of the high-speed loading spindle is 0, which is negligible for rigid-body vibration. The second and third order natural frequency are very close, and it can be seen from the figure that the vibration modes are orthogonal and can be regarded as multiple root. Similarly, the natural frequency of the fourth and fifth order, the sixth order and the seventh order are also very close and the vibration modes are orthogonal. The eighth-order vibration mode is the radial expansion characteristic of the spindle. In order to ensure the safety and test accuracy of the test-bed, it is generally stipulated that the maximum speed of the test-bed should not exceed 75% of the minimum critical speed, that is, not more than $35912 \times 75\% = 26934\text{r/min}$. The maximum speed of the spindle is 4000r/min, which is much smaller than the critical speed required. Therefore, the high-speed loading spindle can avoid resonance region and guarantee the running safety and detection accuracy of the test-bed.

5. Numerical simulation results and discussion
The structure of high-speed loading spindle is composed of rectangle spline, transition shaft, neck of axle and axle body. The whole structure is symmetrical. Due to the size of the test-bed in the layout requirements, the total length of the high-speed loading spindle remains unchanged. For ease of study, the length of the rectangular spline, the length of the transition shaft, the total length of neck of axle and axle body remain unchanged. In order to facilitate the assembly of the spindle, the diameter of the transition shaft is always smaller than the inner diameter of the rectangular spline 2mm. The diameter of neck of axle is determined by the diameter of the bearing, and the diameter of axle body is selected according to the choice of bearing. Based on the research method of parametric discussion, the influence of different sizes of rectangular splines, different diameter neck of axles and different span on the static and dynamic performance of the spindle is studied, and the optimal structure of the spindle is obtained.

5.1. The Static And Dynamic Performance of The Spindle Structure with Different Specifications of The Rectangular Spline and Different Diameter Neck of Axle
Rectangular splines and deep groove ball bearings have been standardized, according to the actual conditions of high-speed loading spindle, seeing the mechanical design manual to select the rectangular spline and deep groove ball bearings which are adapt to the actual conditions. Considering the high torque of high-speed loading spindle, the middle series rectangular spline used for medium load is selected. The stiffness of the bearing greatly affects the static and dynamic performance of the spindle. The stiffness of the bearing increases as its inner diameter increases, but the bearing critical speed decreases as the diameter of the inner diameter increases, and large-size diameter of the bearing heat more. So the selection principle of bearing size is within the allowable range of the critical speed, taking into account the impact of temperature, select the large size of the bearing [4]. Taking into account the assembly of the high-speed loading spindle, the inner diameter of the bearing shall be greater than the outer diameter of the rectangular spline. Select combined spindle structure parameters shown in Table 3, select the bearing parameters shown in Table 4.
In order to study the influence of the combined spindle structure on the static and dynamic performance. The influence of spindle structure with different specifications of rectangular spline and different diameter neck of axle on the static and dynamic performance of the spindle is obtained by parametric discussion method, as shown in Fig. 8. Fig. (a) Shows the effect of different combined spindle on the maximum stress of the spindle. It can be seen from the curve that the maximum stress of the spindle is determined by the size of the rectangular spline. The larger the size of the rectangular spline is, the smaller the maximum stress of the spindle is, and the increase of the diameter of neck of axle can only make the maximum stress reduction. Fig. (b) Shows the effect of different combined spindle on the maximum displacement of the spindle. From the curve we can see that the maximum displacement curve is irregular, but the maximum displacement of the combined spindle structure of 10 groups is the smallest. Fig. (c) Shows the effect of different combined spindle on the second-order natural frequency of the spindle. It can be seen from the curve that the second-order natural frequency of the spindle decreases slightly in group 2 and then rises linearly. In summary, you can choose different specifications of the rectangular spline and different diameter of neck of axle to control the static and dynamic performance of the spindle, thereby improving the performance of the test-bed. The maximum stress and maximum displacement of the group 10 are the smallest and the second-order natural frequency is the largest, so the selection group 10 is the optimal combined spindle structure to carry on the next step optimization.

| Group Number | Rectangular spline specifications N×d×D×B | Bearings type | The diameter of axle body Da/mm |
|--------------|------------------------------------------|---------------|-------------------------------|
| 1            | 10×92×102×14                            | 6221          | 125                           |
| 2            | 10×92×102×14                            | 6022          | 125                           |
| 3            | 10×92×102×14                            | 6024          | 135                           |
| 4            | 10×92×102×14                            | 61926         | 142                           |
| 5            | 10×92×102×14                            | 61828         | 149                           |
| 6            | 10×102×112×16                           | 6024          | 135                           |
| 7            | 10×102×112×16                           | 61926         | 142                           |
| 8            | 10×102×112×16                           | 61828         | 149                           |
| 9            | 10×112×125×18                           | 61926         | 142                           |
| 10           | 10×112×125×18                           | 61828         | 149                           |

| Bearing type | Inner diameter d/mm | Outer diameter D/mm | Bearing width B/mm | Ball diameter $D_w$/mm | Ball number /z | Bearing support stiffness $K_r$/N·mm |
|--------------|---------------------|---------------------|--------------------|------------------------|---------------|-------------------------------------|
| 6221         | 105                 | 190                 | 36                 | 26.988                 | 10            | 165200923.5                         |
| 6022         | 110                 | 170                 | 28                 | 18.256                 | 14            | 190220784.8                         |
| 6024         | 120                 | 180                 | 28                 | 19                     | 14            | 194058181                           |
| 61926        | 130                 | 180                 | 24                 | 15.081                 | 18            | 222287322.7                         |
| 61828        | 140                 | 175                 | 18                 | 10.319                 | 26            | 265594620.4                         |
5.2 Influence of Span on Static and Dynamic Performance of High-Speed Loading Spindle

Spindle span refers to the distance between the supporting force acting points of the two adjacent bearings. In the process of spindle optimization design, in addition to the improvement of the structure, the calculation and analysis of the optimal span between the bearings is still one of the most interesting content. Based on the combined spindle structure of group 10, the other parameters are kept constant, and the finite element static and dynamic analysis of the high-speed loading spindle is carried out with the span as the optimization target. Then, according to the calculation results, the change curve can be drawn, and the influence of the spindle span change on the static and dynamic performance of the spindle can be obtained. The spindle span is varied from 100 to 220mm, and the interval 20mm is analyzed once.

As shown in Figure 9, Fig. (a) shows the effect of spindle span on the maximum stress of the spindle. It can be seen from the curve that the span has little effect on the maximum stress of the spindle, and there is a significant decrease in the maximum stress only when the span is 180mm. Fig. (b) shows the effect of spindle span on the maximum displacement of the spindle. It can be seen from the curve that when the span is less than 200mm, the maximum displacement fluctuates slightly, and when the span is greater than 200mm, the maximum displacement increases greatly. Fig. (c) shows the effect of spindle span on the second-order natural frequency of the spindle. It can be seen from the curve that the second-order natural frequency of the spindle increases with the increase of the span, and the value of the natural frequency remains basically unchanged when the span is greater than 200mm. Considering the optimal span of 160mm, the stiffness in the static analysis is large, the deformation is small, and the second-order natural frequency is the largest.

| Rectangular spline specifications | Bearing type | Span/mm | The maximum stress /MPa | The maximum displacement /mm | Second-order natural frequency/Hz |
|----------------------------------|--------------|---------|-------------------------|-----------------------------|----------------------------------|
| N×d×D×B                         |              |         |                         |                             |                                  |
| 10×102×112×16                   | 6024         | 218     | 101.6                   | 0.1724                      | 598.54                           |
| 10×112×125×18                   | 61828        | 160     | 82.81                   | 0.087                       | 695.23                           |

As can be seen from Table 5, the maximum stress of the spindle is reduced by 18.79MPa and 22.7%, and the maximum displacement is reduced by 0.0872mm and 50.6%. The second-order natural frequency is increased by 40.3%.
frequency is increased by 96.69Hz and 16.2%. It can be seen that the static and dynamic performance of the optimized high-speed loading spindle has been greatly improved.

6. Conclusion
The following conclusions can be drawn in this paper:
(1) The maximum stress of the high-speed loading spindle is mainly determined by the size of the rectangular spline. The larger size of the rectangular spline is, the smaller the maximum stress is, and the increase in the diameter of neck of axle can only slightly reduce the maximum stress of the spindle.
(2) The increase in the diameter of the rectangular spline and the diameter of neck of axle can increase the second-order natural frequency of the high-speed loading spindle. But the increase in the size of the rectangular spline of high-speed loading spindle second-order natural frequency rise higher.
(3) Increasing the spindle span can make the second-order natural frequency of the high-speed loading spindle increase significantly, but will remain substantially constant after increasing to a certain value.
(4) Through the parameter optimization, the static and dynamic performance of the high-speed loading spindle has been greatly improved, which provides the theoretical basis for improving the performance of the high-power hydraulic transmission test-bed.

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