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Structural and Modal Analysis of Rolling Bearing Based on ANSYS Software

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Abstract: Based on the operating principles of rolling bearings and actual boundary conditions, using the SKF6180 deep groove ball bearing as a reference, a dynamic simulation model was established based on the ANSYS Workbench platform. Structure and modal analysis were conducted under the free and constrained model conditions for the bearing system, obtaining low-order modal frequencies and vibration modes. The results indicate that the self-vibration frequency of the bearing under constrained conditions is significantly higher than under free modal conditions. When the inner ring of the deep groove rolling bearing is constrained, the critical speed of the bearing system is highest, exhibiting optimal dynamic characteristics. Through modal and vibration mode analysis of the bearing, it shows that the dynamic stability of the cage is relatively weak, making it an improvement target for enhancing the dynamic characteristics of the bearing system. By applying appropriate constraint boundary conditions, the dynamic characteristics of rolling bearings can be effectively improved, providing a solid basis for engineering applications and structural optimization of bearing products.

Keywords: Rolling Bearing; Modal Analysis; Frequency Analysis; Constraint; Finite Element Method.

1. Introduction

Deep groove ball bearings are the most commonly used rolling bearings and are widely applied in various types of engineering machinery equipment [1]. In recent years, with the continuous improvement of advanced manufacturing technologies and automation production levels, modern machinery has increasingly higher requirements for the dynamic characteristics of bearings. Compared to other types of bearings, deep groove ball bearings not only have simple structures, low friction coefficients, high manufacturing precision, and low maintenance costs, but also can simultaneously withstand radial and axial loads, providing reliable support for the high-speed, high-precision development and safe operation of engineering machinery. Dynamic characteristics are important indicators for evaluating the performance of rolling bearings [2]. This paper takes the Swedish SKF6180 deep groove ball bearing as the research object, analyzes and compares the dynamic characteristics and critical speeds of the bearing system under different boundary conditions, providing references for the design and selection of rolling bearings.

With the application of computer-aided software in the mechanical industry, finite element analysis software has been widely used in the field of mechanical structural component mechanics characteristics analysis and vibration response research [3-5]. Modal analysis serves as the foundation for studies on structural vibrations, noise, fault diagnosis, and dynamic responses; harmonic response analysis is a method for studying the system's dynamic response under different frequency sinusoidal loads. Through harmonic response analysis, the response values of structures at the frequencies of external excitation loads can be determined, thereby avoiding mechanical resonance phenomena and fatigue damage caused by forced vibrations [6-7].

Dynamic characteristics are crucial indicators for evaluating the performance of rolling bearings. This paper takes the Swedish SKF6180 deep groove ball bearing as the research object and uses Pro/E three-dimensional modeling software to create a three-dimensional model of the rolling bearing. The model is imported into ANSYS, and based on meshing, loading, and boundary constraints, modal finite element analysis of the rolling bearing is conducted to obtain its structural and modal characteristics, which can provide certain reference basis for bearing structural optimization.

2. Rolling Bearing Structure

Deep groove ball bearings are open, unsealed bearings primarily used in sealed environments such as reducers and gearboxes. They feature high speeds and excellent free rotation effects. Compared to other types of bearings, deep groove ball bearings can not only withstand pure radial loads but also simultaneously handle both radial and axial loads.

Using the SKF6180 deep groove ball bearing produced by SKF Sweden as a reference, establish the solid model of the bearing part shown in **Figure 1**. The structure of the SKF6108 deep groove ball bearing consists of an inner ring, outer ring, balls, and cage. In this structure, the inner ring and outer ring are concentrically assembled, the ball set is mounted inside the cage, and it makes contact with the inner ring raceway and the outer ring raceway. The assembled bearing component model must have no interference phenomena [8].

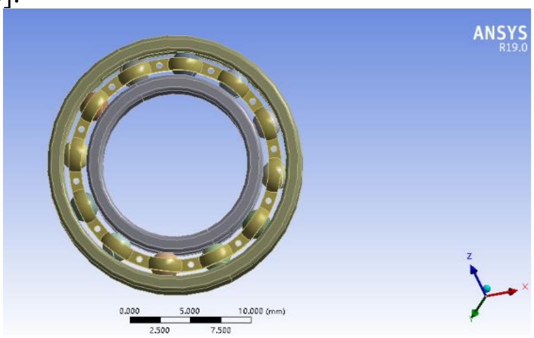

Figure 1. Solid Model of SKF6180 Deep Groove Ball Bearing

In ANSYS Workbench, a finite element model of the SKF6180 deep groove ball bearing was established, as shown in **Figure 2**. The bearing structure was meshed using tetrahedral solid elements, and the contact between the bearing balls, inner ring, outer ring, and cage were set as rigid contact.

Rolling bearings for high-speed rotating components generally require that the inner ring, outer ring, and balls have good wear resistance and impact toughness, as well as high hardness and contact fatigue strength. The cage, on the other hand, needs to have good elasticity, stiffness, wear resistance, and thermal conductivity [9]. The SKF6180 deep groove ball bearing is made from fully hardened high-carbon chromium bearing steel (GCr15) for the inner ring, outer ring, and balls. This type of steel maintains excellent mechanical properties at high temperatures, ensuring the stability and lifespan of the bearing during high-speed operation. The cage is made by stamping J-grade low-carbon steel sheet (08#), which not only has good elasticity and stiffness but also effectively dissipates heat, preventing performance degradation due to heat accumulation caused by friction. The material properties of the SKF6180 deep groove ball bearing are listed in **Table 1**, detailing specific parameters such as hardness, tensile strength, and elongation for each part, ensuring users have a comprehensive understanding of the bearing's performance characteristics.

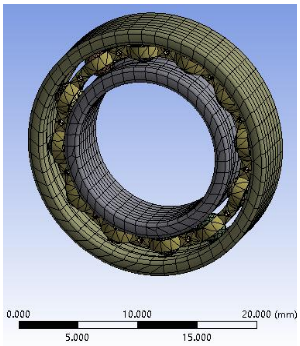

Figure 2. SKF6180 Deep Groove Ball Bearing Finite Element Model

Table 1. SKF6180 Deep Groove Ball Bearing Material Properties

Material type	E/GPa	u	g/(kg/m^3)
Bearing steel (GCr15)	208	0.3	7800
Low-carbon steel (08#)	203	0.3	7850

3. Rolling Bearing Free Modal Analysis

From the theory of dynamics, it is known that free modes are inherent characteristics of structural bodies. Through free mode analysis, one can obtain the natural frequencies and mode shapes that characterize the vibration state of the system, thereby providing important basis for evaluating and predicting the dynamic characteristics of the vibration system. Without considering boundary conditions, a free mode analysis was performed on the SKF6180 deep groove ball bearing assembly, calculating its first to twelfth natural frequencies. The distribution of free mode frequencies is shown in **Figure 3**. Comparing each natural frequency, it is found that the first to sixth natural frequencies of the SKF6180 deep groove ball bearing assembly are very small. This is because that from the first order to six modes of the structure in an unconstrained state are all rigid body modes, and their natural frequency values are generally zero. These rigid body modes typically manifest as overall translation or rotational motion without causing any deformation. Further analysis reveals that starting from the seventh mode, the natural frequency significantly increases, indicating that the structure begins to exhibit more complex vibration patterns, including local deformations and stress concentration phenomena. This change is crucial for understanding the dynamic behavior of bearings in actual working environments, which helps optimize design and improve reliability.

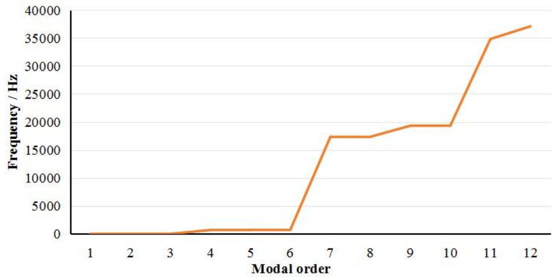

Figure 3. Free Mode Frequency Distribution Diagram

The modal analysis is the basis of studying structural vibration and describing the dynamic characteristics of the mechanism [10,11]. By means of modal analysis of rolling bearings based on ANSYS software, the relevant modal parameters of rolling bearings can be obtained, which lays a foundation for the study of vibration response of rolling bearings. It can be seen from Figure 3 that as the mode order increases, the natural frequency will increase at different speeds. The natural frequencies are zero from first order to third order, the natural frequencies of the 4th to 6th orders are not zero but very weak relative to the vibration frequency of the bearing. It shows that the first 6 order of rolling bearing in free mode is rigid body vibration, and rolling bearing is not easy to produce vibration deformation. The frequency growth from 7 order to 10 order is relatively flat, however the growth rates of 11 order and 12 order are relatively fast.

Starting from the 7th order mode, the natural frequency values of the SKF6180 deep groove ball bearing assembly increase sequentially. The 7th order natural frequency is referred to as the base frequency, which is an important parameter for evaluating the dynamic characteristics of the bearing assembly. As shown in Figure 3, the 7th order natural frequency of the SKF6180 deep groove ball bearing is as high as 17,333 Hz, far exceeding its operating speed frequency under oil lubrication conditions (300 Hz). In actual operating conditions, it is difficult for this deep groove ball bearing to exceed its base frequency because the higher natural frequencies after the base frequency are harder to activate, so the bearing system will not experience corresponding free vibrations. This high natural frequency allows the SKF6180 deep groove ball bearing to exhibit excellent stability during operation, reducing mechanical failures caused by resonance. Therefore, the modal characteristics in the free mode have a minimal impact on the SKF6180 deep groove ball bearing, ensuring its reliability and long life in high-speed operating environments.

Using ANSYS for modal analysis of rolling bearings can yield relevant modal parameters, laying the groundwork for research on the vibration response of rolling bearings. The free modal frequencies of the rolling bearings obtained from simulation are shown in Table 1. From Table 1, it can be seen that as the modal order increases, the natural frequency increases at different rates; the frequency growth between the 7th and 10th orders is relatively gentle, while the growth rate between the 11th and 12th orders is faster. The first three natural frequencies of the rolling bearing are zero, and the natural frequencies from the 4th to 6th orders are non-zero but very weak compared to the bearing vibration frequency, indicating that the first six orders in the free modal state are rigid body vibrations, making it difficult for the rolling bearing to undergo any vibrational deformation.

The deformation of the rolling bearing at the 7th to 10th modal stages are shown in **Figures 4, 5, 6 and 7**. The 7th mode shape shows the upper and lower parts of the outer ring of the rolling bearing bending inward. In the 8th mode, the entire rolling bearing deforms into an elliptical shape. The 9th mode shape indicates that the inner ring of the bearing undergoes outward protrusion deformation. The 10th mode shape involves a certain angle of torsional deformation occurring on the inner circular ring.

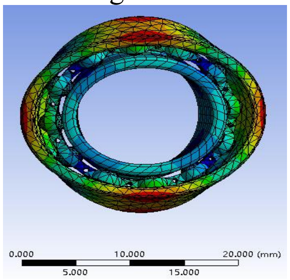

Figure 4. The 7th Order Free Modal Vibration Mode

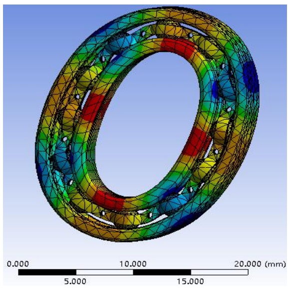

Figure 5. The 8th Order Free Modal Vibration Mode

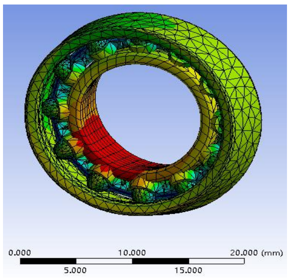

Figure 6. The 9th Order Free Modal Vibration Mode

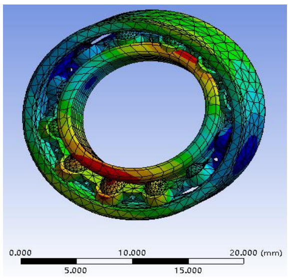

Figure 7. The 10th Order Free Modal Vibration Mode

4. Rolling bearing constraint modal analysis

The modal analysis of a structure is related to its own shape, material, and constraints, among other factors [12]. Compared to free modal analysis, modal analysis under constrained conditions better reflects the actual operating state of bearings. When the inner ring of deep groove rolling bearing is restrained, the constrained modal analysis were carried out. The mode frequencies of rolling bearing under constrained conditions from 1 order to 8 order are shown in Figure 8. As shown in **Figure 8**, the natural frequency of the bearing under constraint conditions is significantly higher than that of the free mode. For example, the fundamental frequency of the constrained mode is 19,334 Hz, which has greatly increased compared to the fundamental frequency of the free mode (17,333 Hz). This indicates that the SKF6180 deep groove ball bearing exhibits more ideal dynamic characteristics under actual operating conditions.

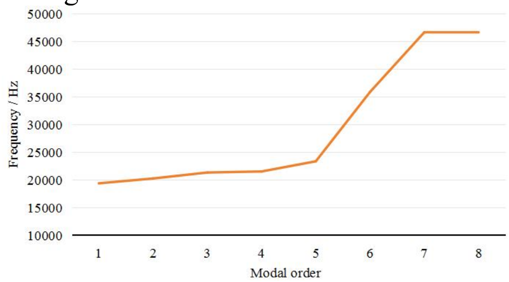

Figure 8. Constraint Mode Frequency Distribution Diagram

Modal vibration modes of the 1st to 4th order under rolling bearing constraints were also carried out as shown in **Figures 9, 10, 11 and 12**. From the diagram and Figures, it can be seen that when the inner ring of the deep groove ball bearing is constrained, the first and second order modal vibration modes mainly manifest as lateral skew deformation driven by the outer ring, accompanied by obvious transverse vibrations. This deformation not only affects the stability of the cage but may also lead to uneven wear on the contact surfaces between the balls and the inner and outer rings. The third and fourth order vibration modes, on the other hand, primarily involve inward bending deformation of the outer ring and cage, showing a clear arc-shaped bending trend, which may further intensify stress concentration within the bearing, leading to fatigue damage.

The vibration modes of deep groove bearings under constrained modal conditions mainly manifest as significant vibrational deformation of the outer ring and cage, with the maximum deformation area concentrated at the edge of the outer ring raceway. This vibrational deformation not only affects the operational stability of the bearing but may also accelerate wear. Additionally, the fundamental frequency of the constrained mode is significantly higher compared to that of the free mode, indicating superior dynamic characteristics of the SKF6180 deep groove ball bearing in actual operating conditions. Specifically, when the inner ring of the deep groove rolling bearing is constrained, the SKF6180 deep groove ball bearing can withstand higher working speeds, thereby maintaining good performance and reliability even under high-speed operation conditions.

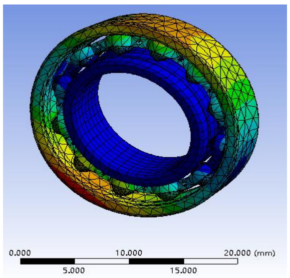

Figure 9. The First Order Constraint Modal Vibration Mode

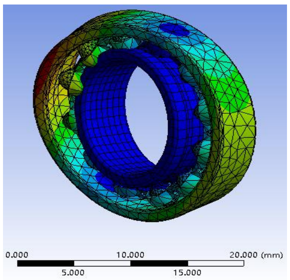

Figure 10. The Second Order Constraint Modal Vibration Mode

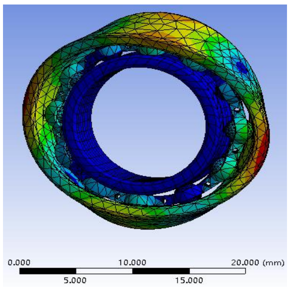

Figure 11. The Third Order Constraint Modal Vibration Mode

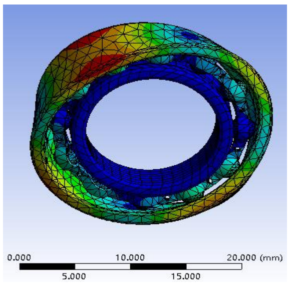

Figure 12. The Fourth Order Constraint Modal Vibration Mode

5. Conclusion

The three-dimensional solid model of SKF6180 deep groove ball bearing was modeled by finite element analysis method, and the modal analysis was carried out. The first six natural frequencies and vibration deformation cloud maps were obtained through modal analysis. The natural frequency of SKF6180 deep groove ball bearing under constraint condition is obviously higher than that of free mode, and the deep groove bearing can adapt to higher working speed under constraint condition, which indicates that the bearing has good dynamic characteristics under actual working conditions.

Acknowledgments

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