Experimental Research on the Influence of Working Conditions on Vibration and Temperature Rise of Si₃N₄ Full-Ceramic Bearing Motors

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Working conditions such as lubrication, preload, and rotational speed have important influence on vibration and temperature rise of the spindle motor. In this study, controlled variable experiments are carried out on the silicon nitride (Si₃N₄) full-ceramic ball bearing and steel bearing of the same type, and the vibration signal characteristics and temperature rise of the spindle motor are tested and analysed, by changing the lubrication conditions, preloads, and rotational speeds of the spindle motor. Through the research, it is found that as the rotational speed increases, the vibration velocity of the Si₃N₄ full-ceramic bearing spindle motor under different preloads and lubrication conditions shows an overall increasing trend; kurtosis generally presents a downward trend and gradually flattens, indicating that although the vibration velocity increases at high speeds, the vibration signal shows a relatively stable state. As the rotational speed increases, the difference of vibration velocity under the condition of applying preload and no preload decreases, indicating that the influence of preload on the vibration of full-ceramic bearing spindle motor decreases with the increase in rotational speeds. At the same time, it is found that \( f_r \) and \( 5f_r \) have greater impact on the vibration of full-ceramic bearing spindle motor, where \( f_r \) is the frequency of the bearing in normal operation, and \( 5f_r \) is 5 times the normal operating frequency. Lubrication conditions have little effect on the temperature rise of full-ceramic bearing spindle motor, and the temperature rise under nonlubricated conditions is even slightly lower than that under grease lubrication conditions. The research results show that the vibration velocity and temperature rise of Si₃N₄ full-ceramic bearing spindle motor are less than those of steel bearing with the same type, indicating that full-ceramic bearing has better performance than steel bearing under the same working conditions.

1. Introduction

As the main source of power, spindle motors are widely used in CNC machine tools, wind turbines, high-speed railway, and new energy automobiles and other fields [1–3], the performance and service life of spindle motors directly determine the service performance and life of mechanical equipment. The common sources of faults in spindle motors can broadly be classified as the followings [4, 5]: bearing faults, stator or armature faults, broken rotor bar and end-ring faults, and eccentricity-related faults. Among all types of faults, bearing is one of the most prevalent factors, almost 40%–50% of all motor failures are bearing related, such as fatigue failures, spalling, crack propagation, friction and wear, electric corrosion, and so on. As an important index to evaluate the performance of spindle motor, rise in vibration and temperature affects the performance and life span of the spindle motor directly [6, 7]. There are many factors that cause the vibration and temperature rise of the spindle motor, and the reasons are also very complicated. For example, the vibration is mainly caused by rotor imbalance, uneven air gap, and abnormal bearings; temperature rise is
mainly caused by winding iron core heating, poor bearing lubrication, bearings wear, and other reasons; among which, the vibration and temperature rise caused by the bearing accounts for a large proportion [8, 9]. Excessive vibration and high temperature rise of the spindle motor not only will produce loud noises and aggravate bearing wear but also may cause damage to the insulation layer or even burn the motor, which will affect the performance and reduce the service life of the spindle motor. Therefore, it is particularly important to control the vibration and temperature rise of the spindle motor.

The main factors affecting the service performance of rolling bearings include the following: bearing materials, structure, manufacturing accuracy, preload, working temperature, and lubrication conditions. Hot isostatic pressed silicon nitride (HIPSIN) is considered to be the most suitable engineering ceramic material for bearings due to its low density, wear resistance, high rigidity, low expansion coefficient, self-lubricating, electrical insulation, and other excellent characteristics [10], and it has become a new direction for modern bearings and has become more and more widely used. There are many reasons for vibration and temperature rise in ceramic bearings during operation, such as frequent changes of rotational speeds, loads, external environment and other factors, friction and wear between the internal components of ceramic bearings, fatigue spalling and crack propagation of ceramic rings and rolling elements, cage fracture [11], existence of bearing clearance, viscosity and friction resistance of lubricating oil [12], and so on. Applying proper axial preloads [8] to the bearing can not only reduce the axial clearance of the bearing but also improve the stiffness of the shaft system to reduce vibration and noise [13]. Suitable lubrication [14, 15] can ensure effective lubrication of spindle motor bearings and reduce bearing wear and the generation of heat by friction, improving the performance and life of bearings. Therefore, it is of great significance to carry out researches on spindle motor vibration and temperature rise, starting from the bearing material, preload, and lubrication conditions.

Researchers have made many contributions in the fields of shaft vibration and motor temperature rise: Wang et al. [11] studied the thermal performance and temperature distribution of ball bearings in the traction motor, the influence of rotational speed and applied load variation on bearing temperature, and the temperature distribution law of each component in grease lubricated bearing are analysed. Jamadar and Vakharia [12] studied the effect of grease viscosity on mechanical vibrations associated with the damaged bearings, and the results show that when the grease viscosity is higher, the amplitude of the bearing presents a lower level, so the service performance of the bearing is improved. He et al. [16] studied the temperature fields of the air-cooled electric spindle by numerical methods, and they also experimentally studied the influence of wind speed on the temperature of the electric spindle and the relationship between rotational speed, vibration, and noise and found that the temperature, vibration, and noise increased with the rotational speed. The research results provide a basis for the optimal design of the air-cooled electric spindle. Kosaka et al. [17] analysed and calculated the temperature fields of the disc permanent magnet motor using the equivalent thermal network method, and the temperature field distribution of each part of the motor was obtained. Liu and Zhang [18] considered the thermal-mechanical coupling factors and established a more accurate thermomechanical coupling dynamic model of the high-speed electric spindle; they quantitatively discussed the dynamic behavior of spindle system and the influence of thermal displacement on the dynamic behavior of spindle system. Zhang and Chen [19] established a thermal engine coupling model of spindle system, which were composed of three coupling submodels of bearing, thermal engine, and motorized spindle dynamics; they analysed the influence of thermal expansion of motorized spindle bearing on the dynamic performance of motorized spindle, and through the research, the effects of rotational speed, cooling water flow, and oil-gas pressure on the dynamic characteristics of spindle were noted. Li et al. [20] used the online adjustment test platform of electric spindle preload to study the influence of air supply pressure and rotational speed on the outer ring temperature rise of the motorized spindle front bearing. The research results show that the steady-state temperature rise of the high-speed motorized spindle increased with the increase in rotational speed and air supply pressure. Through the online control of the bearing preload, the active control of the thermal characteristics of the motorized spindle can be realized. Zhang et al. [21] took the optimized heat transfer coefficient as the boundary condition to calculate the internal temperature fields and thermal deformation of the high-speed spindle, established a high-speed motorized spindle thermal deformation prediction model, and verified the prediction accuracy. Other aspects, such as the relationship between temperature of the internal components of the bearing and friction heat generation power [22–24], influence of changes in bearing structural parameters, contact thermal resistance and bearing temperature on the nonlinear thermal characteristics [25], prediction of bearing temperature fields distribution through the thermal-mechanical coupling model [26], influence of thermal related fit clearance between the bearing outer ring and pedestal on the vibration characteristics of full-ceramic bearings [27], have also been extensively studied, and effective conclusions have been drawn.

It can be seen from the above that researchers have conducted in depth researches on shaft vibration and temperature rise and have obtained many valuable results. However, most of the present studies focus on traditional steel bearings and relatively few involve full-ceramic bearings. Compared with traditional steel bearings, ceramic bearings are more suitable for occasions with high speed, heavy load, and electric corrosion, such as spindle motors, because of their low density, wear resistance, high stiffness, low expansion coefficient, and electrical insulation, making it a new direction of rolling bearing research. Although when the difference between the characteristics of new ceramic materials and traditional metal materials are considered, various macro- and microfactors in ceramic bearing assembly and multi-interface system have extremely complex effects on bearing service performance, which brings many new problems, such as the multifield coupling relationship.
between the rotational speed, load, and temperature fields and the elastic-plastic deformation, vibration noise, and thermal effect of ceramic bearings during operation. Therefore, in this study, the experimental method is used to explore the influence of lubrication conditions, preload, and rotational speed on the vibration and temperature rise of Si$_3$N$_4$ full-ceramic bearing and steel bearing spindle motors. To verify the application effect of full-ceramic bearing in spindle motor, this study verifies that the full-ceramic bearings have more excellent performance compared with traditional steel bearings in the aspects of reducing vibration and temperature rise. It has certain scientific significance and engineering application value to structure optimization, design, manufacture, and service performance of full-ceramic bearing for different working conditions.

2. Experimental Method

2.1. Development of Experimental Bearings. The most common processing method of Si$_3$N$_4$ and other engineering ceramic materials is grinding. Compared with other processing methods such as chemical processing and optical processing, the grinding has the advantages of simple processing technology, high processing efficiency, high dimensional accuracy, low surface roughness, and few surface and internal cracks; relatively high reliability engineering ceramic parts can be obtained through this processing method. The grinding process of full-ceramic bearings are divided into the grinding process of ceramic balls, inner ring, and outer ring. The processing route is shown in Figure 1. The structure and samples of the developed Si$_3$N$_4$ full-ceramic ball bearings are shown in Figure 2.

2.2. Assembly of Spindle Motor with Full-Ceramic Bearings. Generally, the inner ring of the bearing and the rotating shaft are interference fit. In traditional assembly process of steel bearing spindle motor, if the interference between steel bearing and rotating shaft is small, it can be assembled by direct pressing, but such installation will not only damage the matching accuracy of bearing and rotating shaft but also affect the service performance of bearings. If the interference is large, it can be assembled by hot fitting. However, for full-ceramic bearings, due to the nonmagnetic properties and low thermal expansion coefficient of ceramic materials, the hot fitting method cannot be used. Therefore, in this study, liquid nitrogen is used to achieve ultralow temperature cooling, and the rotating shaft is cooled to make it shrinken, ensuring the clearance between the ceramic inner ring and the rotating shaft and achieving damage-free assembly to improve the assembly and running accuracy of the full-ceramic bearing spindle motor. After the bearing assembly is completed, the rotor system is dynamically balanced, and then, the spindle motor assembly is completed. In the static test of the assembled spindle motor, the radial runout of the spindle motor is in the range of 1 μm to 2 μm. The assembled spindle motor is shown in Figure 3.

2.3. Experimental Devices and Procedure. The experiments are carried out in the dust-free laboratory with ambient temperature of 25 degree centigrade ±2 degree centigrade and humidity of ≤75%. The model of the spindle motor used in the experiments is Z18-44P0XA30, and the performance parameters are shown in Table 1. The bearings used in the experiments are 6206 Si$_3$N$_4$ full-ceramic bearings (the materials of inner ring, outer ring, rolling element, and cage are Si$_3$N$_4$, Si$_3$N$_4$, and PEEK, respectively) and traditional 6206 steel bearings (the materials of inner ring, outer ring, rolling element, and cage are all bearing steel). Structure parameters and material parameters of the tested bearings are shown in Tables 2 and 3. The experimental devices and schematic diagram are shown in Figure 4.

In the experiments, the rotational speed of spindle motor is changed under the conditions of the controlling preload and lubrication conditions unchanged; the vibration and temperature rise experiments of Si$_3$N$_4$ full-ceramic ball bearings and steel bearings are carried out. The rotational speeds selected in the experiments are 2000 r/min–16000 r/min, with an interval of 2000 r/min, a total of 8 groups of rotational speed conditions. The preload condition refers to adding a corrugated spring washer to the shaft end of the spindle motor with a preload of 300 N; the lubricating condition refers adding an appropriate amount of grease to the bearings, and the model of grease is KLUBER NBU15. The experimental procedure is shown in Figure 5.

3. Vibration Frequency Characteristics and Heat Generation of Bearings

3.1. Frequency Characteristics of Vibration. In the bearing system, rotational frequency and its multiplication frequency are the main frequency components of the bearing
Figure 1: Processing route of full-ceramic bearing.

Figure 2: Structure and samples of full-ceramic bearings. (a) Structure of 6206 full-ceramic bearing. (b) Samples of Si₃N₄ full-ceramic bearings.
vibration. In addition, the vibration caused by the rolling frequency of the rolling elements in the inner and outer raceways also has a significant impact on the performance of bearings. The calculation methods of the characteristic frequency of each component of the bearing are as follows [28, 29].

As shown in Figure 2, definition

\begin{align}
    r_i &= f_i D_w, \\
    r_e &= f_e D_w, \\
    \gamma &= \frac{D_w \cos \alpha}{d_m},
\end{align}

where \( f_i \) and \( f_e \) are the coefficients of raceway curvature radius of the inner ring and outer ring, respectively.

The relationship between the pitch diameter and the diameter of the inner and outer rings of the bearing is as follows:

\begin{align}
    d_m &= \frac{1}{2} (d_i + D_e), \\
    d_i &= d_m - D_w \cos \alpha, \\
    D_e &= d_m + D_w \cos \alpha.
\end{align}

Assuming that the outer ring is fixed and the inner ring rotates with the rotating shaft, the linear speed of the inner ring raceway can be expressed as follows:

\begin{equation}
    v_i = \frac{1}{2} \omega r_i.
\end{equation}

Assuming that the rolling elements run in pure rolling state in the raceway of inner and outer rings, the rotational speed of the cage can be expressed as

\begin{equation}
    v_c = \frac{1}{2} v_i = \frac{1}{4} \omega d_i = \frac{1}{4} \omega (d_m - D_w \cos \alpha). \quad (4)
\end{equation}

Expressed in the form of frequency as

\begin{equation}
    f_c = \frac{1}{2} f_r \left( 1 - \frac{D_w}{d_m} \cos \alpha \right) = \frac{1}{2} f_r (1 - \gamma). \quad (5)
\end{equation}

Therefore, the rotational frequency of the inner ring and outer ring relative to the cage can be expressed as

\begin{align}
    f_{ic} &= f_r - f_c = \frac{1}{2} f_r (1 + \gamma), \\
    f_{ec} &= f_c - \frac{1}{2} f_r (1 - \gamma).
\end{align}

Table 1: Performance parameters of the spindle motor.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (kW)</td>
<td>4.0</td>
</tr>
<tr>
<td>Rated voltage (V)</td>
<td>330</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>9.3</td>
</tr>
<tr>
<td>Rated frequency (Hz)</td>
<td>103</td>
</tr>
<tr>
<td>Maximum speed (rpm)</td>
<td>16000</td>
</tr>
<tr>
<td>Rated torque (N·m)</td>
<td>12.7</td>
</tr>
<tr>
<td>Series (P)</td>
<td>4</td>
</tr>
<tr>
<td>Moment of inertia (kg·m²)</td>
<td>5.4e-3</td>
</tr>
</tbody>
</table>

Table 2: Structure parameters of 6206 bearing.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter ( d ) (mm)</td>
<td>30</td>
</tr>
<tr>
<td>Outer diameter ( D ) (mm)</td>
<td>62</td>
</tr>
<tr>
<td>Pitch diameter ( d_m ) (mm)</td>
<td>46</td>
</tr>
<tr>
<td>Bearing width ( B ) (mm)</td>
<td>16</td>
</tr>
<tr>
<td>Diameter of ball ( D_w ) (mm)</td>
<td>9.525</td>
</tr>
<tr>
<td>Raceway radius of inner ring ( r_i ) (mm)</td>
<td>4.91</td>
</tr>
<tr>
<td>Raceway radius of outer ring ( r_e ) (mm)</td>
<td>5</td>
</tr>
<tr>
<td>Number of rolling elements ( z )</td>
<td>9</td>
</tr>
<tr>
<td>Radial clearance ( u_r ) (μm)</td>
<td>14</td>
</tr>
</tbody>
</table>
Table 3: Material parameters of the bearing.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Si₃N₄</th>
<th>GCr15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g cm⁻³)</td>
<td>3.2</td>
<td>7.85</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (k⁻¹)</td>
<td>3.5 × 10⁻⁶</td>
<td>3 × 10⁻⁵</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>310</td>
<td>207</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.26</td>
<td>0.30</td>
</tr>
<tr>
<td>Thermal conductivity (w m⁻¹ k⁻¹)</td>
<td>35</td>
<td>45</td>
</tr>
</tbody>
</table>

Figure 4: Experimental devices and schematic diagram: (a) Frequency converter. (b) Spindle motor. (c) Laser vibrometer. (d) Vibration data acquisition instrument. (e) Infrared thermal imager. (f) Temperature data acquisition. (g) Experimental schematic diagram.
Experimental research on the influence of working conditions on the vibration and temperature rise of Si3N4 full-ceramic bearing motors

![Experimental procedure diagram]

Assuming that the number of rolling elements is \( z \), the rotational frequency of the rolling elements passing through the inner and outer ring raceways can be expressed as:

\[
\begin{align*}
    f_b &= \frac{Z}{2} f_r (1 + \gamma) \\
    f_c &= \frac{Z}{2} f_r (1 - \gamma).
\end{align*}
\]

The rotational frequency of the rolling elements can be expressed as:

\[
    f_b = f_c \frac{d_i}{D_w} = \frac{m_f}{2D_w} (1 - \gamma^2).
\]

When the vibration signal is transformed by the fast Fourier transform, if the frequency spectrum contains the high vibration value at the above characteristic frequency, it indicates that the characteristic frequency has contributed to the vibration of the bearings.

3.2. Heat Generation inside the Bearings. Heat inside the bearing is mainly generated by friction between the rolling elements, inner ring, and outer ring of the bearing. Palmgren [30] has summarized the calculation formulas of the bearing friction torque under load and no-load conditions through a large number of experiments.

Friction torque caused by lubricant viscosity under no-load condition:

When \( \nu_n \leq 2000 \),

\[
    M_0 = 160 \times 10^{-7} f_0 d_m^3.
\]

where \( f_0 \) is the coefficient related to bearing type and lubrication, \( \nu \) is the dynamic viscosity of the lubricant, and \( n \) is the rotational speed of the bearing.

For load related friction torque \( M_1 \),

\[
    M_1 = f_1 P_1 d_m,
\]

where \( f_1 \) refers to the coefficient related to the bearing type and load, and \( P_1 \) refers to the equivalent dynamic load of the bearing.

Therefore, the bearing friction torque can be expressed as:

\[
    M = M_0 + M_1.
\]

During the working process of the bearings, the rolling elements are subjected to centrifugal force, which makes the friction torque of the inner ring and outer ring different. Therefore, according to the difference of inner ring and outer ring raceway radius \( d_i \) and \( d_o \), the total friction torques are divided into inner and outer ring friction torque components, that is, inner ring friction torque is \( M_i = 0.5M \cdot D_w/d_i \), and outer ring friction torque is \( M_e = 0.5M \cdot D_w/d_o \).

Under the condition of high-speed rotation, in addition to the rotation of inner ring and the revolution of the rolling elements, the rotation sliding between rolling elements and inner raceway of the bearing is also one of the main movements. The friction torque produced by rotation sliding has a great influence on the total friction torques, which should be considered in the calculation of heat generation. Therefore, the heat generated by rotation friction is added to above formula, so as to make the empirical formula more accurate.

\[
    M_s = \frac{3\mu Q_a E_{(\eta)}}{8}
\]

where \( M_s \) is the rotation friction torque of the rolling elements, \( a \) is the major semiaxis of the contact ellipse, \( \mu \) is the friction coefficient between the rolling elements, inner ring raceway, and outer ring raceway, \( Q \) is the normal contact load between the rolling elements, inner ring raceway, and outer ring raceway, and \( E_{(\eta)} \) is the second-type elliptic integral function of the raceway contact area.

When \( \nu_n \geq 2000 \),

\[
    M_0 = 10^{-2} f_0 (\nu_n)^{2/3} d_m^3,
\]

where \( f_0 \) is the coefficient related to bearing type and lubrication, \( \nu \) is the dynamic viscosity of the lubricant, and \( n \) is the rotational speed of the bearing.
4. Results and Discussion

4.1. Influence of Working Conditions on Vibration

4.1.1. Variation of Vibration Velocity and Kurtosis. A large number of researches [31–36] have shown that, as a numerical statistic reflecting the distribution characteristics of random variables, kurtosis is particularly sensitive to shock signals, and it can well reflect the large pulse signal generated by bearing vibration, especially suitable for early fault diagnosis of bearings. The vibration velocity and kurtosis of Si₃N₄ full-ceramic bearings and steel bearings spindle motors under different working conditions are shown in Figures 6–8, respectively. Of which, the kurtosis index K is a numerical statistic reflecting the distribution characteristics of random variables, and it is a fourth-order cumulant. The calculation formula is given as follows:

$$K = \frac{\int_{-\infty}^{\infty} \left[ x(t) - \bar{x} \right]^4 p(x) dx}{\sigma^4} \quad (15)$$

where $x(t)$ is the instantaneous amplitude, $\bar{x}$ is the mean amplitude, $p(x)$ is probability density, and $\sigma$ is standard deviation.

As shown in Figure 6(a), under the condition of grease lubrication without preload, the vibration velocity of the spindle motor shows a continuous upward trend with the increase in rotational speed. Under the condition of preload applied with grease lubrication, the vibration velocity shows a trend of first rising, then falling, and then rising with the increase in rotational speed. When the rotational speed is not higher than 8000 r/min, the vibration velocity continues to rise. Within the range of 8000 r/min–10000 r/min, the vibration velocity shows a downward trend. After 10000 r/min, the vibration velocity continues to increase. When the rotational speed is lower than 8000 r/min, the preload has greater influence on the vibration velocity. With the increase in the rotational speed, the rising speed of the vibration velocity with preload is higher than that without preload, indicating that the impact of preload on the vibration velocity decreases gradually. As shown in Figure 6(b), with the increase in rotational speed, the kurtosis of the spindle motor with and without preload present a trend of first decline and then stable; the decline rates are 94.2% and 87.6%, respectively. The maximum kurtosis occurs when the rotational speed is 2000 r/min, indicating that the spindle motor has a high-amplitude vibration signal at low speed. With the increase in rotational speed, the change of kurtosis tends to be gentle after 6000 r/min, indicating that the vibration signal is relatively stable. The kurtosis of the spindle motor with preload applied at lower rotational speed is obviously greater than that with no preload, but as the rotational speed increases, the gap decreases.

Vibration velocity and kurtosis changes of Si₃N₄ full-ceramic bearing spindle motor with the increase in rotational speed under nonlubricated condition is shown in Figure 7. As shown in Figures 7(a) and 7(b), the change trend of vibration velocity and kurtosis are similar to that under grease lubrication condition because the ceramic material has certain self-lubrication performance. However, for the vibration velocity, when the rotational speed is 8000 r/min, the vibration velocity under the condition of applying preload is even higher than that under the condition of no preload, which may be caused by the resonance because the rotational speed is close to the first-order critical speed of the spindle motor in this condition. For kurtosis, when the rotational speed is lower than 10000 r/min, the kurtosis value without preload under nonlubricated condition is significantly higher than that with applying preload; this may be due to that under the condition of no preload and nonlubrication, the axial clearance of full-ceramic bearing is bigger and looseness phenomenon occurs, resulting in the generation of vibration signals with high amplitude.

Variation of vibration velocity and kurtosis of spindle motor with steel bearings at different rotational speeds are shown in Figure 8. As shown in Figure 8(a), under the condition of grease lubrication without preload, the vibration velocity increases first and then decreases with the increase in the rotational speed. When the rotational speed is lower than 8000 r/min, the vibration velocity increases rapidly with the increase in the rotational speed. After 8000 r/min, the vibration velocity shows a slow downward trend. Under the condition of applying preload and grease lubrication, the vibration velocity presents a trend of first rising, then falling, and then rising as the rotational speed increases. When the rotational speed is not higher than 8000 r/min, the vibration velocity continues to rise. In the range of 8000 r/min–10000 r/min, the vibration velocity shows a slight downward trend. After 10000 r/min, the vibration velocity continues to rise again. After 8000 r/min, the difference of the vibration velocity under the conditions of applying preload and no preload is gradually reduced, indicating that as the rotational speed increases, the influence of the preload on the vibration velocity decreases gradually. As shown in Figure 8(b), with the increase in the rotational speed, the kurtosis shows a continuous downward trend, under both conditions of applying preload and no preload, and the rate of decrease is 83.8% and 73.5%, respectively. Compared with Si₃N₄ full-ceramic bearings, the downward trend is gentler. The maximum kurtosis occurs at 2000 r/min, indicating that the spindle motor has a high-amplitude vibration signal at low speed. When the rotational speed is 2000 r/min and 12000 r/min, the spindle motor with preload and without preload have almost the same kurtosis value, and when the rotational speed is between 2000 r/min and 12000 r/min, the kurtosis with preload is significantly greater than that without preload, but as the rotational speed increases, the gap gradually decreases. When the rotational speed is higher than 12000 r/min, the kurtosis with preload becomes lower than that without preload.

4.1.2. Effect of Frequency Multiplication. Performing fast Fourier transform on the measured vibration signals, the frequency domain components of the vibration signals are observed and analysed, as shown in Figures 9–11.
Effect of frequency multiplication on the vibration velocity of Si$_3$N$_4$ full-ceramic bearings spindle motor under the condition of grease lubrication and applying preload is shown in Figure 9(a). As can be seen from Figure 9(a), the vibration velocity is mainly affected by $f_r$ frequency multiplication ($f_r$) and 5 frequency multiplication ($5f_r$), and as the rotational speed increases, the overall vibration velocity is on the rise. When the ceramic bearings are running at low speed (less than 5000 r/min), $5f_r$ contributes the most to the vibration velocity, but for medium and high speed (higher than 6000 r/min), $f_r$ become the largest contributor to the vibration velocity, followed by $5f_r$. The $2f_r$ and $3f_r$ have little effect on the vibration velocity and the change is relatively stable. Figure 9(b) shows the effect of frequency multiplication on the vibration velocity of the Si$_3$N$_4$ full-ceramic bearing spindle motor under the condition of no preload. When the rotational speed is not higher than 4000 r/min, the effect of each frequency multiplication on vibration velocity basically the same, but when the rotational speed is higher than 4000 r/min, $f_r$ has the greater effect on the vibration velocity, the second is $5f_r$, with the increase in the rotational speed, the effect on the vibration velocity shows a trend of
The vibration velocity of Si\textsubscript{3}N\textsubscript{4} full-ceramic bearing spindle motor under nonlubricated condition. As can be seen from Figure 10(a) that under the condition of applying preload, the variation trend of frequency multiplication effect on vibration velocity is basically the same as that under the same condition with grease lubrication. This is because the ceramic material has certain self-lubrication performance, and the lubrication state has little effect on the vibration velocity of Si\textsubscript{3}N\textsubscript{4} full-ceramic bearing under the condition of applying preload. Under the condition of no preload, as shown in Figure 10(b), the 3\textit{f}_r under nonlubricated condition...
fluctuates more than that under grease lubrication condition. This may be because there is no grease filling and lead to the bearing axial clearance increases.

Figure 10: Effect of frequency multiplication on the vibration velocity for Si$_3$N$_4$ full-ceramic bearings under nonlubricated condition. (a) Condition of applying preload. (b) Condition of no preload.

Figure 11: Effect of frequency multiplication on the vibration velocity for steel bearings under grease lubrication condition. (a) Condition of applying preload. (b) Condition of no preload.
greatest effect on the vibration velocity, followed by $5f_r$ and $2f_r$ has the least effect. This is due to that under the condition of no preload, with the increase in rotational speed, the clearance between the rolling elements and raceways in the bearing becomes larger caused by the centrifugal force, resulting in greater impact of $3f_r$ and $5f_r$ on the vibration.

4.1.3. Comparison of Si3N4 Full-Ceramic Bearings and Steel Bearings. Figure 12 shows the vibration velocity comparison of Si$_3$N$_4$ full-ceramic bearings and steel bearings under grease lubrication condition, with the increase in rotational speed. Among them, Figure 12(a) is the condition of applying preload, and Figure 12(b) is the condition of no preload. As can be seen from Figure 12, the vibration velocity of Si$_3$N$_4$ full-ceramic bearing is always lower than that of steel bearing, regardless of whether the preload is applied or not. Under the condition of applying preload, compared with steel bearing, the maximum reduction in vibration velocity of Si$_3$N$_4$ full-ceramic bearing is 45.6%, which occurs at the speed of 4000 r/min. Under the condition of no preload, the maximum reduction in vibration velocity is 55.3%, which occurs at the speed of 6000 r/min. Thus, it can be seen that the vibration performance of Si$_3$N$_4$ full-ceramic bearings in the spindle motor is superior under the same working conditions.

4.2. Influence of Working Conditions on Temperature Rise. Infrared thermal imager is a kind of equipment that uses infrared detector and optical imaging objective lens to receive the infrared radiation energy distribution pattern of the measured target and then embody it on the photosensitive components of the infrared detector. It does not need to directly touch the object to monitor the thermal image in the infrared wavelength spectrum. The thermal image corresponds to the thermal field distribution of the surface layer of the object. The difference of different tones indicates the different temperature of the measured object. The common infrared thermal imager works in the mid-infrared (3~5 μm) or far-infrared (8~14 μm) band, respectively. The schematic diagram of the infrared thermal imager analysis/monitoring system used in the experimental research is shown in Figure 13.

4.2.2.1. Temperature Rise under Different Working Conditions. The running-in procedure used in the test is as follows: the start-up rotational speed is 1000 r/min, and the step of speed-up is 1000 r/min; the rotational speed is increased every 10 min before 6000 r/min, and every 20 min after 6000 r/min; after reaching the limit speed, the spindle motor maintains the speed and runs for a total time of 6 hours. During the period, the infrared thermal imager is used to collect the temperature data of the spindle motor.

Figures 14 and 15 show the variation of temperature rise at different parts of the steel bearing and Si$_3$N$_4$ full-ceramic bearing spindle motor. As can be seen from Figures 14 and 15, whether steel bearings or Si$_3$N$_4$ full-ceramic bearings, the spindle motor presents the highest temperature rise at the position of front bearing, followed by the rear bearing, and with the lowest temperature rise at the shaft end. This is because for the front and rear bearings, the rotational friction of the bearing and electromagnetic heating between the stator and rotor can lead to the temperature rise, leading to the rise in temperature of the two positions higher than the shaft end. At the same time, due to the shaft end is exposed to the air, the convection heat dissipation effect is better, so the temperature rise is relatively lower. Although there is a fan to cool down the spindle motor during operation, the fan blows from the rear bearing to the front bearing, so the heat dissipation effect of the rear bearing is better than the front bearing, resulting in the lower temperature rise of the rear bearing than the front bearing.

Comparing Figures 14(a) and 14(b), it can be found that under the same working conditions, the temperature rise of the spindle motor with preload is significantly higher than that without preload. For the front bearing, rear bearing, and shaft end, the temperature rise of the spindle motor under the condition of applying preload is 21.3%, 18.3%, and 18.5%, respectively, higher than that with no preload applied. This is because the preload reduces the gap between the rolling elements, inner ring, and outer ring, which increases the friction between the rolling elements, the inner ring, and outer ring during the bearing operation, resulting in the increase in heat generation. Therefore, in the process of designing and assembling the spindle motor, an appropriate preload should be selected.

The temperature rise comparison of Si$_3$N$_4$ full-ceramic bearing spindle motor under grease lubrication and non-lubrication conditions are shown in Figures 15(a) and 15(b). As can be seen from Figure 15, for both the conditions of grease lubrication and nonlubrication, the temperature rise of the spindle motor shows a trend that first rises rapidly and then gradually stabilizes. The temperature rise under non-lubricated condition is not much different from that under grease lubrication condition and even slightly lower than the temperature rise under grease lubrication condition. This is because Si$_3$N$_4$ ceramic material has certain self-lubrication performance, and self-lubrication film between the ceramic balls, inner ring, and outer ring can be formed in the process of operation, reducing the generation of friction heat. For Si$_3$N$_4$ full-ceramic bearings with grease lubrication, grease not only plays a certain role in lubrication but also plays a certain role in hindering the operation of bearings, increasing the heat generation of bearings. At the same time, the addition of grease is not conducive to heat dissipation, so the temperature rise is slightly higher than that without lubrication.

4.2.2. Comparison of Temperature Rise between Si3N4 Full-Ceramic Bearings and Steel Bearings. Figure 16 shows the comparison of the temperature rise for Si$_3$N$_4$ full-ceramic bearings and steel bearings spindle motor. It can be seen from Figure 16 that under the same working conditions, the temperature rise of Si$_3$N$_4$ full-ceramic bearing is always lower than that of steel bearing. For front bearing, back bearing, and shaft end, the temperature rise
Figure 12: Vibration velocity comparison of Si$_3$N$_4$ full-ceramic bearings and steel bearings under grease lubrication condition. (a) Condition of applying preload. (b) Condition of no preload.

Figure 13: Schematic diagram of infrared imager analysis/monitoring system.
of Si$_3$N$_4$ full-ceramic bearing spindle motor is 12.5%, 17.5%, and 16.8% lower than that of steel bearing spindle motor, respectively. Under grease lubrication condition, the temperature rise of Si$_3$N$_4$ full-ceramic bearing spindle motor with preload is almost equal to that of steel bearing spindle motor without preload, whereas the temperature rise of Si$_3$N$_4$ full-ceramic bearing spindle motor under nonlubricated condition is even slightly lower than that of under lubrication condition. Thus, it can be seen that the temperature rise performance of Si$_3$N$_4$ full-ceramic bearings in the spindle motor is better under the same working conditions, and for full-ceramic bearings, the amount of grease added should be lower than that of steel bearings.
In this study, controlled variable experiments are carried out on $\text{Si}_3\text{N}_4$ full-ceramic ball bearings and steel bearings of the same type; the vibration signal characteristics and temperature rise of the spindle motor are tested and analysed by changing the lubrication conditions, preloads, and rotational speeds of the spindle motor. The following conclusions are obtained:

1. With the increase in rotational speed, the vibration velocity of $\text{Si}_3\text{N}_4$ full-ceramic bearing spindle motor generally increases and the kurtosis decreases under different preload and lubrication conditions, indicating that the vibration signal is relatively stable, even though the vibration velocity increases at high speed.

2. With the increase in rotational speed, the difference of vibration velocity under condition of applying preload and no preload decreases, indicating that the effect of the preload on the vibration of full-ceramic bearing spindle motor decreases with the increase in rotational speed; At the same time, $f_r$ and $5f_r$ have greater impact on the vibration of the full-ceramic bearing spindle motor, followed by $2f_r$ and $3f_r$.

3. Lubrication conditions have little effect on the temperature rise of full-ceramic bearing spindle motor, and the temperature rise under nonlubricated conditions is even slightly lower than that under grease lubrication conditions.

4. Under same working conditions, compared with steel bearings, the vibration velocity of full-ceramic bearing spindle motor decreases by 45.6%–55.3% and the temperature rise decreases by 12.5%–17.5%.

The vibration velocity and temperature rise of the full-ceramic bearing spindle motor are less than those of steel bearings with the same type. It shows that $\text{Si}_3\text{N}_4$ full-ceramic bearing has better performance than steel bearing under same working conditions.

### Data Availability

The data used to support the findings of this study are included within the paper.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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### References


