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Review

A Review of Key Technologies for High-Speed Motorized Spindles of CNC Machine Tools

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Abstract: The high-speed and high-precision motorized spindle is the future development trend of the CNC machine tool field, and has become the focus of research in the world. High-speed motorized spindles tend to develop in the direction of high precision, high speed, low energy consumption, high efficiency, and high reliability. We undertake a through, systematic review of the development history perspective of the research on precision bearing technology, dynamic balancing technology, thermal error measurement and compensation technology with regard to the key technologies of high-speed motorized spindles. On this basis, the current level of development of key technologies for high-speed motorized spindles is analyzed, and the objective advantages and disadvantages of existing technologies are summarized. Finally, the development tendency of high-speed motorized spindle technology is predicted and foreseen.

Keywords: high-speed motorized spindle; precision bearing; dynamic balancing; thermal error measurement and compensation; development trend

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1. Introduction

As modern machine tools are developing towards high speed and high precision, the technical requirements for the spindles of machine tools are increasing. The motorized spindle is one of the core functional components of high-speed machine tools; the motor of a motorized spindle is placed inside the spindle unit of the machine tool to drive the spindle. Therefore, the machine drive structure is simplified, and "zero drive" is achieved [1,2]. Because the motorized spindle has the advantages of its compact structure, is lightweight, has small inertia and good dynamic performance, the dynamic balance of the machine tool is improved and the vibration and noise are avoided. The structure of traditional rolling bearings makes it difficult to meet the requirements of high speed and high precision for high-speed machine tools, so the research of bearings is one of the key research objects in the field of high-speed machine tools [3]. As the key support technology for high-speed motorized spindles, bearings must meet the requirements of high-speed operation, and have high rotary accuracy and low-temperature rise, in addition to long service life, especially with regard to maintaining the accuracy. The current high-speed motorized spindle applied bearings are mainly angular contact ball bearings, liquid floating bearings, air bearings, and magnetic bearings. But the speed and precision of the spindle-bearing improvement is based on the premise of high-precision dynamic balance. For motorized spindles, the unbalance phenomenon is inevitable due to the influence of factors such as manufacturing, installation error, and material unevenness. Therefore, the research on the dynamic balance characteristics of the high-speed motorized spindle is also a hot issue in the key technology of the motorized spindle. At the same time, the built-in motor and bearings will generate a lot of heat when the spindle is running at high speed. The internal structure of the motorized spindle is compact, and if the heat cannot be removed in time it will lead to thermal deformation of the parts, which will affect the preload state of the bearings and the machining accuracy of the machine. For ultra-precision machining machines, the thermal error of high-speed motorized spindle operation is as high as 90% [4], so the thermal error restricts the improvement of machining accuracy for the processing machine. Proposing a reasonable and effective method to suppress thermal error is necessary to improve the accuracy and performance of motorized spindles' machining guarantee. Therefore, studying the bearing technology, dynamic balancing technology, and thermal error measurement and compensation technology of high-speed electric spindles is necessary. The architecture diagram of the three technologies synergistically influencing the development of high-speed motorized spindles is shown in Figure 1.

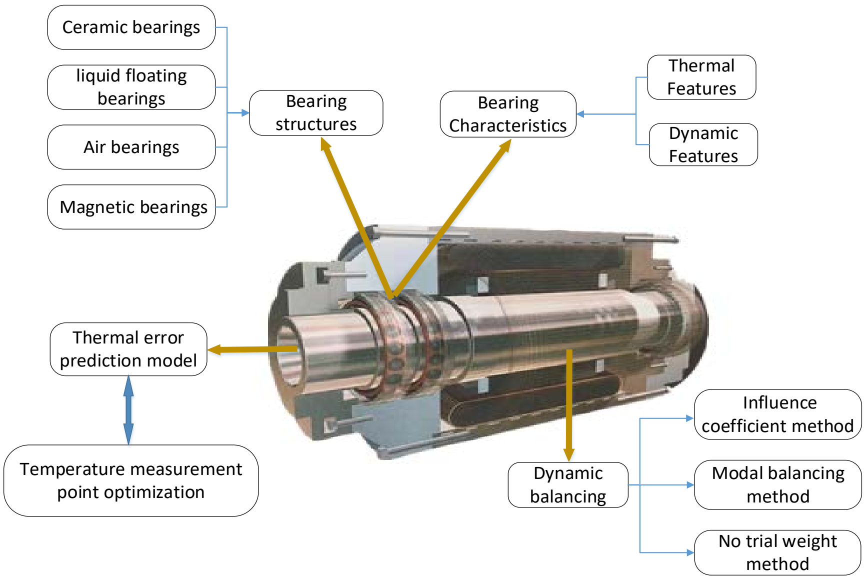


Figure 1. Analysis diagram of high-speed electric spindle technology.

2. Recent Developments in Precision Bearing Technology

The high-speed precision bearing is one of the core supporting components of a high-speed motorized spindle. Bearings are often in high-speed or ultra-high-speed operation, so the bearings must have a series of characteristics such as good high-speed performance, high dynamic load-carrying capacity, superior lubrication performance, and low heat generation. At present, high-speed precision bearings have become the key research and development technology in the world. There are four main types of bearings for high-speed spindles, including angular contact ceramic ball bearings, liquid floating bearings, air bearings, and magnetic bearings. The specific classification is shown in Figure 2 [5]. In addition, after extensive literature research, recent surveys are presented in this section and summarized in Table 1.

2.1. Existing Survey Studies on the Structural Design of Precision Bearings

Angular contact ceramic ball bearings are universally used for high-speed spindle bearings. The advantages of angular contact ceramic ball bearings are their simple structure, high rigidity, and high load-carrying capacity. But the ball bearings have the defects of large vibration amplitude and poor accuracy retention, resulting in a shorter life of the ball bearings.

In [6], the grease-lubricated ceramic bearing with a piezoelectric ceramic inner ring was invented. The author invented an improved structure for the ceramic bearing applied to the steel shaft, due to the temperature change generated by the high-speed operation of the spindle causing the ceramic material bearing inner ring to broke or slip, and the noise of the ceramic bearing affecting the overall quality of the equipment, as shown in Figure 3a. Different from the structure of traditional ceramic bearings, a new type of dynamic pressure gas radial ceramic bearing was designed. Driven by the high-speed rotating spindle, the mating gap between the gas film of the inner ring of the bearing sleeve and the shaft tile provides the spindle stabilization [7], as shown in Figure 3b.

Table 1. Research work on bearing structures.

Reference	Brief Summary	Type of Bearing	Objective
Wu et al. [6]	Grease lubricated ceramic bearing with piezoelectric ceramic inner ring	Ceramic bearing	Avoid the noise caused by fracture or slipping of the inner ring of the bearing
Liu et al. [7]	New Dynamic Pressure Gas Radial Ceramic Bearing	Ceramic bearing	High stability of high-speed rotating spindle
Jiang et al. [8]	Liquid hydrostatic bearing of the slotted water cavity type with varying opposing areas	Liquid floating bearing	Provide large hydrostatic load capacity and overcome the defect of low rotation accuracy of spindle at high speed
Zhang et al. [9]	Hydrostatic floating bearing of through-hole type	Liquid floating bearing	Simple structure, easy to achieve the purpose of spindle suspension
Ko et al. [10]	Hydrostatic bearing monitoring system and monitoring method	Liquid floating bearing	Real-time monitoring of hydrostatic bearing performance and fault warning
Yu et al. [11]	Ultra-precise air bearing with active compound throttling type	Air bearing	Suppress micro-amplitude vibration of air-bearing, improve dynamic stiffness
Yin et al. [12]	Air bearing with replaceable throttle plug	Air bearing	Effectively avoid the phenomenon of "air hammer" in bearing
Keun et al. [13]	Improved structure of the new air bearing	Air bearing	Avoid thermal deformation of bearing or spindle caused by dynamic instability of the rotor and high speeds
Chen et al. [14]	Hybrid magnetic bearing structure	Magnetic bearing	Effective simplification of magnetic floating bearing structure, saving cost
Zhang et al. [15]	Protective structures for magnetic bearings and magnetic assemblies	Magnetic bearing	Solve the problem of spindle and bearing wear due to easy failure of the magnetic bearing protection structure
Chen et al. [16]	Coil type axial permanent magnet electric magnetic bearing	Magnetic bearing	Realize axial bidirectional self-stabilization, less resistance and lower energy consumption

The liquid floating bearing is a non-direct contact bearing, and the supporting medium is liquid. The liquid floating bearing has the characteristics of small wear, large support stiffness, strong damping and shock absorption, high rotary accuracy, and a theoretical infinite life.

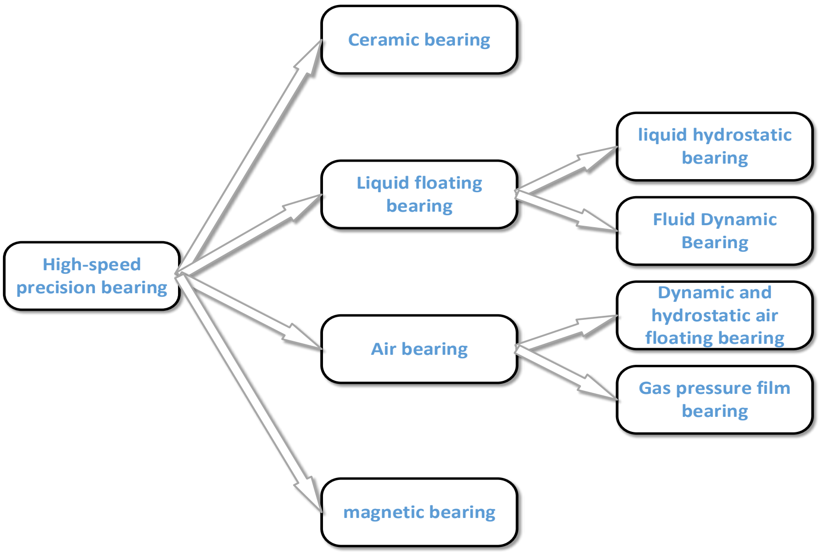


Figure 2. High-speed precision bearings classification.

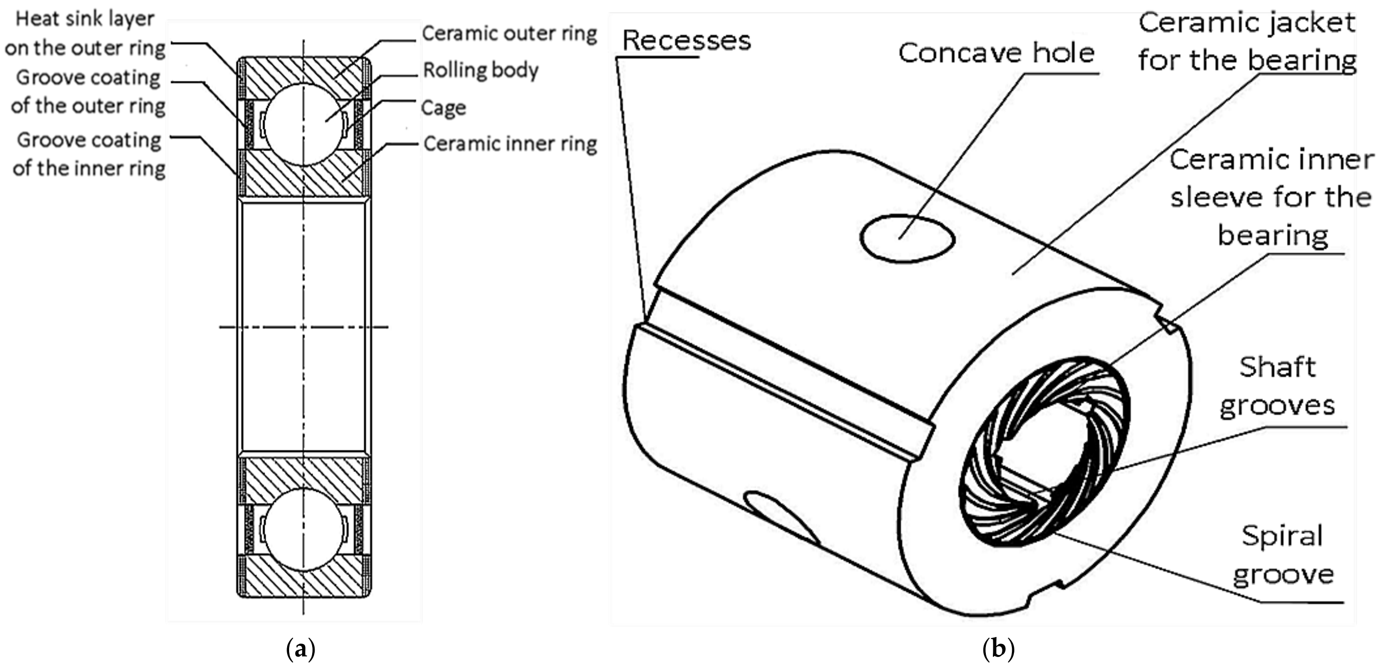


Figure 3. Structure type of angular contact ceramic ball bearings. (**a**) A grease lubricated ceramic bearing with piezoelectric ceramic inner ring; (**b**) A new type of dynamic pressure gas radial ceramic bearing.

In [8], the authors designed a liquid hydrostatic bearing with a slotted water cavity of unequal area. The direction of action of the external load on the bearing points to the slotted water cavity, and the journal position is biased in the direction of the slotted water cavity to achieve the purpose of external throttle pressure regulation. The pressure and bearing area in the hydrostatic groove around the slotted water cavity is larger than the equal opposite water cavity, and a large hydrostatic bearing force is generated in the groove, as shown in Figure 4a. Addressing the problem that the overall structure of a hydrostatic bearing is more complex and not easily serviced, the authors of [9] proposed a monitoring system and method for the hydrostatic bearing. By using multiple sensors to monitor the state parameters of the hydrostatic bearing device, multiple state parameters are sent to the computing unit and use the model of the computing unit to establish a performance prediction model with multiple state parameters. The authors achieved real-time monitoring of the hydrostatic bearing performance and the pre-checking of faults. To solve the problem of complex structures of liquid hydrostatic bearings mentioned above, the new structure designed by the authors of [10] achieves high-speed rotation of the spindle, as shown in Figure 4b. The through-holes are opened in the housing of the bearing. The liquid cavity formed between the outer wall of the sleeve and the inner wall of the bearing housing and the through-holes is connected. When the spindle and the sleeve are installed, a slit appears. With the liquid flowing through the liquid chamber and entering the slit, the liquid in the gap causes the pressure to increase due to the viscous property and finally the spindle floats.

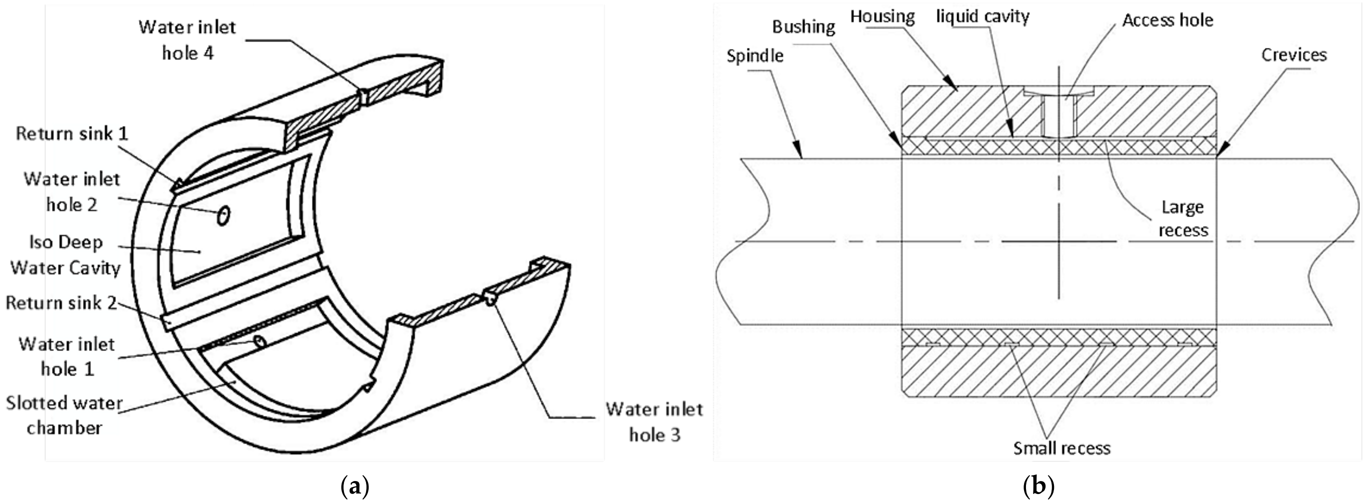
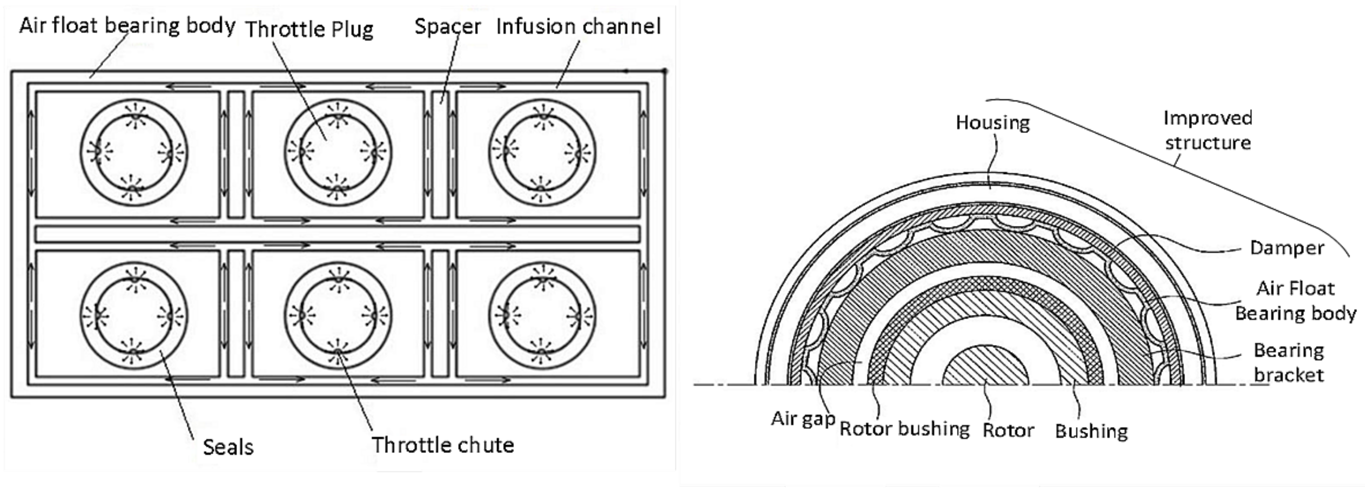


Figure 4. Structure type of liquid floating bearings. (**a**) A liquid hydrostatic bearing with a slotted water cavity of unequal area; (**b**) An oil pressure bearing.

Gas is used as the supporting medium of air bearings in order to achieve ultra-high-speed and frictionless operation. However, the viscosity of the gas medium is extremely low and one thousandth of the lubricating oil's viscosity, resulting in a low stiffness of the air bearing. Air bearings are used in high-speed precision machining with low loads.

In [11], the authors proposed that an ultra-precision air bearing is suitable for ultra-precision manufacturing. The signal is produced by the compound throttling control unit, and the drive unit analyzes the signal for expansion and contraction. The throttling height and throttling area are adjusted to change the pressure distribution in the air film gap. To make the maintenance of air float bearings easy, the authors of [12] replaced the conventional single outlet hole with a replaceable throttle plug and throttle slot. The throttle plug is provided with a throttle slot and inserted into the outlet slot, and the throttle slot is connected to the outlet slot to realize the formation of a high-pressure air film on the floating surface, as shown in Figure 5a. Different from the traditional air-bearing, the authors of [13] designed a new air bearing structure that consisted of three main parts: a bearing support, spring, and damper. The part of the bearing bracket that mates with the rotor is made of a rigid body. The rigid body and radial shaft structure are used to support the air. The bearing bracket is supported by springs and dampers to eliminate the energy generated by the vibration of the bearing bracket, as shown in Figure 5b.



(**a**) (**b**)

Figure 5. Structure type of air bearings. Magnetic bearing (**a**) An air bearing with replaceable throttle plug; (**b**) A new air bearing structure.

The magnetic bearing can make the spindle reach high speeds without mechanical contact. However, the cost is high, the control system is too complicated, the heat problem is not easy to solve, and magnetic bearings are suitable for special applications.

In [14], the authors invented a structure of the hybrid levitation bearing and combined active and passive levitation techniques. The uncontrolled structure with passive levitation simplifies the structure of the magnetic bearing, and the magnet structure with a mixture of electromagnetic and permanent magnet facilitates energy savings, as shown in Figure 6a. The protective structure of magnetic bearings is prone to failure, leading to accelerating the wear of spindles and bearings; the authors of [15] investigated a protective structure for magnetic bearings and magnetic bearing assemblies to address this problem. To reduce the energy consumption of magnetic levitation bearings to a lower level and save costs, the authors of [16] designed a magnetic bearing with an axial permanent magnet motor. The axial bi-directional self-stabilization was achieved without a control system, and the bearing was subjected to less resistance and consumed less energy. The magnetic bearing of the coil type is shown in Figure 6b.

2.2. Development of Bearing Thermal Performance Research

The thermal characteristics of the spindle-bearing system are the main constraint to improving the cutting speed and machining accuracy under the high-speed operation of machine tools. Scholars in developed countries are still relatively early in their research on the thermal characteristics of spindle-bearing systems. In this section, the research results related to the development of the thermal properties of bearings are presented. These are also summarized in Table 2.

Scholars are still in the relatively early stages of this research and have proposed basic thermal theories. The authors of [17] first proposed a heat source model for bearings which laid the foundation for subsequent studies to calculate the thermal characteristics of spindles, but the model was limited to use under low and medium-speed operating conditions. In the same year, the authors of [18] Fafnir Bearing Company in the United States further proposed the calculation method of friction force and friction moment in the contact area of the raceway; the method is mainly used to solve the bearing spin-sliding friction heat generation. In [19], the authors of SKF Bearing Company, Philadelphia, PA USA, proposed a method for calculating the temperature network distribution of bearing systems. Empirical formulas were summarized regarding the forced convection heat transfer coefficient of the lubricant on the bearing surface, laying the foundation for the establishment of a bearing heat transfer model. Based on the above mentioned literature, the authors of from the University of Michigan, Ann Arbor, MI, USA [20] established a heat transfer network inside the bearing and investigated the effect of transient preload force changes caused by uneven thermal expansion of the bearing. Based on the phenomenon that the thermal deformation of the bearing causes a change in the preload force, the authors at Purdue University in West Lafayette, IN, USA [21] established a model of a thermally induced preload of motorized spindle and proposed a scheme to adjust a thermally induced preload in order to analyze the change of preload caused by thermal expansion. However, the effect of heat loss on the motor was not considered in the modeling. In [22], the authors proposed a finite element difference method to establish an analytical model of the motorized spindle heat source, and a detailed theoretical analysis of the heat source and heat transfer mechanism of the spindle system was calculated. Based on the heat generation mechanism of bearings proposed in [19], the authors of [23] further proposed a qualitative power flow model. The model is used to calculate the thermal power loss of a high-speed motorized spindle and the temperature rise of each component. However, the effect of the thermal expansion of bearings on the dynamic characteristics of the spindle is not considered.

Attempting to address the problem that motor heating is not considered in [21], the authors of [24] studied the loss in heat generation of the motor and friction heat generation of bearings in the high-speed motorized spindle and analyzed the heat dissipation characteristics of the oil-water heat exchange cooling system and oil-air lubrication system. A finite element analysis model of the temperature field of the high-speed motorized spindle was established, and the temperature field of the spindle was calculated using ANSYS software. The authors from Chongqing University, Chongqing, China [25] developed a thermal-mechanical coupling model of a single-row angular contact ball bearing. The authors analyzed the friction loss and dynamic support stiffness of the bearing during spindle operation by studying the thermal response of the system and the influencing factors of the preload mode. By establishing the electromagnetic loss model, the heat generation pattern of the bearing and motor was obtained. In the same year, the authors of [26] developed a power flow model of a motorized spindle based on the law of energy conservation. The motor loss model was refined and analyzed by considering the relationship between various losses. The model makes the heat calculation of the thermal state model more accurate. In [27], the authors of Xi'an Jiaotong University, Xi'an, China established a thermal-mechanical coupling analysis model regarding the influence of spindle speed, initial preload force, and ambient temperature on bearing preload force. The transient temperature rise and thermal deformation of the spindle system are calculated by the finite element method, and the thermal preload force and radial stiffness of the bearing are calculated and tested by the preload force test for the bearing preload force variation. Aiming at the difficult problem of measuring bearing preload, a thermally induced preload testing system for bearings was developed [28]. In contrast to the traditional contact-time measurement or infrared measurement methods, the authors proposed a new measurement technique that uses fiber-optic grating sensors to monitor the preload force of bearings online, using the amount of change in wavelength to determine the preload force. However, the fiber optic grating is highly sensitive to temperature and strain, and the fiber optic grating sensor is highly susceptible to ambient temperature changes; there is a situation that the measured data is not accurate. In the same year, a new thermal resistance network model was established based on the fractal theory [29]. The authors analyzed the steady-state and transient temperatures at the nodes by listing the heat balance equations of the key nodes of the motorized spindle system. The accuracy of the contact thermal resistance and thermal resistance network model between circular contact surfaces was verified through fractal parameter identification, heat transfer and temperature rise experiments. The results show that this theory can predict the temperature rise of each component of the spindle system.

Table 2. Bearing thermal performance research works.

Reference	Brief Summary	Year	Objective
Palmgren et al. [17]	The bearing heat source model is proposed for the first time	1959	The subsequent research on thermal characteristics of spindle has laid a foundation
Jones et al. [18]	The calculation method of friction force and friction moment in the contact area of the raceway is proposed	1959	Mainly used to solve for bearing spin-sliding friction heat generation
Harris et al. [19]	A temperature network distribution method for bearing system is proposed	1973	Laying the groundwork for a heat transfer model of the bearing
Stein et al. [20]	Internal heat transfer network of the bearing is established	1994	The effect of transient preload force changes caused by uneven thermal expansion of the bearing is investigated
Tu et al. [21]	Thermally induced preload force model for motorized spindles is proposed	1996	Analysis of the changes in bearing preload force caused by thermal expansion
Bossmanns et al. [22]	Analysis model of motorized spindle heat source based on finite element difference method is proposed	1999	Effective analysis and calculation of the heat source and heat transfer mechanism of the spindle system
Bossmanns et al. [23]	A qualitative power flow model is proposed	2001	To provide a theoretical basis for the subsequent study of the power balance of heat generation and heat dissipation in a motorized spindle
Huang et al. [24]	A finite element model of the temperature field of high-speed motorized spindle was established	2003	The loss heat generation of motor and friction heat generation of bearing is studied
Chen et al. [25]	A thermal-mechanical coupling model of a single-row angular contact ball bearing is established	2013	The factors influencing the thermal response and preload mode of the system are investigated
Chen et al. [26]	The motorized spindle power flow model was established based on the law of energy conservation	2013	Refined analysis of the motor loss model for more accurate heat generation calculations in the thermal state model
Zhou et al. [27]	The thermal-mechanical coupling analysis model of high-speed motorized spindle is established	2015	The effects of spindle speed, initial preload and ambient temperature on bearing preload are studied
Lu et al. [28]	A thermally induced preload testing system for bearings is established	2021	A new measurement technique for online monitoring of bearing preload is proposed
Meng et al. [29]	The thermal resistance network model based on fractal theory is proposed	2021	Reliability of fractal theory applied to thermal resistance network models for predicting temperature rise is demonstrated

2.3. Research Progress on the Thermal-Dynamic Coupling Performance of Spindle and Bearing

In the actual operation of motorized spindles, heat generation in the motor and bearings causes changes in bearing preload and stiffness. Heat generation is an important factor affecting the thermal deformation of the spindle and the dynamic characteristics of the spindle-bearing system. At present, the thermal dynamic coupling performance of spindle-bearing has been studied by many scholars and is summarized in Table 3.

Table 3. Research work on the thermal-dynamic coupling performance of spindles and bearings.

Reference	Brief Summary	Year	Objective
Kim et al. [30]	An integrated thermal-mechanical prediction model was developed	2001	Study on the frictional torque and heat generation of bearings to change the spindle system stiffness angle
Jiang et al. [31]	The calculation model of thermal deformation and inherent frequency of the spindle is proposed	2001	The problem of nonlinear characteristics of bearing load and bearing deformation and the effect of frictional heat is solved
Lin et al. [32]	The dynamic-thermal functional model of the integrated high-speed motorized spindle is established	2003	The effect of thermally induced preload on bearing stiffness and overall spindle dynamics is quantitatively discussed
Li et al. [33]	The dynamics model of the spindle-bearing "thermal-mechanical coupling" system is established.	2004	Motorized spindles with complex physical characteristics or geometries are solved
Holkup et al. [34]	The thermal-mechanical coupling model of the spindle-bearing system is established based on the finite element method	1996	The spindle-bearing system model can accurately predict the temperature distribution and thermal displacement of the system is verified
Song et al. [35]	The spin-generated heat model of the bearing is established	1999	Analysis of the causes of bearing failure provides guidance for predicting dangerous bearing failures
Yu et al. [36]	A coupled model of dynamic-thermal characteristics of the bearing is established based on the thermal network method	2001	Study on the effect of thermal deformation on bearing contact parameters under different operating conditions
Liu et al. [37]	The thermal-mechanical coupling dynamics model of a high-speed motorized spindle is established	2003	To provide a theoretical basis for subsequent research on thermal compensation of high-speed motorized spindles

In [30], the authors of the Gwangju Institute of Science and Technology, Gwangju, Korea, developed an integrated thermal-mechanical prediction model. The frictional torque of the bearing and the heat generation cause the change of the space to change the angle of the spindle system's stiffness. And the cooling part of the spindle system and the control method are designed optimally.

For the nonlinear characteristics of bearing load and bearing deformation and the effect of frictional heat, the authors of [31] established a computational model of thermal deformation and inherent frequency of the spindle. In [32], the authors established a comprehensive dynamic-thermal functional model of a high-speed motorized spindle. The effect of a thermally induced preload on bearing stiffness was discussed. And the variation of centripetal force and gyroscopic moment of the rotating spindle was profiled. However, thermal deformation of the rotor due to external loads has not been considered. At the same time, the factors of speed and temperature rise of the rotor that changes the support stiffness of the spindle have not been analyzed. Based on the consideration of the bearing stiffness, contact load, and dynamic response of the spindle support, the authors of [33] established a thermal-mechanical coupling dynamics model of the spindle and bearing. By coupling the thermal expansion at the bearing connection and the heat transfer in the whole system with the dynamic model of a spindle, the thermal expansion and dynamic characteristics of the bearing were simulated and analyzed. The effect of the remaining variables on the inherent frequency was analyzed. The dynamics model is capable of solving motorized spindles with complex physical characteristics or geometrical forms. The authors from the Czech Technical University in Prague, Czech [34] developed a thermal-mechanical coupling model of the spindle-bearing system based on the finite element method. At the same time, the effects of the heat generation of the motor and bearings on the spindle components were considered, and the transient changes of temperature, deformed lubricant viscosity, and bearing stiffness were analyzed. The results show that the spindle-bearing system model is capable of predicting the temperature distribution and thermal displacement of the system. On the basis of [34], the authors of Jilin University, Changchun, China [35] established a bearing heat generation model considering the spin-generated heat of bearings, analyzed the spin-generated heat of bearings, and dissected the causes of bearing failure under the thermal-force coupling characteristics of bearings at high spindle speeds. The spin-generated heat model guides the failure prediction of bearings. In [36], the authors from Shanghai University, Shanghai, China considered the thermal deformation of the part due to frictional heat generation in the bearing. The steady-state temperature field model of the bearing was established by using the thermal network method, and the coupled dynamic-thermal characteristics model of the bearing was further proposed. The results show that thermal deformation has a large impact on the bearing under high-speed operation. And the thermal deformation under different operating conditions leads to disparate contact parameters of the bearing. The authors of [37] established a coupled thermal-mechanical dynamics model for a high-speed motorized spindle and analyzed the coupling relationship between the bearing model, the thermal model, and the spindle dynamics model. The dynamic behavior of the spindle system and the thermal displacement of the system were investigated, and the accuracy of the predictive model was verified through experiments to improve the model accuracy. The thermal-mechanical coupling dynamics model provides theoretical support for the subsequent thermal compensation of high-speed motorized spindles.

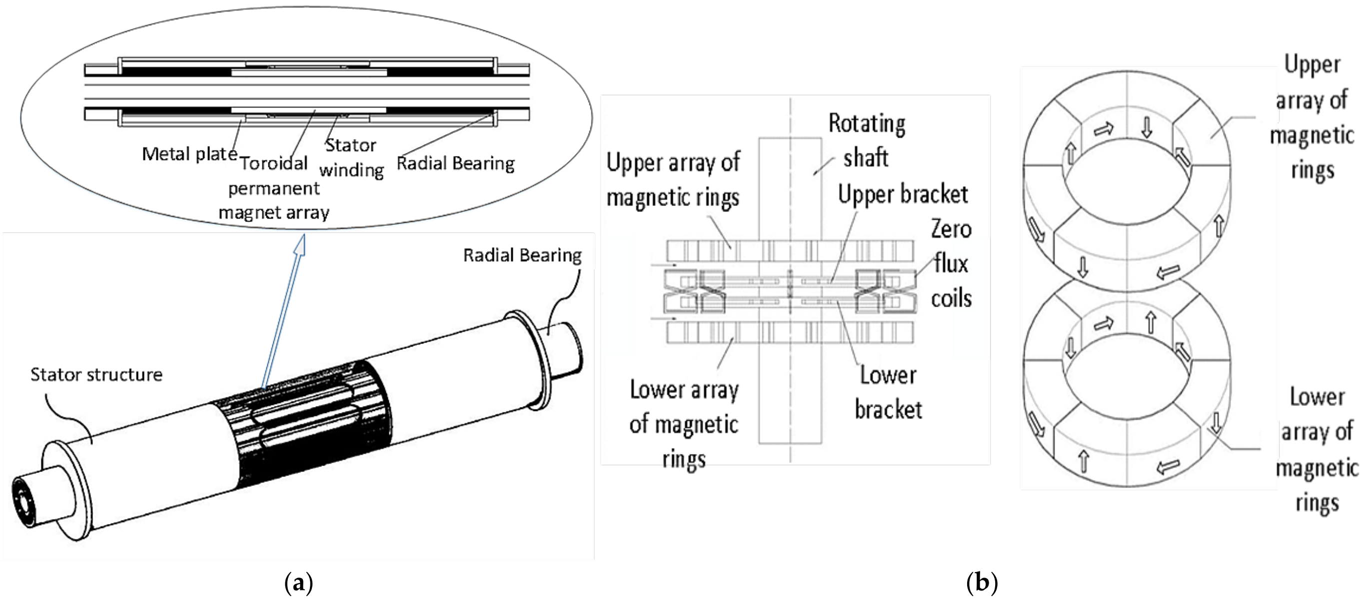


Figure 6. Structure type of magnetic bearing. (**a**) A hybrid magnetic bearing system; (**b**) A coil type axial permanent magnet electric magnetic bearing.

3. Recent Research on Dynamic Balance Technology

In the case of high-speed rotation and cutting, a small unevenness in the operation of the motorized spindle will produce a huge centrifugal force resulting in the vibration of the whole machine tool. Excessive vibration causes serious wear inside the spindle, increasing the dynamic load carried by the spindle, and the life and accuracy of the spindle are reduced. The dynamic characteristics of high-speed motorized spindles affect the machining quality and cutting ability. Therefore, the study on dynamic balancing characteristics of high-speed motorized spindles is a hot issue in the key technology of motorized spindles.

To achieve an accurate dynamic balancing of the post-installation motor rotor, the factors of force and self-excited vibration ability that cause dynamic balancing of the problems are considered. The designed components of a spindle are considered in terms of the effects of two different vibrations to ensure good running accuracy at high speed. The dynamic balancing method is the necessary condition and method for online dynamic balancing of high-speed motorized spindles. The primary method of dynamic balancing for rigid spindles is the influence coefficient method. The main methods of dynamic balancing for flexible spindles are the modal balancing method and no trial weight balancing method. Recent research works have been summarized in Table 4.

Table 4. Research work on the dynamic balance technology.

Reference	Brief Summary	Method	Objective
Zhang et al. [38]	Influence coefficient method for maximum total phase difference	Influence coefficient method	Provide the theoretical basis for the two-sided impact factor method
Chen et al. [39]	Online dynamic balancing method for low pressure rotors with least squares influence factor		The vibration amplitude of the rotor is reduced
Wang et al. [40]	Single plane influence coefficient method		The problems of misalignment and long equilibrium time during mass movement are solved
Zhang et al. [41]	Single plane influence coefficient method		The choice of counterweight position is proposed
Zhao et al. [42]	Dual-plane influence coefficient method		Verified that the dual-plane influence coefficient method is more effective in optimizing vibration measurement points
Zhang et al. [43]	Dual-plane influence coefficient method		The effect law of counterweight size with counterweight plane shift was found
Zhu et al. [44]	Single and dual-plane influence coefficient method		The multifaceted influence coefficient method applied to flexible rotors is derived
Khulief et al. [45]	Combined influence coefficient method and modal equilibrium method		Low-speed balancing problem of high-speed rotors is solved
Qu et al. [46]	Holographic spectrum theory	Modal equilibrium method	A new technique of holographic spectrum is introduced on the basis of the modal balance method
Liu et al. [47]	On-site holographic dynamic balancing method		Multiple sensor information is fused with flexible rotor balancing technology to improve rotor balancing accuracy
Chen et al. [48]	Modal dynamic balance method for flexible rotors		The reliability of the flexible rotor modal dynamic balancing method was verified
Liu et al. [49]	Dual-plane spindle balancing method based on the modalities of the spindle		The validity of dual-plane dynamic balancing method is proved
Zhong et al. [50]	Modal equilibrium theory		Avoid the blindness of choosing the frontal and balance speed

Table 4. *Cont.*

Reference	Brief Summary	Method	Objective
Sun et al. [51]	The dynamic balancing method without trial weight based on multi-factor coupled finite element dynamics model	No trial weight method	The unbalanced vibration of each stage of the spindle is suppressed
Bin et al. [52]	The least squares method solves the system of equilibrium vector equations to obtain the equilibrium counterweight		Complete dynamic balancing of the flexible spindle without trial weight is achieved
Jia et al. [53]	The dynamic balancing method without trial weight for high-speed flexible rotors		The problem of low balancing efficiency due to multiple test weights required for traditional dynamic balancing is solved
Zhang et al. [54]	Based on a multivariant finite element analysis model, the dynamic balancing method without trial weight is performed		The model can accurately describe the dynamic characteristics of the spindle
Xu et al. [55]	Dynamic balancing method without trial weight		The method is proven to reduce the unbalance of rotating shafts
Zhang et al. [56]	Genetic algorithm and particle swarm optimization are combined to identify multi-point unbalance of rotor		The reliability of neural network algorithms for online prediction of rotor's unevenness is proposed
Zhang et al. [57]	the dynamic balancing method without trial for modalities		Suppression of vibration caused by rotor unbalance

3.1. Influence Coefficient Method

The influence coefficient method of a rigid spindle includes the single plane influence coefficient method and double plane influence coefficient method. The difference is whether the ratio of spindle length to spindle diameter is greater than 1. If the spindle length is larger than the diameter, the double-plane influence coefficient method is suitable. When the spindle length is short, the single-plane influence coefficient method is favored.

The single plane influence coefficient method is a way used for dynamic balance calibration of rigid rotor shaft systems. The influence factor α represents the amplitude of vibration generated at the testing surface per unit weight, and the impact factor is expressed as

$$\alpha = B - A/Q \tag{1}$$

If the rotor is balanced, a counterweight is required on the calibration surface, as expressed by the following equation:

$$Q_0 = A/\alpha. \tag{2}$$

The authors of [38] proposed an influence coefficient method with the maximum total phase difference to select two ideal correction planes. When the dual correction planes are selected separately in the sensitive region, the overall amplitude of the correction vector is minimized. A scheme is provided for the subsequent study of the two-sided influence coefficient method. In [39], authors at Northwestern Polytechnic University, Fremont, CA, USA established a least-squares influence coefficient based field dynamic balancing method for low-pressure rotors for large culvert ratio turbofan engines. During a weight test, the amplitudes detected on the three pivot points of the rotor were reduced by 75%, 78.8% and 68%. When the influence coefficient is used again, the balance without trial weight can be carried out. The amplitudes at the three pivot points were reduced by 66.7%, 72% and 81%. The authors of [40] used the influence coefficient method for online dynamic balancing of the spindle to achieve amplitude reduction of the spindles at different rotational speeds. Compared with the experimental process of manual balancing, the feasibility and accuracy of the mass block movement path are higher. The authors solved the misalignment problems and long balancing time during the mass block movement. The authors of [41] used the single-plane influence coefficient method for an online dynamic balancing experimental study of the electromagnetic slip ring type. The oscillatory characteristics of the experimental platform and the influence of the spindle speed on the online dynamic balancing system were analyzed, and the selection method of the counterweight position was proposed. Theoretical support is provided for studying dual-plane dynamic balancing and modal analysis.

The idea of the dual-plane influence coefficient method is proposed based on the single-plane influence coefficient method. Two calibration planes (1, 2) and two detection planes (A1, A2) perpendicular to the spindle are established, as shown in Figure 7.

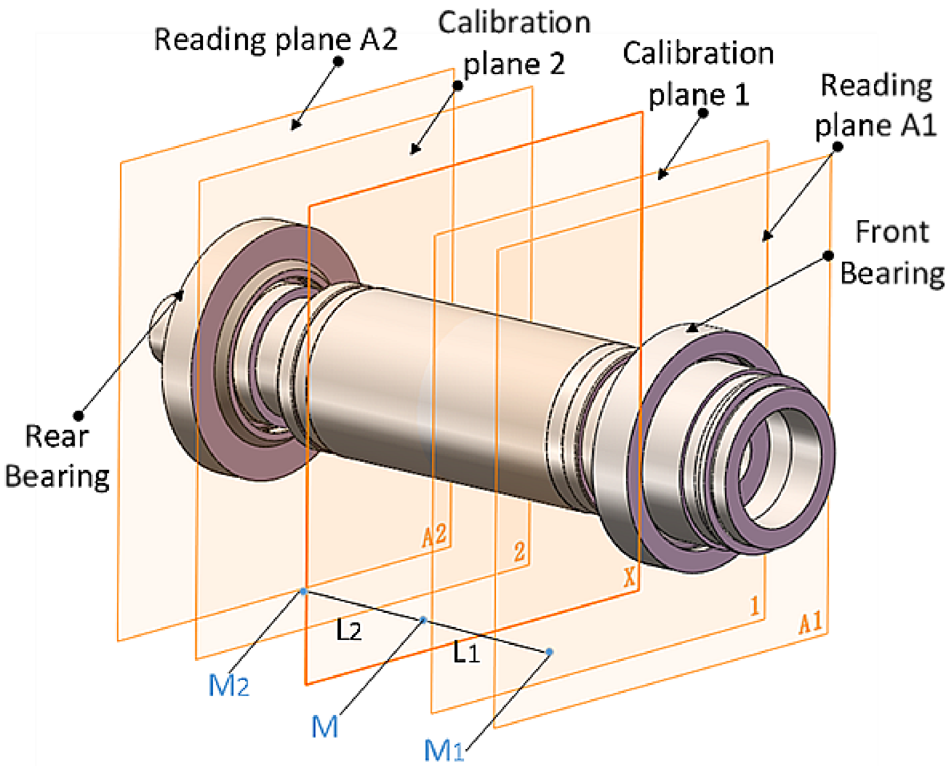


Figure 7. Theoretical diagram of two plane influence coefficient method.

The sensor records the values of the two measurement surfaces without counterweight as A_{10} and A_{20}. The additional weight is performed on calibration surface 1 to obtain the values of A_{11} and A_{21} on the two test surfaces. Then the counterweight on calibration surface 1 is removed and the additional weight is performed on calibration surface 2 to obtain the two values of A_{12} and A_{22} on the test surfaces. The resulting calibration surface 1 weighting on the A_1 and A_2 surfaces is α_{11} and α_{12}, as shown in the following equation. The formula is as follows:

$$\begin{cases} \alpha_{11} = A_{11} - A_{10}/Q_1 \\ \alpha_{12} = A_{12} - A_{20}/Q_1 \\ \alpha_{21} = A_{21} - A_{10}/Q_2 \\ \alpha_{22} = A_{22} - A_{20}/Q_2 \end{cases} . \tag{3}$$

Substituting the influence coefficients into the above equation, the required calibration masses Q_{10} and Q_{20} for calibration surface 1 and calibration surface 2 are

$$\begin{bmatrix} Q_{10} \\ Q_{20} \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \begin{bmatrix} A_{10} \\ A_{20} \end{bmatrix} \tag{4}$$

For the dynamic balancing problem of the dual-plane influence coefficient method, the authors of [42] analyzed that the single plane dynamic balancing method in reducing the vibration of one measurement point will lead to an increase in the oscillatory trend of the other measurement point. The effect of vibration was not eliminated. On this basis, the better effect of using the biplane influence coefficient method to optimize vibration measurement points was proposed. The authors of [43] studied the effect of counterweight size with counterweight plane transferring in the dual-plane influence coefficient method, the optimal configuration plane selection position was proposed, and the law of the additional weight was found. With the gradual study of the influence coefficient method by the aforementioned scholars, the authors of [44] studied the single plane influence coefficient method and the dual-plane influence coefficient method for rigid rotor dynamic balancing. The multi-plane influence coefficient method applied to flexible rotors was derived. The dual-plane influence coefficient method was focused on the calibration of rigid spindle dynamic balancing. The results showed that the dual-plane influence coefficient method achieved good results in the online dynamic balancing of spindles.

3.2. Modal Balancing Method

The modal balancing method is also called the vibration pattern balancing method. Based on the vibration principle of the rotating shaft, the vibration of the spindle at a certain speed is calculated, and the vibration mode is decomposed into the main vibration modes of each order. Then the main vibration modes are balanced to achieve the balance of the whole rotor system. Most scholars have made great progress in researching modal balancing methods to apply the modes to balance the spindle. Figure 8 shows the first three mode shapes of the spindle.

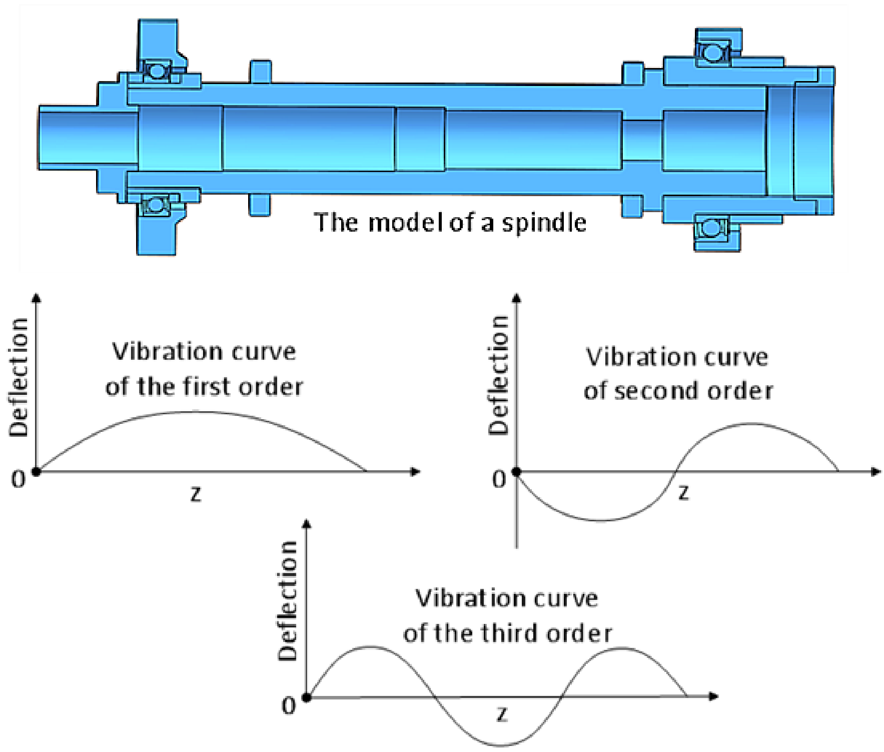


Figure 8. Modal vibration pattern of the first three orders of the spindle.

Foreign scholars have studied the modal balance method relatively early. Since 1953, Melatal first proposed the concept of the modal balance method and analyzed the characteristics of the critical speed corresponding to the main vibration patterns orthogonal to each order. In 1983, based on Melatal's research, Saito S. et al. developed a new imbalance response method for liquid film bearing-flexible rotors. The problem of choosing the calibration surface during modal balancing was solved, the position of the unbalanced mass was corrected, and the problem of gravitational sag was handled. Distinguishing from the previous single modal balancing method for solving vibration problems, the authors of [45] proposed a scheme incorporating influence coefficient and modal balancing techniques for solving the low-speed balancing of high-speed rotors. The applicability and reliability of the plan combined with the influence coefficient method and modal balance technique are verified by building a flexible rotor dynamic balancing experimental bench. With the continuous development of technology, researchers have introduced a new technique of holographic spectrum based on the modal balance method. The authors of [46] introduced the holographic spectrum technique based on the modal equilibrium method. The performance of the rotor balancing process on the holographic spectrum was analyzed, and the effect of rotor balancing was predicted by using the phase-shifted ellipse. Based on the holographic spectrum theory, the authors of Guangdong Power Grid Corporation Institute of Electric Power Science, Guangdong, China. [47] are the first to use a field holographic dynamic balancing method that integrates multiple sensor information with flexible rotor dynamic balancing technology. A genetic algorithm was used to optimize the data and improve the accuracy and efficiency of rotor balancing. In [48], the authors of Northwestern Polytechnic University, Fremont, CA, USA proposed a modal dynamic balancing method for a flexible rotor considering the influence of elastic support. The critical speed and the modal vibration pattern of the rotor were found by using the finite element model. The experimental results show that the relative error between the critical speed and the measured results is 0.36%, and the modal confidence of the first-order calculated and measured vibration patterns is 0.9906. The authors of [49] used a dual-plane spindle dynamic balancing method to reduce the amplitude of the spindle at 5000 r/min from 12 μm to 1.2 μm. The effectiveness of the dual-plane dynamic balancing method was demonstrated. The equilibrium speed is determined according to the modal balance theory, and the authors of [50] used the three-trial weight method for calculating the weight. The finite element method was established to model the rotor, and the correction plane was selected by sensitivity analysis. The results show that the residual vibration of the rotor is reduced and the blindness of the traditional balancing method for selecting the front side is avoided.

3.3. No Trial Weight Method

Dynamic balancing method without trial weight is a new method to obtain the amplitude and phase of spindle unbalance without adding counterweight to the spindle. The dynamic balancing method without trial weight is based on the traditional modal balancing method combined with finite element analysis. By considering the model shape of the spindle, critical speed and other factors, the amplitude and phase of the spindle unbalance are calculated. Figure 9 shows the dynamic balance flow of the mode without trial weight.

In [51], the authors used the finite element method to establish the dynamics model of the spindle with multi-factor coupling and proposed a dynamic balancing method without trial weight based on the finite element dynamics model of the high-speed motorized spindle. The spindle unbalance vibration of each order is suppressed. To reduce the number of test weights and save balancing time, the authors of [52] used the least squares method to obtain the required balancing of the additional weight for the shaft system by solving the system of balancing vector equations. The counterweight balancing test was performed on four planes of the shaft system, resulting in a reduction of up to 53% at a single point. The complete balancing of the flexible spindle system without test weights was achieved. In response to the problem of low balancing efficiency due to the need for multiple trial weight in conventional balancing, the authors of [53] proposed a high-speed flexible rotor modal balancing method without trial weight. After balancing without trial weight, the first-order amplitude of the spindle is reduced by 60.6% and the second-order amplitude is decreased by 74%. The balancing efficiency and the safety of balancing are improved. With the increase of factors affecting the dynamic balance of the high-speed electric spindle under consideration, the authors of [54] constructed a multi-variant finite element analysis model of a high-speed motorized spindle, and the bending vibration pattern and the amplitude-frequency response of the spindle were calculated. The results showed that the errors of the first three resonant frequencies calculated using the dynamics model and the experimental measurements were 0.16%, 4.38%, and 5.95%. The analysis model is capable of accurately describing the dynamic characteristics of the spindle. The authors of [55] designed a counterweight block conforming to the dynamic balancing scheme and established a bearing support model. The simulation was carried out using the dynamic balancing method without trial weight and the vibration acceleration during the actual counterweight was measured. The dynamic balancing scheme was verified by experiments. The results show that the dynamic balancing method without trial weight can reduce the unevenness during the rotation of a spindle. Artificial intelligence algorithms applied to the modal dynamic balancing method without trial weight had a positive effect. The authors of [56] used a combination of genetic algorithm and particle swarm optimization to achieve accurate identification of the multi-point unbalance of rotors. The results show that the integrated genetic algorithm and particle swarm optimization are effective in predicting the rotor unbalance online and guiding the dynamic balancing method without trial weight. The cost of on-site balancing is reduced and the balancing efficiency is improved. To suppress the vibration caused by the unbalance of the rotor, the authors of [57] based their study on the modal trial-weightless dynamic balancing method. By collecting the vibration data below the critical speed, simulation analysis and experiments show that the vibration caused by unbalancing is suppressed. The smooth and safe operation of the rotor at high speed is ensured.

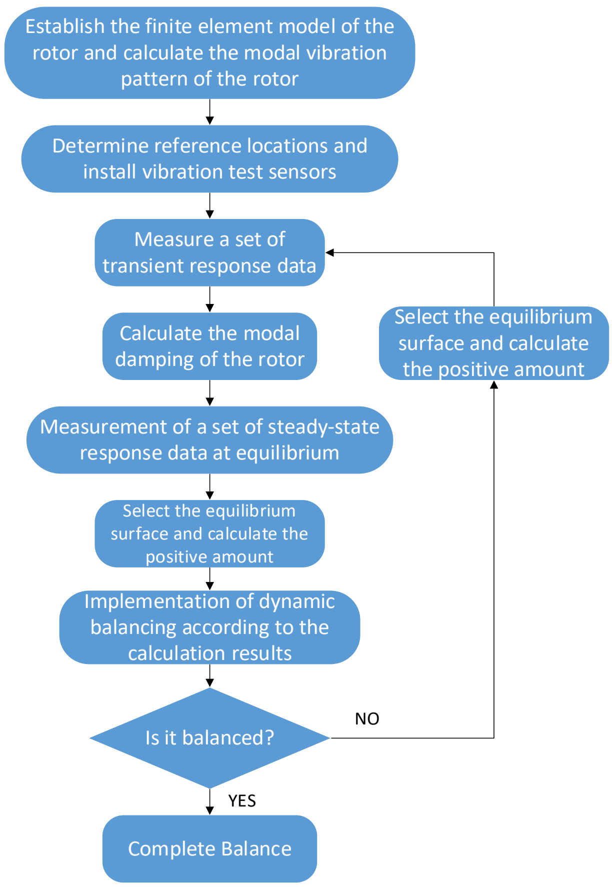


Figure 9. Flow chart of the modal dynamic balancing method without trial weight.

4. Research Progress of Thermal Error Measurement and Compensation Technology

4.1. Temperature Measurement Point Optimization Technology

Temperature measurement point optimization is one of the primary research directions in the field of thermal error compensation for machine tools. Regarding the optimization of temperature measurement points of the spindle, extensive research has been conducted by a wide range of scholars. The methods used mainly include the stepwise regression method, fuzzy clustering method and gray system theory.

The stepwise regression method is the preferred method to study multivariate modeling, but in some cases, the calculation takes a long time when the variables are large. In addition, the stepwise regression method only considers the correlation between the thermal error and each temperature, which leads to coupling between temperature variables in thermal error modeling and reduces the model accuracy. Therefore, the stepwise regression method is used for thermal error models with a small number of independent variables. In [58], the authors proposed an improved binary grasshopper optimization algorithm (IBGOA) combined with a stepwise regression method for temperature-sensitive point screening. Compared with the traditional fuzzy C clustering (FCM), the predictive error was reduced to about 30% on average.

The fuzzy clustering method aggregates temperature measurement points into multiple categories, and one temperature point from each category is selected for calculating thermal error. After the variables are classified and then grouped, the most relevant variables are selected as the basic variables of the category. The more representative temperature variables are selected from the basic variables and applied to modeling. The fuzzy clustering method avoids the coupling between variables and improves the efficiency of finding the optimal temperature measurement point. However, gray system theory is suitable for a small sample size. Scholars tend to integrate the fuzzy clustering method with the gray theory to filter the optimized temperature variables. In [59], the authors used gray system theory to optimize the temperature variables in the thermal error model from 16 to four. The robustness of the model and the prediction accuracy was improved. The authors of [60] used fuzzy C-mean clustering and correlation analysis to optimize the temperature variables from 24 to 5. In [61], the authors used a k-means clustering algorithm to cluster and filter the temperature measurement points at different locations. The relationship between temperature and thermal error of the spindle was analyzed by Pearson correlation coefficient calculation, and the number of temperature measurement points was reduced from 8 to 2. The optimal combination of measurement points was selected and applied to the thermal error modeling. The authors of [62] proposed a method for optimization of temperature measurement points based on a combination of fuzzy clustering and gray theory. The 64 temperature variables were divided into 10 for clustering, and the screened three temperature variables were used in the thermal error prediction model.

Research work on the optimization of temperature measurement points is also summarized in Table 5.

Table 5. Research work on the optimization of temperature measurement points.

Reference	Method	Type
Sun et al. [58]	Improved Binary Locust Optimization Algorithm and Stepwise Regression Method	Stepwise Regression Method
Yan et al. [59]	Gray System Theory	Gray System Theory Method
Shen et al. [60]	Fuzzy C-means clustering and correlation analysis method	Fuzzy clustering method
Zhou et al. [61]	K-means clustering algorithm	Fuzzy clustering method
Zhang et al. [62]	Fuzzy clustering combined with gray theory	Fuzzy clustering method

Therefore, too much temperature measurement point selection will bring too much measurement error, and too little temperature measurement point selection will result in incomplete information contained in the temperature data. So a scientific temperature measurement point optimization strategy is crucial. By using intelligent algorithms to filter multiple temperature measurement points, effective temperature measurement points are obtained, and in the process of modeling thermal errors in a high-speed motorized spindle, effective temperature variables are helpful to improve the accuracy and generalization ability of prediction models for thermal error compensation.

4.2. Thermal Error Compensation Modeling Technology

The thermal error prediction model of the high-speed motorized spindle is the core of the thermal error compensation system. Using temperature data to predict the change of thermal displacement, the establishment of the thermal error prediction model affects the accuracy and generalization ability of the thermal error compensation system. In the study of thermal error modeling of high-speed motorized spindles, researchers have widely used the multiple regression method, gray theory and neural network method. In this section, the research results related to thermal error modeling are presented and summarized in Table 6.

Table 6. Research work on thermal error prediction models.

Reference	Brief Summary	Method	Effect of Prediction Accuracy
Xue et al. [63]	Partial least squares regression method	Multiple linear regression method	Average
Miao et al. [64]	Unbiased estimation splitting method	Multiple linear regression method	Good
Zhou et al. [65]	Classical multiple linear regression method	Multiple linear regression method	Fair
Jiang et al. [66]	Standard grey system model	Multiple linear regression method	Average
Zhang et al. [67]	Serial Grey neural network and parallel grey neural network	Grey theory	Good
Wang et al. [68]	Comparison of grey prediction model and BP neural network prediction model	-	-
Ma et al. [69]	Particle swarm optimization optimized BP model	Neural network	Good
Xie et al. [70]	Thinking evolutionary algorithm optimized BP model	Neural network	Good
Wu et al. [71]	Simulated annealing algorithm coupled with particle swarm algorithm to optimize BP model	Neural network	Good
Sun et al. [72]	Bat algorithm optimized BP model	Neural network	Excellent
Lv et al. [73]	Generalized radial basis function neural network prediction model	Neural network	Good
Zhang et al. [74]	Optimization of radial basis function neural network model by genetic algorithm	Neural network	Excellent

The multiple regression method is more predictive in thermal error modeling. The authors of [63] established a multiple linear regression model based on the partial least squares regression method and analyzed the relationship between the data of each temperature measurement point and the thermal error. The results showed that the model value was 103.4072 and the coefficient of determination was 0.9858. The model had a strong predictive ability, but there was a defect of inaccurate prediction accuracy. The unbiased estimation algorithm for multiple linear regression appears to distort the parameter estimates of the model when dealing with thermal error modeling with multiple covariance. Therefore, the authors of [64] proposed an unbiased estimation splitting algorithm for dealing with covariance data. The algorithm divides the modeling process into multiple steps to complete, and each step only regresses one independent variable. The comparison results show that the predictive accuracy and robustness of the unbiased estimation splitting model are better than the classical multiple linear regression model. Based on the multiple linear regression method, the authors of [65] established a cooling prediction model for motorized spindles by considering the factors of flow rate and the temperature of cooling water. The accuracy of the model was verified by three test methods, including a judgment coefficient test, a significance test of the regression coefficient, a significance test of the regression equation, and residual analysis. The influence of motorized spindle heat on machining performance is reduced, and the purpose of thermal error compensation is achieved.

Gray theory was earlier applied to thermal error prediction models. Based on a genetic algorithm to search for the optimal dimension n and weight value λ, the authors of [66] proposed an optimal thermal error modeling strategy based on the standard gray model (GM [1,1]). This prediction model reduces the original error by 80%. In [67], the authors combined gray models with artificial neural networks to build serial gray neural networks (SGNN) and parallel gray neural networks (PGNN) to predict thermal errors. The results showed that the gray neural network methods improved the robustness and predictive accuracy compared with the traditional gray theoretical model and artificial neural network. However, the gray theory suffers from a lack of predictive accuracy compared to artificial neural networks. The authors of [68] compared the GM (1, n) gray prediction model and the BP neural network prediction model. The results showed that the average relative error between the predictive results of the BP neural network model and the measured results was 5.19%, which was smaller than the average relative error between the predictive results of the gray prediction model and the measured results. Therefore, the artificial neural network prediction model is more effective in improving the accuracy of spindle thermal error prediction. In [69], the authors proposed a new criterion of the particle swarm optimization (PSO) to improve the generalization ability of the model by optimizing the parameters of the BP model with particle swarm optimization. By establishing the thermal error PSO-BP model of the spindle, the convergence and convergence speed of the original model were improved, and the predictive accuracy of the prediction model was improved. To reduce the thermal errors generated during spindle operation, the authors of [70] analyze the shortcomings of the simulated annealing algorithm (SAA) and the particle swarm optimization (PSO). The BP neural network prediction model was optimized by coupling the SAA model to the PSO model, and the accuracy of the prediction model was experimentally verified. The results show that the coupled model reduces the maximum error value generated in the y-axis direction from 7.3 μm to 2.3 μm and the maximum error value in the z-axis direction from 7.5 μm to 2.6 μm compared to the BP neural network model. The authors of [71] used the Bat Algorithm (BA) to optimize the initial values of the wavelet neural network (WNN). The initial connection weights, scale factor, and translation factor parameters are introduced. A thermal error prediction model of the spindle was developed and compared with the WNN prediction model and BP neural network prediction model. The results showed that the maximum residuals were reduced by 25.8% and 34.8%. Due to the shortcomings of BP neural networks in training time and prediction accuracy, the radial basis function neural network (RBFNN) has become a new research hotspot in the field of modeling motorized spindles. To address the problems of low efficiency of thermal error modeling and unsatisfactory prediction accuracy of the model, the authors of [71] proposed a generalized radial basis function neural network (RBF) modeling method and applied the model to the thermal error modeling of CNC machine tools. The results show that the generalized RBF neural network model of thermal error has the advantages of high prediction accuracy and strong generalization ability. Compared with the traditional RBF neural network modeling method, the generalized

RBF neural network modeling method has higher modeling efficiency and better model robustness and predictive performance. The generalized RBF neural network model for thermal errors is an effective modeling method for real-time compensation of thermal errors in CNC machine tools. The authors from Huazhong University of Science and Technology, Wuhan, China [72] established a genetic algorithm radial basis function neural network prediction model (GA-RBFNN). Compared with the traditional RBFNN model and the least-squares multiple linear regression prediction model, the residual range is controlled at [1.94, −1.76] μm. The GA-RBFNN prediction model has higher prediction accuracy.

All of the above methods are data-driven models, also known as black box models. Although the accuracy of thermal error prediction models is improved, data-driven modeling has inherent drawbacks. A model with good predictive performance can be built only when enough input and output data are available. When the acquired data are not comprehensive enough, the model built is difficult to adapt to various situations, resulting in poor robustness. In addition, by obtaining enough input and output data will increase the experimental difficulty in identifying the parameters of the thermal characteristics of the machine tools. Even if a data-driven model is established, the exact relationship between the input and output variables is not known.

5. Development Trend of High-Speed Motorized Spindle Technology

With the rapid development of high-speed cutting, CNC technology and the needs of practical applications, the performance of the high-speed motorized spindle of CNC machine tools has put forward higher and higher requirements. Based on the analysis of the key technologies of the high-speed motorized spindle, the research direction of high-speed motorized spindle unit technology is summarized. The main aspects are as follows.

(1) The development of high precision, high reliability and long life of CNC machine tools is the goal. At present, the precision and reliability of the use of CNC machine tools need to meet higher requirements. As one of the core functional components of CNC machine tools, the high-speed motorized spindle requires higher precision and reliability.
(2) With the improvement of the bearing technology as the goal, the problems of high cost, large structures and difficult to control of magnetic bearings need to be solved. Research and development of high speed and high power shaftless high-speed motorized spindles with magnetic bearings as support must be undertaken.
(3) To improve the running accuracy of the motorized spindle, the research on the generalization of dynamic balancing technology, using a dynamic balancing method that capable to balance the rigid spindle and flexible spindle at the same time, which would help to reduce the impact of vibration on the high-speed motorized spindle, must be accelerated.
(4) To reduce the influence of heat generation and thermal error of the spindle, and improve the accuracy of the spindle, research on the application of computer simulation technology in the design of high-speed motorized spindles must be strengthened, and the development of highly reliable modeling methods to realize the compensation of errors must be achieved.

6. Conclusions

With the generalization of the research and application of high-speed motorized spindles, high-speed and high-precision cutting processing has been pushed to a new height. The high-speed motorized spindle incorporates high-speed precision bearing technology, dynamic balancing technology, thermal error measurement and compensation technology, etc. This article briefly describes the four structural types of high-speed precision bearings and the influence of the thermal and dynamic characteristics of the bearings on the performance of high-speed motorized spindles. The basic principle and process of achieving dynamic balancing technology are outlined, and the dynamic balancing methods adopted at this stage for rigid and flexible spindles are discussed. The temperature measurement point optimization method and thermal error compensation modeling method applied to high-speed motorized spindles of CNC machine tools are outlined. Finally, the future research directions of CNC machine tools, bearing technology, dynamic balancing methods, and thermal error modeling methods are foreseen. The field of high-speed motorized spindles has great potential to develop and replace traditional machining machines, so all aspects of the technology require further in-depth research.

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