High-Speed Motorized Spindles of CNC Machine Tools

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Contributor: Ye Dai

High-speed motorized spindles tend to develop in the direction of high precision, high speed, low energy consumption, high efficiency, and high reliability.

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

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.

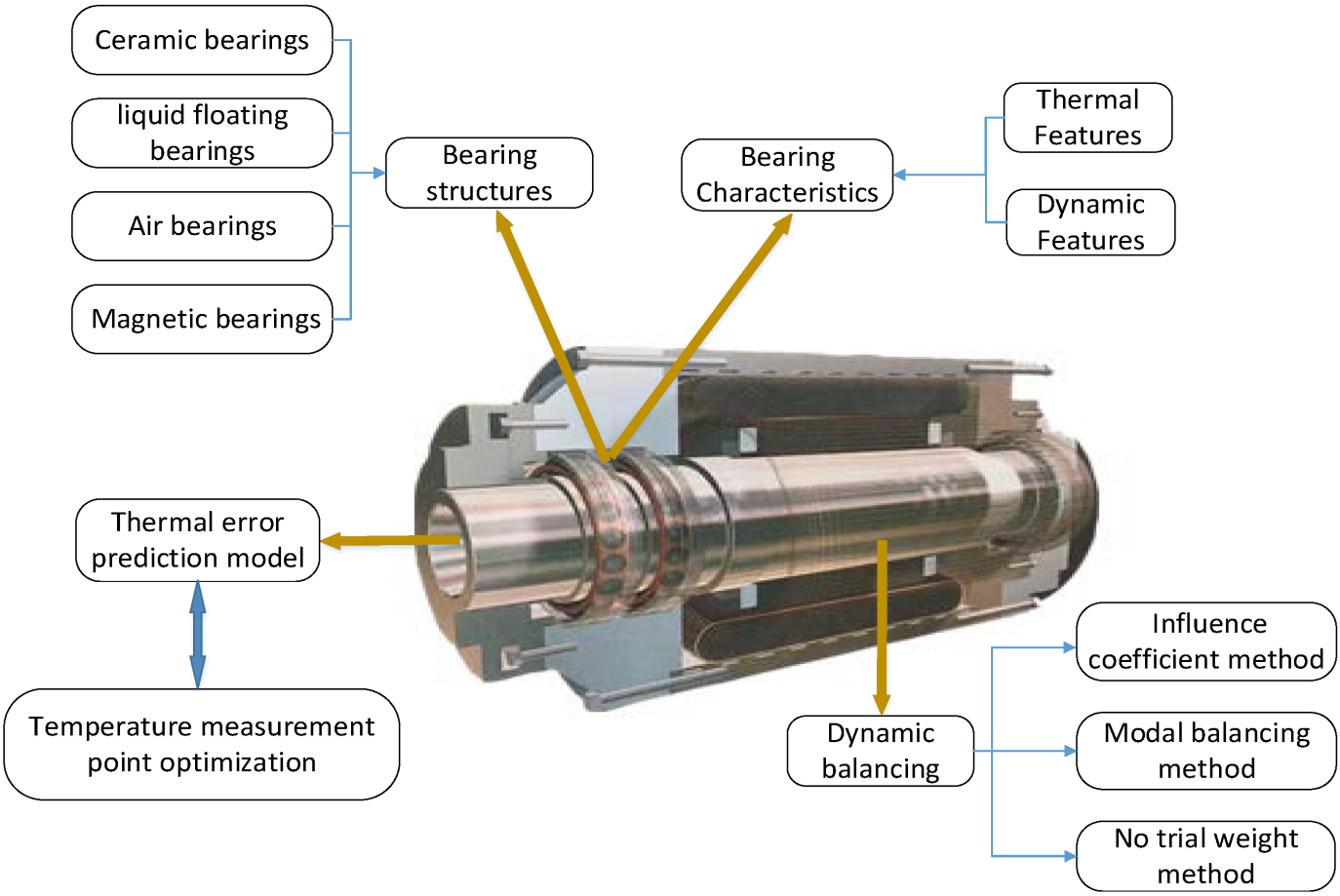

Figure 1. Analysis diagram of high-speed electric spindle technology.

2. 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 [4]. In addition, after extensive literature research, surveys are presented in this section and summarized in **Table 1**.

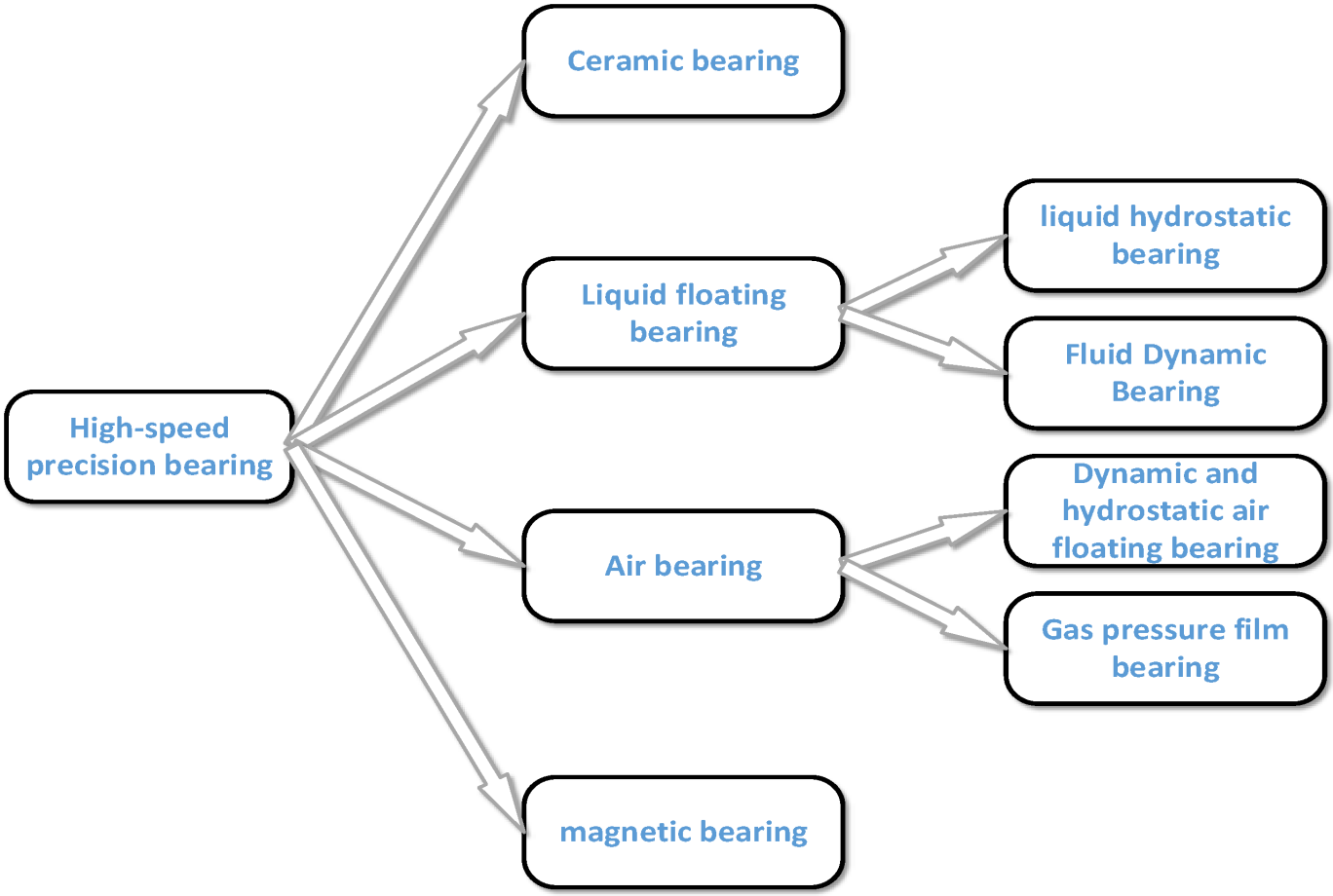

Figure 2. High-speed precision bearings classification.

Table 1. Research work on bearing structures.

参考	小结	轴承类型	目的
Wu et al. [5]	Grease lubricated ceramic bearing	Ceramic bearing	Avoid the noise caused by fracture or slipping of the inner ring of the bearing
Liu et al. [6]	New Dynamic pressure gas radial ceramic bearing	Ceramic bearing	High stability of high-speed rotating spindle
Jiang et al. [7]	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. [8]	Hydrostatic floating bearing of through-hole type	Liquid floating bearing	Simple structure,easy to achieve the purpose of spindle at high speed
Ko et al. [9]	Hydrostatic bearing monitoring system and monitoring method	Liquid floating bearing	Real-time monitoring of hydrostatic bearing performance and fault warning

参考	小结	轴承类型	目的
Yu et al. [10]	Ultra-precise air bearing with active compound throttling type	Air bearing	Suppress micro-amplitude vibration of air-bearing, improve dynamic stiffness
Yin et al. [11]	Air bearing with replaceable throttle plug	Air bearing	Effectively avoid the phenomenon of "air hammer" in bearing
Keun et al. [12]	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. [13]	Hybrid magnetic bearing structure	Magnetic bearing	Effective simplification of magnetic floating bearing structure,saving cost
Zhang et al. [14]	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. [15]	Coil type axial permanent magnet electric magnetic bearing	Magnetic bearing	Realize axial bidirectional self-stabilization, less resistance and lower energy consumption

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 3**.

Table 3. Research work on the dynamic balance technology.

Reference	Brief Summary	Method	Objective
Zhang et al. [16]	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. [17]	Online dynamic balancing method for low pressure rotors with least squares influence factor		The vibration amplitude of the rotor is reduced

Reference	Brief Summary	Method	Objective
Wang et al. [18]	Single plane influence coefficient method	Modal equilibrium method	The problems of misalignment and long equilibrium time during mass movement are solved
Zhang et al. [19]	Single plane influence coefficient method		The choice of counterweight position is proposed
Zhao et al. [20]	Dual-plane influence coefficient method		Verified that the dual-plane influence coefficient method is more effective in optimizing vibration measurement points
Zhang et al. [21]	Dual-plane influence coefficient method		The effect law of counterweight size with counterweight plane shift was found
Zhu et al. [22]	Single and dual-plane influence coefficient method		The multifaceted influence coefficient method applied to flexible rotors is derived
Khulief et al. [23]	Combined influence coefficient method and modal equilibrium method		Low-speed balancing problem of high-speed rotors is solved
Qu et al. [24]	Holographic spectrum theory		A new technique of holographic spectrum is introduced on the basis of the modal balance method
Liu et al. [25]	On-site holographic dynamic balancing method		Multiple sensor information is fused with flexible rotor balancing technology to improve rotor balancing accuracy
Chen et al. [26]	Modal dynamic balance method for flexible rotors		The reliability of the flexible rotor modal dynamic balancing method was verified
Liu et al. [27]	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. [28]	Modal equilibrium theory		Avoid the blindness of choosing the frontal and balance speed
Sun et al. [29]	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

Reference	Brief Summary	Method	Objective
Bin et al. [30]	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. [31]	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. [32]	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. [33]	Dynamic balancing method without trial weight		The method is proven to reduce the unbalance of rotating shafts
Zhang et al. [34]	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. [35]	The dynamic balancing method without trial for modalities		Suppression of vibration caused by rotor unbalance

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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 4**.

Table 4. Research work on thermal error prediction models.

参考	Brief Summary	Method	Effect of Prediction Accuracy
Xue et al. [36]	Partial least squares regression method	Multiple linear regression method	Average
Miao et al. [37]	Unbiased estimation splitting method	Multiple linear regression method	Good
Zhou et al. [38]	Classical multiple linear regression method	Multiple linear regression method	Fair
Jiang et al. [39]	Standard grey system model	Multiple linear regression method	Average
Zhang et al. [40]	Serial grey neural network and parallel grey neural network	Grey theory	Good
Wang et al. [41]	Comparison of grey prediction model and BP neural network prediction model	-	-

参考	Brief Summary	Method	Effect of Prediction Accuracy
Ma et al. [42]	Particle swarm optimization optimized BP model	Neural network	Good
Xie et al. [43]	Thinking evolutionary algorithm optimized BP model	Neural network	Good
Wu et al. [44]	Simulated annealing algorithm coupled with particle swarm algorithm to optimize BP model	Neural network	Good
Sun et al. [45]	Bat algorithm optimized BP model	Neural network	Excellent
Lv et al. [46]	Generalized radial basis function neural	Neural network	Good

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.

References

1. Zhang, L.X.; Li, C.Q.; Li, J.P.; Zhang, K.; Wu, Y.H. The temperature prediction mode of high speed and high precision motorized spindle. J. Mech. Eng. 2017, 53, 129–136.

2. Jiang, S.Y.; Zhang, S.W. Progress in the key technologies of high speed motorized spindle supported by water-lubricated bearings. Mach. Des. Manuf. Eng. 2016, 45, 11–17.
3. Xiong, W.L.; Sun, W.B.; Liu, K.; Xu, M.H.; Pei, T. Active magnetic bearing technology development in high-speed motorized spindles. J. Mech. Eng. 2021, 57, 1–17.
4. Peng, X.L.; Li, Z. Review of spindle motor technology. Electron. Meas. Technol. 2020, 43, 1–7.
5. Wu, Y.H.; Xia, Z.X.; Li, S.H.; Chen, S.Z.; Sun, J.; Wang, H.; Tain, J.X.; Wang, Y.H. A Kind of Grease Lubricated Ceramic Bearing with a Piezoelectric Ceramic Inner Ring. China Patent 2019. under review.
6. Liu, X.L.; Xia, Z.X. A Kind of Dynamic Pressure Gas Radial Ceramic Bearing. China Patent 2018. in press.
7. Jiang, S.Y.; Xu, W.Z. A Kind of Hydrostatic Water Bearing with Slotted Water Chamber Against Unequal Area Water Chamber. China Patent, 2019, under review.
8. Zhang, F.Q. A Kind of Hydrostatic Liquid Floating Bearing. China Patent 2018. in press.
9. KO, P.H.; Chan, C.M.; Chan, S.T.; Xu, W.Z. Hydrostatic Bearing Monitoring System and Method. U.S. Patent 2017. under review.
10. Yu, P.L.; Kong, J.Y.; Yang, J.T. An Active Air Float Bearing With Variable Air Film Shape. China Patent 2020. under review.
11. Yin, Z.Q.; Zhuang, Z.W. A Kind of Air Floating Bearing. China Patent 2021. in press.
12. Ryu, K.H. Air Bearing and Rotor System. U.S. Patent 2020. in press.
13. Chen, H.X.; Mao, K.; Han, S.C.; Wu, Z.X.; Zhou, D.S.; Lv, M.D.; Zhang, Z.H.; Gong, J.; Hu, D.Y.; Li, P.; et al. A Hybrid Magnetic Levitation Bearing System. China Patent 2020. in press.
14. Zhang, F.H.; Hu, Y.S.; Zhang, X.B.; Xu, W.Z. Protective Structure for Magnetic Bearing and Magnetic Bearing Assembly. U.S. Patent 2020. in press.
15. Chen, Y.; Deng, Y.C.; Tang, W.; Li, L.W.; Miu, X.Y.; Li, Q.; Wang, M. A Coil Type Axial Permanent Magnet Electric Magnetic Floating Bearing. China Patent 2017. in press.
16. Zhang, S.H.; Zhang, Z.M. A method to select correcting faces of a double-face dynamic balancing rotor. Adv. Mech. Eng. 2016, 8, 1687814016682892.
17. Chen, X.; Liao, M.F.; Zhang, X.M.; Wang, S.J. Field balancing technology for low pressure rotors of high bypass ratio turbofan engines. J. Nanjing Univ. Aeronaut. Astronaut. 2017, 32, 808–819.
18. Wang, Z.; Tu, W.; Li, J.; Liu, M.H.; Zhu, F.L. High Speed Spindle Online Dynamic Balancing Control Strategy and Experimental Research. Mach. Tool Hydraul. 2019, 47, 61–66.

19. Zhang, K.; Zhang, C.Y.; Zhang, L.X.; Wu, Y.H. Performance Analysis and experiment of electromagnetic ring balancer during operation. J. Vib. Meas. Diagn. 2018, 38, 34–38.
20. Zhao, W.Z.; Chen, J.; Zhou, R.M.; Gu, W.F.; Hua, M. Application of double-side dynamic balance method in a two-stage adjustable vane axial flow fan. Power Equip. 2018, 32, 434–436.
21. Zhang, Z.C.; He, L.D.; Wan, F.T.; Li, Z.W.; Chen, Z. Law of weights transfer based on double-sided dynamic balance. J. Mech. Electr. Eng. 2019, 36, 712–716.
22. Zhu, Y.T.; Yao, Y.G.; Huang, K.; Li, D.Y.; Zhang, H.T.; Zhai, D.Y. The study of influence coefficient method and its application in the dynamic balancing for high-speed spindle. Mech. Electr. Eng. Technol. 2021, 50, 228–235.
23. Khulief, Y.A.; Oke, W.; Mohiuddin, M.A. Modally Tuned Influence Coefficients for Low-Speed Balancing of Flexible Rotors. J. Vib. Acoustics. 2014, 136, 024501: 1–024501: 5.
24. Qu, L.S.; Zhang, X.N.; Wu, S.T.; Qiu, H.; Xu, B.G. Flexible rotor holographic field dynamic balancing technology and application. J. Manuf. Sci. Eng. 2005, 12, 75.
25. Liu, S.; Qu, L.S. A study of methods for an on-site shafting dynamic balance based on a holographic spectrum technology. J. Eng. Therm. Energy Power 2009, 24, 24–30.
26. Chen, X.; Liao, M.F.; Liu, Z.C.; Li, Y. Model balancing method for flexible rotors with elastic supports. J. Nanjing Univ. Aeronaut. Astronaut. 2016, 48, 402–409.
27. Liu, C.; Liu, G. Field dynamic balancing for rigid rotor-AMB System in a magnetically suspended flywheel. IEEE/ASME Trans. Mechatron. 2016, 21, 1140–1150.
28. Luo, Z.; Wei, Y.H.; Hou, X.J.; Wang, F. Dynamical Balance and Verification of a Rotor System Based on Sensitivity Analysis. J. Vib. Test. Syst. Dyn. 2018, 3, 271–280.
29. Sun, H. Analysis of Imbalance Vibration Behavior of High Speed Spindle and Research of its Suppression Method. Master’s Thesis, Xidian University, Xi’an, China, 2015.
30. Bin, G.F.; He, L.D.; Gao, J.J.; Li, L.B. High-speed dynamic balancing method for low pressure rotor of a large steam turbine based on modal shape analysis. J. Vib. Shock 2013, 32, 87–92.
31. Jia, S.X.; Zheng, L.X.; Deng, W.Q.; Mei, Q. Development of modal balancing system without trail weights for high speed flexible rotors. J. Vib. Shock 2018, 38, 1108–1113.
32. Zhang, Y.; Sun, H.; Hu, Z.B. Behavior analysis and suppression strategy for unbalanced vibration in high-speed spindle. J. Xi’an Jiaotong Univ. 2019, 53, 24–29.
33. Xu, Y.; Yi, J.; Deng, H.; Zhou, F.; Han, Z.J.; Zeng, M.H. Dynamic balance method without trial weights for a folding shaft based on the reverse structural designing. J. Vib. Shock 2019, 38, 263–270.

34. Zhang, R.X.; Wen, G.R.; Zhang, Z.F.; Xu, B. Multi-unbalances identification of rotor system integrated with GA-PSO method. J. Vib. Meas. Diagn. 2019, 39, 801–809.
35. Zhang, Y.; Li, M.; Yao, H.Z.; Gou, Y.J.; Wang, X.Y. A modal-based balancing method for a high-speed rotor without trial weights. Mech. Sci. 2021, 12, 85–96.