The International Journal of Advanced Manufacturing Technology (2018) 98:2737–2745
https://doi.org/10.1007/s00170-018-2444-5

ORIGINAL ARTICLE

A frequency domain dynamic response approach to optimize the dynamic performance of grinding machine spindles

Miaoxian Guo[1] · **Xiaohui Jiang**[1] · **Zishan Ding**[1] · **Zhouping Wu**[2]

Received: 25 January 2018 / Accepted: 16 July 2018 / Published online: 24 July 2018

Abstract

The dynamic performance of the grinding machine spindle determines its ultimate vibration resistance and the machining accuracy. To gain better dynamic performance of the grinding machine spindle system, the integrated evaluation and optimization method should take both manufacturing process and machine tool into account. In this paper, a frequency domain dynamic response approach is proposed to study the optimization. This approach considers the dynamic grinding force from the view of spindle imbalance and frequency response function (FRF) by means of modal frequency and dynamic stiffness. The dynamic grinding force is analyzed experimentally to verify the vibration excitation force in process. Furthermore, the optimization process by finite element method is conducted with the intermediate dynamic parameter improvement by structural optimum design. Applying on a high-speed machine tool, the case studies are illustrated to demonstrate the implementation of the proposed method; the dynamic response optimization approach results shows, to achieve the vibration response in grinding process, it is necessary and priority to improve the dynamic stiffness of the spindle.

Keywords Dynamic response · Optimization · Dynamic performance · Grinding machine spindles

1 Introduction

With recent developments in manufacturing industries to satisfy the accuracy and surface finish requirements, there is a growing demand for dynamic performance of the grinding machine tools. In modern application, the overwhelming majority of machine tools are equipped with motorized spindles, which contributes heavily to productivity, precision and quality of the machined products [1, 2]. The researchers have focused on motorized spindle units for high-speed and high-performance cutting. Numerous works have been carried out and to study the dynamic performance of spindle units by testing, modeling, analysis, and optimization. The aim of modeling and analysis of spindle units is to simulate the performance of the spindle and optimize its dimensions during the design stage in order to achieve the high dynamic performance.

In field of dynamic performance modeling and analysis of grinding machine tool, the unfavorable phenomenon of chatter vibration is one of the most critical errors in grinding and should be detected and avoided in advance [3, 4]. In the process of designing, machine tool virtual models are required to predict the dynamic behavior and to optimize the machine tool performance. For this purpose, the different influencing factors of mass, stiffness, and damping properties as well as friction forces, feed drive controls, and movements have to be considered in the simulation [5]. Zaeh et al. developed a new method for simulation of machining performance by integrating finite element and multi-body simulation for machine tools, in which the spindle is critical [6]. Lin et al. present an integrated model with experimental validation and sensitivity analysis for studying various thermo-mechanical-dynamic spindle behaviors at high speeds; the results show it is useful for differentiating quantitatively different effects on the spindle behaviors [7]. Wu et al. developed a thermodynamics coupled model of high-speed motorized spindle system, and studied the effect of parameters of the spindle system on the dynamic behavior of the grinding machine [8]. The works achieve the critical factors that influence the dynamic performance of machine, especially for the grinding spindles.

✉ Miaoxian Guo
miaoxian.guo@live.com

[1] College of Mechanical Engineering, University of Shanghai for Science and Technology, No.516 Jungong Road, Yangpu, Shanghai 200093, China

[2] Shanghai Aerospace Equipment Manufacturing Company Limited, Shanghai 200245, China

Furthermore, the final step is to optimize the dynamic performance in application situation by means of process analysis, structural dimensions re-setup, and material design. Fredin et al. present the strategy to solve several optimization algorithms and continuously updating bounds and constraints, together with post processing of the results. The holistic methodology can predict and optimize a complete machine tool's properties, exploring the potential of a full optimization study [9]. Wu et al. proposes a modified two-level optimization approach for the concept design of a machine tool. The principal dimensions of all the structural parts can be determined, minimizing the weight of the machine while maintaining sufficient stiffness [10].

Altintas and Cao presented general finite element method to predict the static and dynamic behavior of spindle systems, and further developed an optimization method to achieve dynamic stiffness by tuning of the spindle modes through optimizing the locations of bearings and the motor for motorized spindles [11]. Li et al. developed a Kriging approximation model coupled with finite element method to substitute the dynamic equations for obtaining the position-dependent natural frequencies of a machine tool, as well as relative positions between the tool and the workpiece during the machining process, and further optimization design the dynamic performance of the machine tool [12]. Huo et al. proposed a holistic integrated dynamic design and modeling approach, which supports analysis and optimization of the overall machine dynamic performance at the early design stage; it can cover the dynamics of the machine structure, moving components, control system, and the cutting process and provides the comprehensive analysis on the performance of the entire machine [13].

Aiming to increase the performance of state-of-the-art HSC- and HPC-machine tools, Neugebauer et al. optimized the mechatronic dynamic behavior by lightweight design, and a manipulation of the stiffness/weight ratio of the machine tool structure [14]. Aggogeri's study investigated the optimization application of metal foams impregnated by phase change materials (PCM) in MT component realization, by their high light and stiffness performances, and showed a complete study and thermal testing validation on a set of prototypes [15]. Xu et al. designed a hybrid headstock to improve the damping capacity by adhesively bonding a damping layer and constraining layer to the surface of the cast headstock [16].

The proposed model and method can be used to improve the design of machine tool and its spindles for targeted machining applications. However, the previous mainly consider some single indicators such as quality and stiffness as the optimization goal. To further solve the dynamic performance optimization problem of the machine tool systematically, it is necessary to investigate the key factors that influence the dynamic performance of the spindle system and whole machine tool. As the key component of grinding machine tools, spindles basically fulfill two tasks: rotate the wheel and transmit the required energy to the cutting zone for metal removal. The wheel/workpiece dynamic interactions introduce unfavorable consequences to the workpiece and grinding wheel [17]; in the paper both grinding process [18, 19] and dynamic characteristics of the spindle system [15, 20] are taken as the research object to optimize the performance of grinding machine spindles by interaction between the manufacturing process and the machine tool structure [21].

Taking the frequency-domain grinding force model-based evaluation method [22], this paper proposed a frequency domain finite element method to determine the dynamic parameters' influence on the overall performance of the grinding spindle in process. And the method is applied to optimize the machine structure as shown in Fig. 1: (1) the dynamic force model is built in the frequency domain based on the process; (2) the frequency response function is measured which contains the dynamic performance information of the machine spindle; (3) optimized FRFs are obtained based on the structural dimension optimization results; (4) the response root mean square values (RMSs) are calculated in the certain spindle speed range; and (5) by comparing the results, the dynamic performance optimization method is analyzed.

2 A frequency domain dynamic response approach

A new non-dimension dynamic force model as Eq. (1–2) is derived in the previous study [23], and it is applied in frequency domain dynamic response approach to analyze the dynamic performance of the machine.

$$f_n(t) = F_{n0} + (F_{n1}sin\omega t + F_{n2}sin2\omega t + F_{n3}sin3\omega t + F_{n4}sin4\omega t + \dots) \tag{1}$$

$$f_t(t) = F_{t0} + (F_{t1}sin\omega t + F_{t2}sin2\omega t + F_{t3}sin3\omega t + F_{t4}sin4\omega t + \dots) \tag{2}$$

The grinding machine spindle is studied in the field of linear system though it is not completely linear. The RMS values are used in calculations regarding power or energy in a signal waveform to have a sense of the dynamic performance. Here, when the FRF and the dynamic force in a certain frequency domain are applied, the response RMS can be computed in the frequency domain, using the following formula:

$$\mathrm{RMS} = \sqrt{\left[\frac{X_0^2}{2} + \sum_{i=1}^{m-1} X_i^2 + \frac{X_m^2}{2}\right]} \tag{3}$$

where m is the number of samples in the range and X_i is the amplitude of every sample. The speed-varying RMS values are the parameters that evaluate the dynamic performance of the machine tool spindle system in the finite element model.

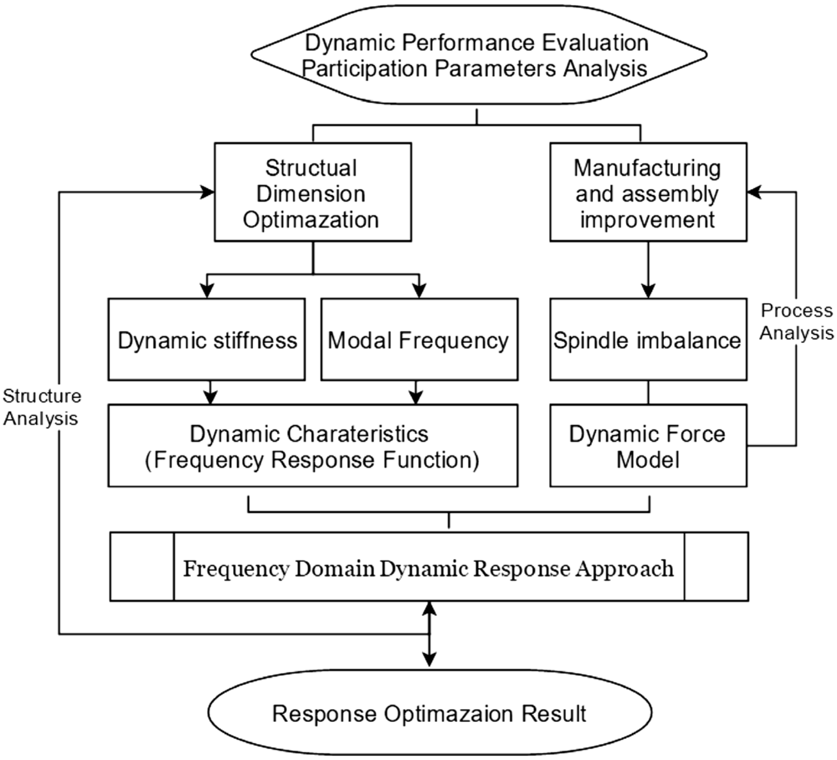


Fig. 1 Dynamic response optimization process

The force model-based dynamic performance evaluation method in this study is an interaction of manufacturing process dynamic force and machine tool structure, involving the characteristics of the dynamic force and the modal frequencies and dynamic stiffness of the grinding machines.

3 The dynamic grinding force analysis

To the most force models, the force is clearly and directly based on depth of cut. Consequently, in this research, it assumes that the dynamic forces are mainly caused by the differences of the depth of cut from the point view of relative vibration in kinematics. Then, the imbalance between the spindle and wheel is the main factor to cause the relative movement between the grinding wheel and the workpiece, which result in the dynamic change of depth of cut. Following this, the dynamic response is studied experimentally applying the dynamic balance instrument.

The spindle and grinding wheel imbalance reflects on the dynamic force is analyzed when the dynamic characteristics, grinding parameters, grinding wheel, and workpiece all remain the same. A high-speed cylindrical grinding machine with online dynamic balance system is applied in the test; the grinding parameters and residual amount of the dynamic imbalance of the spindle wheel system are showed in Table 1, in which the dynamic imbalance is an average value by system setting and average measurement. In the process, the vibration and dynamic force signal are tested with Kistler three dynamic force instrument (Type 9347C) and Kistler three direction accelerometer (Type 8762A5), and the signal is acquired by LMS SCADAS.

Accordingly, the dynamic force is exited extra vibration response on the rotation vibration. Then, by analyzing the vibration response of the excitation force separately, the vibration of spindle system caused by dynamic force can be obtained. Figure 2 showed the radial dynamic force and vibration RMS value under different imbalance condition and fast Fourier transformation (FFT) of dynamic force. The imbalance levels in the diagram represent the unbalanced residual amount in Table 1. It is found that the dynamic balance of spindle determines the strength of vibration response. The larger the imbalance is, the greater the dynamic excitation force is, and the greater the RMS value of final vibration response is. Therefore, it is effective to apply the frequency-domain force model-based evaluation method to optimize the dynamic performance of the machine tools.

4 Optimization study

The frequency domain dynamic response approach to optimize the dynamic performance of grinding machine spindles is based on intermediate parameter (rather than structural dimension parameter). The influence of key factors (modal frequency and dynamic stiffness) is analyzed in the paper, and its comprehensive analysis is applied to the dynamic performance optimization analysis of grinding machine spindle.

Table 1 Experimental parameters of dynamic grinding force analysis

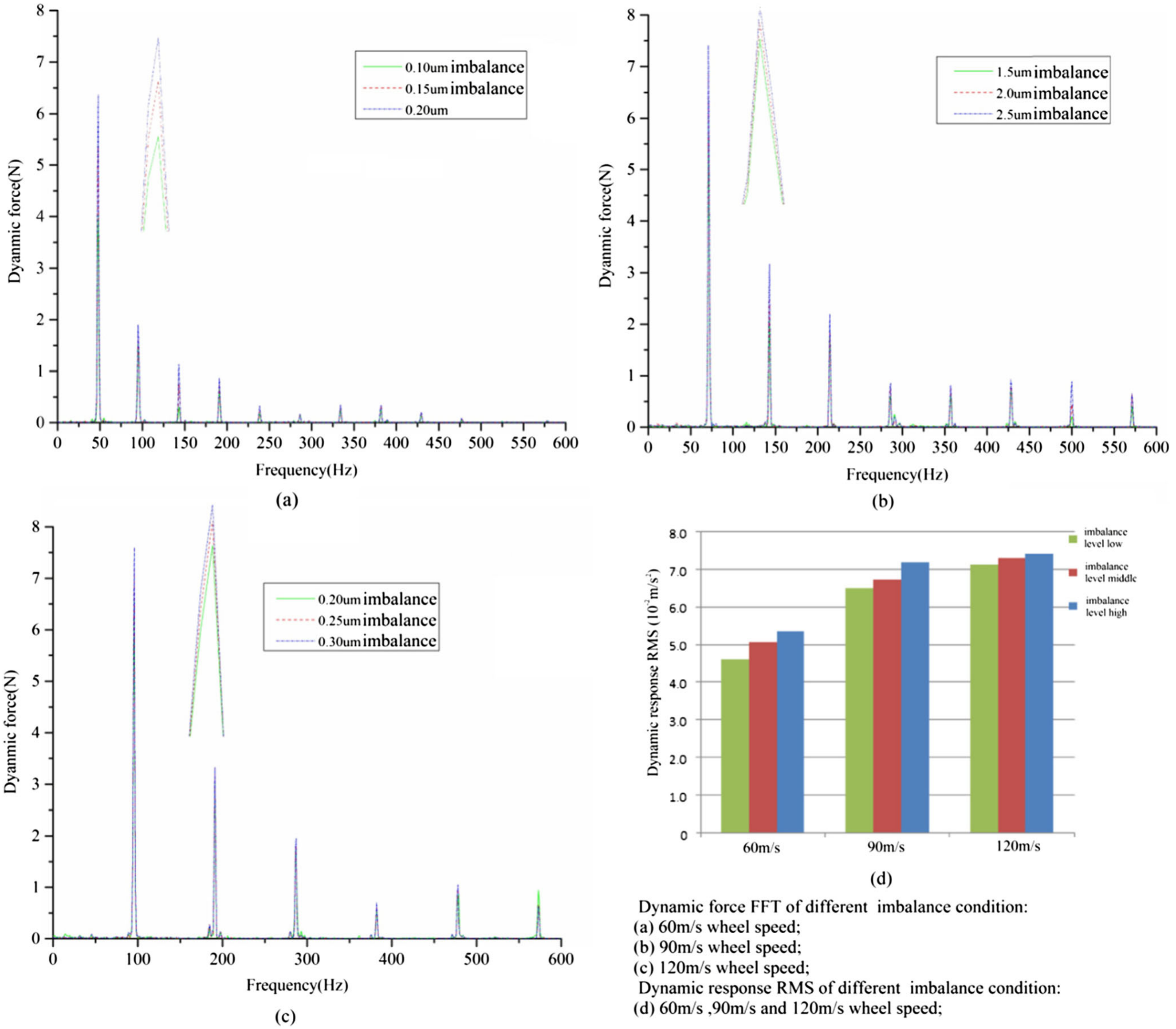
V_w (m/s)	0.05			0.05			0.1		
a_p (μm)	3			5			6		
RPM (r/min)	2866			4300			5732		
V_s (m/s)	60			90			120		
Imbalance(μm)	0.10	0.15	0.20	0.15	0.20	0.25	0.20	0.25	0.30

4.1 Simplified frequency domain dynamic force models

It can also be obtained from the empirical study of the dynamic force of grinding [23]; the grinding force amplitude can be converted and simplified for computer calculation proposal. Then the dynamic force model is calculated as follows.

$$f(t) = k\omega(sin\omega t + 1/2sin2\omega t + 1/3sin3\omega t + 1/4sin4\omega t + \ldots) \quad (4)$$

Here, 'k' is the balance factor to compare the simulation force with the experiment; taking 'k' as 1, the differences before and after optimization can be compared in the results. Though the force model is simplified, it can reflect the dynamic characteristics of grinding force at different rotating speed



Dynamic force FFT of different imbalance condition:
(a) 60m/s wheel speed;
(b) 90m/s wheel speed;
(c) 120m/s wheel speed;
Dynamic response RMS of different imbalance condition:
(d) 60m/s ,90m/s and 120m/s wheel speed;

Fig. 2 Dynamic force and vibration response RMS of different imbalance condition

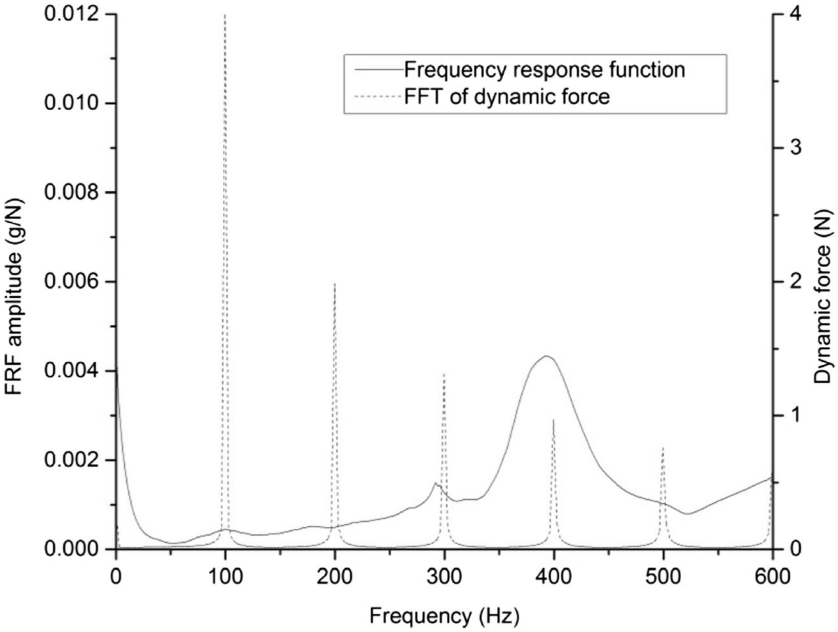


Fig. 3 FRF and FFT of dynamic force in the same frequency domain

from the view of general analysis of the machine tools. In this paper, to avoid high frequency modes' influence, the first ten Fourier coefficients of the force have been applied in calculating of RMS values. And the 0–500 Hz range of the dynamic force is applied in the optimization process.

4.2 Optimization parameters analysis

The interpretation for an RMS in this study is to find the response when a grinding dynamic force is applied on the machine. The force is based on the characteristics in grinding, and the FRF contains the dynamic performance information of the machine. In the dynamic force and FRF analysis in Fig. 3, the dynamic stiffness of the structure are the dominant factors influencing the machining dynamic characteristics of the grinding machines, while the modal frequency deciding the wave of the vibration level [22]. In the paper, both the dynamic stiffness and modal frequency are studied for the optimization process.

The FRFs amplitude shows that the dynamic flexibility and can also reflect the corresponding dynamic. What is more, the FRF contains information regarding the system frequency; it reflect the mode and modal frequency in the analyzed location. Therefore, by FRFs calculation can be applied to optimize the dynamic performance of grinding machine spindles.

4.3 Modal frequency optimization and FRF improvement

As studied in the previous section, the modal frequency will determine the strength of the vibration by the frequency response function. The harmonic frequency of the dynamic forces would lead to the difference in the frequency and distribution of the final vibration. To investigate the result the modal frequency acting on the dynamic response RMS, the method of modal frequency optimization is conducted on the grinding machine spindle system (Fig. 4). This paper conducted optimization by setting the first-order modal frequency as object. It is found that to increase diameter of the rear bearing can effectively improve the first modal frequency. The results of the first eight modal frequencies are listed in Table 2.

The modal frequency is usually changed by structural modification, and the amplitude of its frequency response function will also be changed. In order to separately quantify the effect of modal frequency enhancement on dynamic performance, especially the vibration response RMS, the percentage of modal frequency increase is converted to the original FRF and the amplitude is normalized. The frequency response function is directly modified by finite element analysis results. Taking the radial frequency response function of one point near the grinding wheel as an example, the frequency response

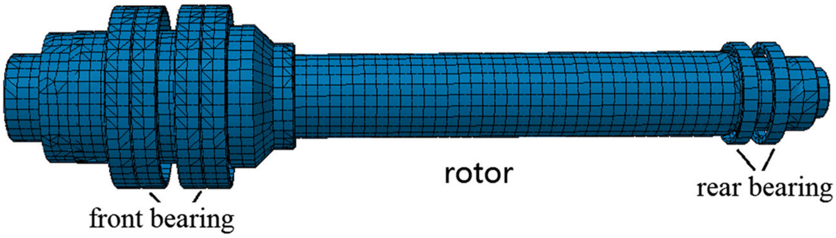


Fig. 4 Rotor FEM model of the spindle

Table 2 Modal frequency of the spindle before and after the optimization process

Order	Modal frequency before optimization (Hz)	Modal frequency after optimization (Hz)	Improvement rate (%)
1	113.7	125.9	10.7
2	290.4	298.8	2.9
3	399.7	409.7	2.5
4	489.4	500.4	2.3
5	603.2	623.8	3.4
6	711.8	721.8	1.4
7	822.7	860.4	4.6
8	979.1	1000.5	2.2

function is shifted to the high frequency as a whole due to the improvement of modal frequency as shown in Fig. 5. At the same time, the theoretical analysis shows that the higher the modal frequency of the excitation mode is, the higher the speed of the machine can reach.

4.4 Dynamic stiffness optimization and FRF improvement

As discussed previously, the greater the amplitude of the force, the greater the amplitude of the frequency response function, the higher the vibration energy. The amplitude of the frequency response function is negatively correlated with the dynamic stiffness, that is to say, the dynamic stiffness greatly determines the amplitude of vibration under excitation force. Especially, the frequency response function near the modal frequency has a prominent impact on the dynamic performance, which determines the vibration response RMS.

With the same spindle, the optimization process is finished by applying the dynamic stiffness as optimization object, the spindle structure as optimization parameters. It can be seen from Fig. 6 that when spindle span and spindle extended length become shorter, and the spindle diameter decreases, the dynamic stiffness characteristics of the tool location can increase by more than 20% after optimization design.

According to the relationship between the acceleration response function and the dynamic stiffness, the amplitude of the radial frequency response function will decrease when the dynamic stiffness of the spindle increase. Similarly, in order to study the influence of dynamic stiffness separately, the optimization effect of measured frequency response function amplitude is normalized without considering the influence of frequency. The frequency response function of the acceleration can be improved by 20% as shown in Fig. 7.

5 Results and analysis

Based on the improvement of modal frequency and dynamic stiffness, the study aims to improve the anti-vibration ability of the grinding spindle system. To further analyze the influence of the modal frequency and dynamic stiffness on vibration response energy by dynamic grinding force in the process, this paper applied the optimized frequency response functions on the frequency domain dynamic response

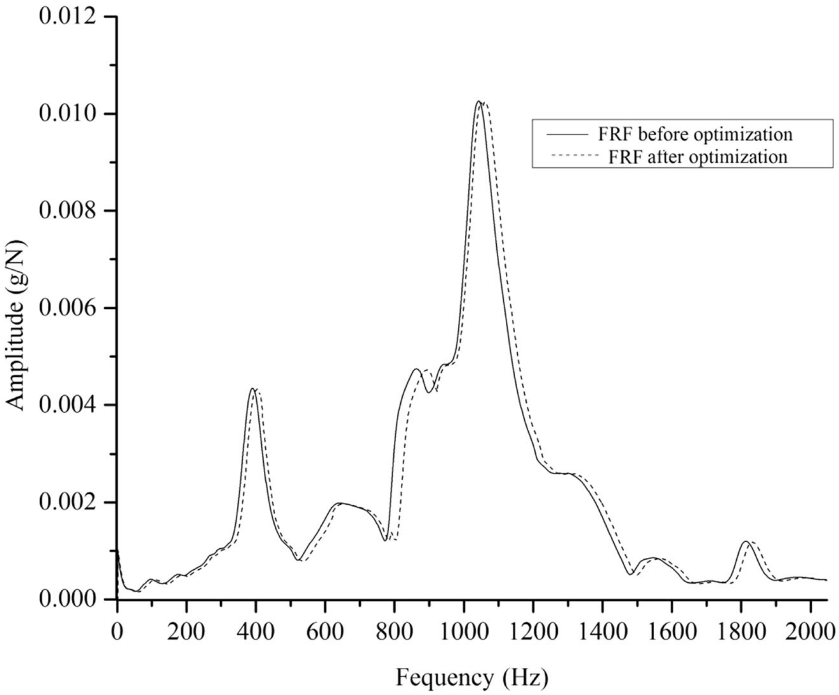
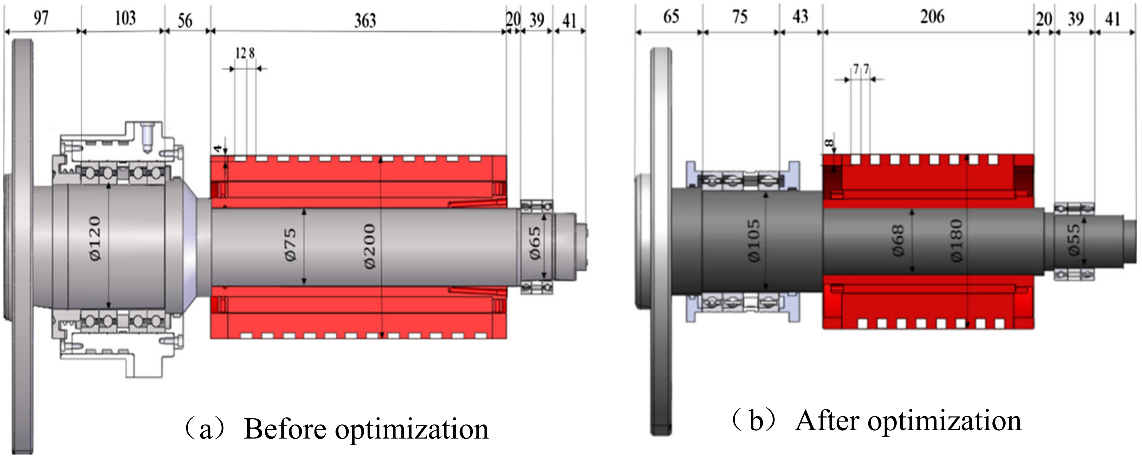


Fig. 5 FRFs before and after the modal frequency optimization and normalization



（a）Before optimization

（b）After optimization

Fig. 6 Spindle structure dimension before and after the dynamic stiffness optimization

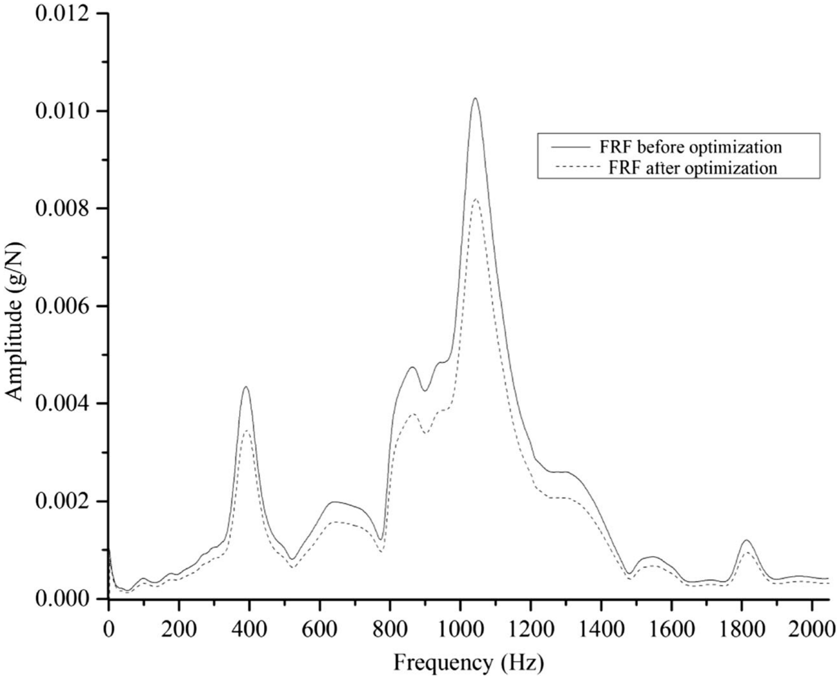
evaluation approach to calculate the vibration response RMS. In Fig. 8, the responses RMSs are calculated in the certain spindle speed range and same frequency range.

It is indicated in the figure, as the modal frequency optimized FRF overall moves to the high frequency, the vibration RMS also presents a high speed trend. And the vibration energy at the same speed is optimized because of the increase of modal frequency. The corresponding rotational speed of the peak vibration energy is also greatly improved. But at the same time, it is also found that the amplitude of the RMS did not decrease so much, only showed a translation phenomenon.

When applying the dynamic stiffness approach, the dynamic performance of the high-speed precision machine tool spindle has been greatly improved. The vibration response RMS amplitude and the overall level of vibration decreases obviously, the dynamic rotation speed for the same vibration level also increase obviously than the modal frequency-based method. Furthermore, it can be found that the dynamic stiffness improvement near its modal frequencies is the main reason, as the frequency response function of peak amplitude is effectively reduced. So in the engineering application, it is valuable to implement the critical structure dynamic stiffness optimization.

Through the above analysis and comparison, it can be found that dynamic stiffness is an important way to optimize the dynamic performance of spindle system. The dynamic stiffness optimization method is effective from the perspective

Fig. 7 FRFs before and after the dynamic stiffness optimization and normalization



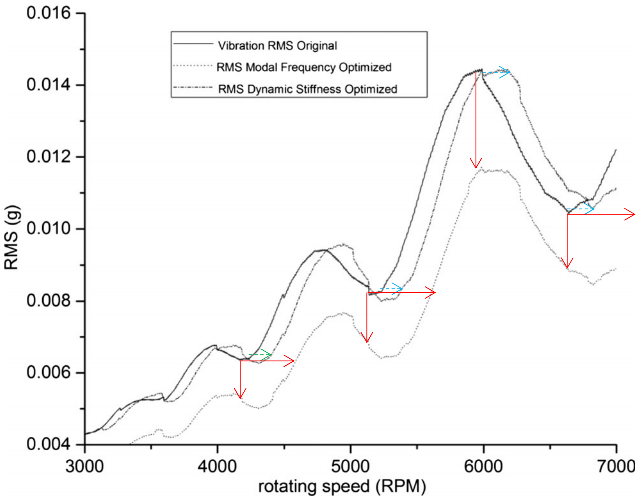


Fig. 8 RMSs comparison applying different optimization FRFs

of overall vibration capability, which makes up for the shortage of modal frequency method that would not improve the vibration average level.

6 Conclusions

In this paper, a frequency domain dynamic response approach to optimize the dynamic performance of grinding machine spindles is proposed. This approach considers the dynamic grinding force and frequency response function in the vibration response calculation. Applying the method, the optimization processes are conducted based on intermediate dynamic parameter (modal frequency and dynamic stiffness), and process vibration response RMS are studied and analyzed. The case study results show that the imbalance of spindle system is the factor that influences dynamic grinding force in the process; the dynamic stiffness of the structure are the main factors determining the machining dynamic characteristics of the grinding machines in the process, while the modal frequency decides the wave of the vibration level. Therefore, in the grinding spindle dynamic performance optimization process, the dominant optimization objective is the dynamic stiffness.

Acknowledgements This project is supported by Shanghai Sailing Program (No.18YF1418400) and Natural Science Foundation of China (No. 50975046).

Nomenclature a_p, Cutting depth, mm; f_n, Normal grinding force in frequency domain, N; f_t, Tangential grinding force in frequency domain, N; F_{nn}, Fourier coefficients of normal grinding force, N; F_{tn}, Fourier coefficients of tangential grinding force, N; k, The balance factor; V_s, Wheel speed, mm/s; V_w, Workpiece speed, mm/s; *RPM*, Rotation per minute, r/min; X_i, Amplitude of data sample; ω, Rotating speed of the wheel, rad/s

References

1. Abele E, Altintas Y, Brecher C (2010) Machine tool spindle units. CIRP Ann Manuf Technol 59(2):781–802
2. Wang X, Yu T, Dai Y, Wang W (2016) Kinematics modeling and simulating of grinding surface topography considering machining parameters and vibration characteristics. Int J Adv Manuf Technol 87(9–12):2459–2470
3. Inasaki I, Karpuschewski B, Lee HS (2001) Grinding chatter—Origin and suppression. CIRP Ann 50(2):515–534
4. Qin Y, Brockett A, Ma Y, Razali A, Zhao J, Harrison C, Pan W, Dai X, Loziak D (2010) Micro-manufacturing: research, technology outcomes and development issues. Int J Adv Manuf Technol 47(9–12):821–837
5. Rebelein C, Vlacil J, Zaeh M (2017) Modeling of the dynamic behavior of machine tools: influences of damping, friction, control and motion. Prod Eng 11(1):61–74
6. Zaeh M, Siedl D (2007) A new method for simulation of machining performance by integrating finite element and multi-body simulation for machine tools. CIRP Ann Manuf Technol 56(1):383–386
7. Lin CW, Jay FT, Joe K (2003) An integrated thermo-mechanical-dynamic model to characterize motorized machine tool spindles during very high speed rotation. Int J Mach Tools Manuf 43(10):1035–1050
8. Wu Z, Li B, Yang J, Sheng X (2013) A thermodynamics coupled modeling approach for analysis and improvement of high-speed motorized spindle system. J Vibroengineering 15(3):1119–1129
9. Fredin J, Jönsson A, Broman G (2012) Holistic methodology using computer simulation for optimisation of machine tools. Comput Ind Eng 63(1):294–301
10. Wu B, Young G, Huang T (2000) Application of a two-level optimization process to conceptual structural design of a machine tool. Int J Mach Tools Manuf 40(6):783–794
11. Altintas Y, Cao Y (2005) Virtual design and optimization of machine tool spindles. CIRP Ann Manuf Technol 54(1):379–382
12. T. Li, X. Ding, K. Cheng, T. Wu (2017) Dynamic optimization method with applications for machine tools based on approximation model. ARCHIVE Proc Inst of Mech Eng C J Mech Eng Sci 1989-1996(203–210)
13. Huo D, Cheng K, Wardle F (2010) A holistic integrated dynamic design and modelling approach applied to the development of ultraprecision micro-milling machines. Int J Mach Tools Manuf 50(4):335–343
14. Neugebauer R, Ihlenfeldt S, Frieß U, Wabner M, Rauh S (2012) New high-speed machine tool structure by holistic mechatronic systems design. Proc CIRP, 1(1):307–312
15. Aggogeri F, Merlo A, Mazzola M (2010) Multifunctional structure solutions for ultra high precision (UHP) machine tools. Int J Mach Tools Manuf 50(4):366–373
16. Xu Y et al (2017) Dynamic optimization of constrained layer damping structure for the headstock of machine tools with modal strain energy method. Shock Vib 2017:1–13
17. Oliveira JFG, França TV, Wang JP (2008) Experimental analysis of wheel/workpiece dynamic interactions in grinding. CIRP Ann Manuf Technol 57(1):329–332
18. Govekar E, Baus A, Gradišek J, Klocke F, Grabec I (2002) A new method for chatter detection in grinding. CIRP Ann Manuf Technol 51(1):267–270
19. González-Brambila O, Rubio E, Jáuregui JC, Herrera-Ruiz G (2006) Chattering detection in cylindrical grinding processes using the wavelet transform. Int J Mach Tools Manuf 46(15):1934–1938
20. E. Kushnir, T. Sheehan (2003) Development of machine tool structure at the early stages of design process. ASME 2003 International

Mechanical Engineering Congress and Exposition, Washington, DC, November, 470: 121–127

21. Brecher C, Esser M, Witt S (2009) Interaction of manufacturing process and machine tool. CIRP Ann Manuf Technol 58(2):588–607
22. Guo M, Li B (2016) A frequency-domain grinding force model-based approach to evaluate the dynamic performance of high-speed grinding machine tools. Mach Sci Technol 20(1):115–131
23. Guo M, Li B, Ding Z, Liang SY (2016) Empirical modeling of dynamic grinding force based on process analysis. Int J Adv Manuf Technol 86(9–12):3395–3405