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## Study on vibration extraction and control characteristics of the high speed spindle online dynamic

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Abstract. In order to solve the mechanical spindle low processing accuracy and precision elements problems which were caused by high speed spindle noise and vibration, a robust and reliable vibration extraction and control scheme of mechanical spindle was proposed. Based on the electromagnetic balancing system and by applying LabV1EW visual instrument, high speed spindle noise reduction and vibration signals filtering were pre- processed and vibration signals sampling, quantization, interception were post-processed. Base frequency vibration signals amplitude and phase were extracted by using different signal extraction methods. Through experiment verification and comparative analysis, the optimal vibration signal amplitude and phase extraction method was selected. By using the influence coefficient method, the influential factors including spindle speed, trial weights magnitude and phase were analysed. The high speed spindle unbalance was calculated and compensated. The high speed spindle electromagnetic balancing device block was controlled accurately. Experimental results showed that the vibration amplitude of the mechanical spindle was obviously reduced and the balance efficiency was greatly improved. The influence coefficient method and the electromagnetic balancing system took an active role in the process of dynamic balancing regulation. Such achievements enriched online dynamic balancing theory and promoted the relevant control technique developments.

#### 1. Introduction

The continuous development of high-speed spindles in recent years and the research and application of rotary rotors represented by high-speed spindles, have become more numerous, so it has put forward higher requirements for the rotation precision and stability during the operation of the spindle [1]. The vibration generated by the operation of spindle causes the failure rate of the high-speed spindle and other components to reach 60% to 70% [2]. For the spindle of the machine tool, although the balance had been corrected and the rotation accuracy had met the requirements, there will still be imbalance of spindle vibration and reduction of rotary precision caused by some factors such as design, manufacture, fatigue wear, load shock in the long run process. Therefore, the unbalance have a great influence on the precision of the machine tool. It is of great significance that the operating characteristics of the

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1 spindle system are improved based on research of characteristics of spindle vibration signal and control characteristics of dynamic balance.

At present, scholars at home and abroad mainly focus on the development and innovation of online dynamic balance methods and their balancing devices. K. Fedem [3] proposed the criteria for discriminating the flexible rotor. For the flexible rotor, the vibration of the spindle caused by the imbalance is related to many factors: magnitude of imbalance, phase angle, stiffness, damping, structure, supporting conditions, and rotation speed. Therefore, the main spindle dynamic balance control methods can be summarized as [4]: modal balance method, no trial weight balance method and influence coefficient method [5]. Liu Rongqiang and Xia Songbo [6] proposed dynamic balance control methods of residual influence coefficients to solve the problem of too large correction weights; Kang Kaining, Wang Peijun et al. [7] proposed a balanced method minimizing the maximum residual vibration, MINMAX method, which could calculate well to eliminate vibration; Zhu Xiangyang, Zhong Binglin [8] studied the method of least squares influence coefficient balance algorithm using the minimized iterative weighting method; Zhang Xiaoxuan, Tang Yunbing et al. [9] proposed a method that could optimize test mass block and residual vibration of spindle based on the least square method of improved genetic algorithm; Field dynamic balancing experiment of grinding wheel shaft finished by College of Mechanical Engineering, Xi'an Jiao Tong University proved that grinding wheel shaft balancing device could control vibration of the spindle accurately and efficiently, it was obvious that the vibration of the spindle was reduced [10]; the non unloading dynamic balance method based on the influence coefficient method proposed by the researcher of the National Key Laboratory of Mechanical Transmission of Chongqing University [11] had the advantages of high balance precision, simple operation and high balance efficiency; the researchers coming from College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology had achieved the precise balance of key parts of machine tool spindle [12]. Meltal had arrived at Modal Balancing Technique through main vibration type of rotor type spindle system at each critical speed; Bishop and Saito, based on the conclusion of Meltal, had solved some problems such as how to choose the mode balance correction and deal with the gravitational drooping in the balance process after a long study [13]. Xu Bingang and Qu Liang Sheng [14] in Xi'an Jiao Tong University realized the combination of modal balance method and hologram technique. Under the condition of a non critical speed, the method could achieve simultaneous equilibrium in a two order mode for rotary rotor with asymmetrical structure; the researchers of the Institute of vibration engineering of Northwestern Polytechnical University have improved the mode balance technology. Using instantaneous amplitude information of spindle raising speed response during the starting process of flexible spindle, flexible rotor was two-plane balanced. The method could quickly and effectively reduce transient residual vibration of rotary spindle without obtaining vibration phase data, and greatly improve the accuracy and efficiency of balancing [15]. Institute of Aeronautical Power Machinery of Aviation Industry Corporation of China and School of Power and Energy Engineering of Northwest University proposed a Balancing method of flexible rotor across second order without trial weights, which solved some problems such as the size of the mass block and multiple shutdown in the process of spindle balance [16]. The vibration amplitude of the rotor was effectively reduced, and numbers of shutdown were reduced in the process of spindle balance. So, accuracy and efficiency of in the balance of the spindle were greatly improved. In summary, some achievements have been made in characteristics of spindle vibration signal and control characteristics of dynamic balance, which has laid a certain theoretical foundation for this study, however, the research results are still lacking in unbalanced vibration signal extraction and control characteristics of dynamic balance of high speed spindle, and vibration signal characteristics and dynamic balancing control characteristics also play an important role in the dynamic balancing efficiency of spindle. This paper mainly studies the extraction and analysis of unbalanced vibration signals of high speed spindle and analysis of control characteristics of online dynamic balance.

#### 2. High-speed spindle unbalanced vibration signal feature extraction method

2.1. High-speed spindle unbalanced vibration signal feature extraction simulation and experiment The correlation filtering method can strictly control the DC component and noise interference in the signal and achieve accurate extraction of the unbalanced signal. Therefore, the correlation filtering method is applied to extract unbalanced signals. The principle of correlation filtering is shown in figure 1.



Figure 1. Correlation filtering principle.

The correlation analysis method issued to extract the amplitude and phase of the vibration signal. This method has the characteristics of fast operation, high accuracy and it is also not easily disturbed by other noise and other signals. The on-line dynamic balance of the spindle is established and completed from the signal pre-processing, post-processing, the extraction of the characteristic value of the fundamental frequency vibration signal, and the on-line dynamic balance using the influence coefficient method as the control method. The flow chart is shown in figure 2.



Figure 2. Flow chart of regulation of online dynamic balance vibration signal.

#### 2.1.1. Analysis of simulated vibration signal results. The vibration signal expression is as follows:

$$y(t) = a_0 + A\sin(\omega t + \delta) + \sum_{i=1}^n a_i \sin(i\omega t + \varphi_i) + s(t).$$
(1)

In the formula,  $a_0$  is the DC component;  $i\omega$  represents different signal frequencies;  $\varphi_i$  is the phase of the vibration signal at each frequency; A is the fundamental frequency amplitude of the vibration signal; s(t) is noise and other interference signals;  $a\sin(\omega t + \phi)$  is a fundamental component signal.

To obtain a more realistic spindle vibration signal, set the following analog simulation signal. The expression of the interference signal of uniform white noise and white noise of Gaussian white noise is expressed as:

$$x(t) = 2 + 6\sin(\omega t + 30) + 3\sin(2\omega t + 20) + 2\sin(3\omega t + 10) + s_1(t) + s_2(t)$$
(2)

The information of the time waveform of the simulated vibration signal is: uniform white noise, standard deviation of a single Gaussian white noise signal is 1, DC component is  $2\mu$ m, fundamental frequency is 10 Hz, fundamental frequency vibration signal is  $6\mu$ m, frequency double vibration signal is  $3\mu$ m, triple frequency vibration signal is  $2\mu$ m and the corresponding initial phase is respectively  $30^\circ$ ,  $20^\circ$  and  $10^\circ$ . The number of sampling points is 1000 and the sampling frequency is 1000Hz.For the simulation of the time-domain waveform of the vibration signal, the harmonic wave signal mixed with white-noise and white Gaussian noise is used as the analog vibration signal in the time domain waveform in the program. The front panel of the program is shown in figure 3.

In this paper, five basic frequency vibration signal extraction methods are selected. In the whole cycle of 10Hz, the vibration signal amplitude and phase extraction operations are respectively performed, and the first 50 sets of calculation results are averaged. The results are shown in table 1.



Figure 3. DC component, uniform white noise, Gaussian white noise mixed harmonic signal.

Extraction Method Vibration parameters	Correlation	Full cycle interception	Traditional FFT	Mutual power	Sine approximation
Average amplitude/µm	6.01	5.98	5.97	6.02	6.05
Average phase/°	30.12	29.97	30.19	30.22	29.88

Table 1. Comparison of the extraction results of the baseband signal under simulation.

2.1.2. Experimental analysis of signal extraction methods. This research is based on the built-in electromagnetic slip ring type dynamic balancing device. The hardware part is composed of motor, eddy current displacement sensor, photoelectric sensor, preamplifier, data acquisition device, system controller and so on. In the dynamic balance measurement, the control command is transmitted to the control device by the computer, so that the control device can accurately control the speed of the motor. The function of the preamplifier is to amplify the vibration signal detected by the eddy current displacement sensor. The photoelectric sensor detects the speed pulse signal of spindle speed; Eddy

current displacement sensor is used to detect vibration signal of vibration point; the data acquisition device adopts the PCI-9234 product from National Instruments in the United States. The function of the product is the A/D conversion function, analog signals detected by sensors are converted into digital signals, and then the digital signals are transmitted to the LabVIEW software to data analysis and processing. The experimental platform is shown in figure 4. The internal structure of the electromagnetic ring is shown in figure 5.



Figure 4. Experimental platform.



Figure 5. The internal structure of the electromagnetic ring.

Under the experimental conditions, the sampling frequency of the vibration signal is set to 1000Hz, the number of sampling points is 1000, the spindle working speed is set to 1500r/min, and the theoretical spindle frequency is 25Hz, so as to better observe the vibration of the spindle working speed, in the shaft the end of the test surface placed mass 10g trial weight. The results of the extraction are shown in table 2.

From table 2, we can see that the theoretical spindle frequency is 25Hz, but during the experimental operation, the spindle frequency detected by the Hall element is not 25Hz. At this time, the analog signal does not fully represent the spindle under actual operating conditions signal.

Using the various vibration signal extraction methods compiled by LabVIEW software, vibration signals with the same frequency as the spindle vibration are extracted, and 50 amplitude and phase data of the rear panel of the program are selected, as shown in figures 6 and 7.

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Extraction Method Signal parameters	Correlation	Full cycle interception	Traditional FFT	Mutual power	Sine approximation
Amplitude/µm	5.52	5.48	5.42	5.35	5.31
Phase maximum/°	33.21	33.18	34.25	34.18	35.34
Phase minimum/°	30.68	31.04	29.97	29.32	30.33
Phase difference/°	2.53	2.14	4.28	4.86	5.01

**Table 2.** Comparison of the results of the fundamental frequency signal extraction under the experiment.



Figure 6. Vibration amplitude comparison.



Figure 7. Vibration phase comparison.

The results obtained under the experimental conditions show that the unbalanced vibration caused by the spindle plus the appropriate test weight has a similarity of 90.78% between the amplitude of the

fundamental frequency vibration and the vibration amplitude of the fundamental frequency under the simulated conditions. The vibration phase fluctuates less, the phase average absolute error is 2.15 degrees, and the accuracy rate is 92.53%. The harmonic signals including the fundamental frequency, double frequency, and triple frequency harmonic signals, mixed noise, and direct current components are approximately used to characterize the vibration of the actual working condition of the spindle. After completing the experiment for the verification of different vibration signal extraction methods and the similarity of 90.78% between the vibration amplitudes of the fundamental frequency under the experimental and simulation conditions, the experimental results can be used as feedback values to correct and modify the spindle of SYL04H-1 lathe based on the experimental platform. Spindles of lathes put forward more realistic expressions of vibration signals, paving the way for follow-up research and constructive reference.

The spindle working condition of this experiment is performed under the condition that the working speed is set to 1500r/min. Therefore, under the condition that the spindle frequency is 25Hz, the vibration signal under the simulation condition is used to replace the spindle vibration signal under real conditions. In the pre-processing of the signal, noise and DC components at different frequencies are subjected to wavelet de-noising, filtering, and other operations. Therefore, in the section of the method for extracting the amplitude and phase of the vibration signal, there is no need to address the type of noise, the size, DC component, etc. as they are studied precisely. The expression of the vibration signal will ignore this part. Only the single-term formula can be used as a symbol substitution. The spindle vibration can be caused by the interference of the mixed harmonic signals of uniform white noise, Gaussian white noise and DC component. The signal expression is:

$$x(t) = e + 5.5\sin(\omega t + 32.5) + 3.2\sin(2\omega t + 20) + 2.4\sin(3\omega t + 10) + s(t).$$
(3)

In the formula, the fundamental frequency of the spindle is 24.6Hz, the vibration signal of the fundamental frequency is 5.5 $\mu$ m, the frequency of the double frequency vibration signal is 3.2 $\mu$ m, and the frequency of the triple frequency vibration signal is 2.4 $\mu$ m. The corresponding initial phase is 30°, 20° and 10°, respectively. The number of sampling points is 1000 and the sampling frequency is 1000Hz. DC component and noise are expressed separately *e*, *s*(*t*).

# 2.2. The effects of high-speed spindle unbalanced vibration signal extraction on dynamic balance and experiments

The cross-correlation algorithm and the DFT signal extraction method applied to the whole cycle were applied to the dynamic balance software test system, respectively. The vibration signal extracted by the cross-correlation algorithm and the DFT extracted whole-period vibration signal were used as the influence coefficient method for on-line dynamic balance. For the input of the item parameters, the parameters such as the influence coefficient, calibration quality and residual unbalance are obtained. The comparison of the spindle dynamic test balance effect and the experimental data are shown in figure 8 and table 3.



Figure 8. Comparison of amplitude before and after balance.

Balancing parameters	Cross correlation method	Full cycle interception	
Initial imbalance	4.75µm∠30°	4.96µm∠85°	
Try to add weight	10g∠210°	10g∠265°	
Unbalance after aggravation	5.36µm∠85°	5.84µm∠110°	
Correction weight	11g∠260°	19g∠115°	
Residual imbalance	0.52µm∠130°	0.67µm∠70°	
Influence factor /µm/(g∙mm)	0.0078∠290°	0.0042∠260°	

Table 3. Spindle dynamic balance experimental data.

Influencing coefficient method online dynamic balance many experiments show that the vibration signal extracted by the cross-correlation algorithm is used as the input of the influence coefficient method, the amplitude of vibration is significantly reduced, the balance accuracy is 89.78%, and the residual balance is lower than the value obtained by the whole cycle interception DFT method. Unbalanced vibration is effectively suppressed. It can be seen that the embedded cross-correlation algorithm program is applied to the dynamic balance software. Each performance parameter meets the design requirements. The effect of the single-plane dynamic balance process is ideal. This test system can be applied to the dynamic balance of other similar working conditions. Promote high-speed spindle double-sided balancing test.

The results show that using the cross-correlation algorithm, the spindle balance efficiency and accuracy are higher, and the spindle vibration is more effectively suppressed. The balance effect is better than the whole cycle interception DFT method, which ensures that the influence coefficient method is the balance regulation strategy accuracy.

#### 3. Experimental research and analysis of the characteristics of on-line dynamic balance of highspeed spindle

#### 3.1. Effect of rotation speed on experimental platform vibration

In order to study the vibration of the spindle rear end after the spindle rotates at higher speed, the vibration displacement sensor is first placed on the side of the end face of the spindle rear end. Recording is started from 1200 r/min without changing the spindle support structure. Every time the 200r/min increase, the amplitude of vibration is continuously increased to 3400r/min, and the vibration intensity of the spindle end is increased.

Change the spindle support method, and place rubbers with light elasticity at the front and rear ends of the spindle. At the rear end of the spindle, the displacement sensor is again placed at the same position as the original one, and the spindle end face vibration detection is performed. After the same experimental measurement method and stepping speed as the previous step, the following experimental results are obtained, as shown in table 4.

During the experimental research, it was found that the vibration of the main shaft and the motor housing was small at the other speeds of the main shaft system. However, when the rotation speed of the rotor system exceeded 2400 r/min, the rear end vibration of the main shaft began to have greater amplitude fluctuations. From the perspective of installation, the rear end of the spindle is relatively weak, and the motor and the belt are connected. The detected roundness of the spindle end face is also large, because the belt drive system affects the vibration of the rear end of the spindle.

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Rotating speed	Spindle front end vibration amplitude	Base vibration amplitude	Motor vibration amplitude	Rear spindle vibration amplitude
1/11111	μΠ	μΠ	μΠ	μΠ
300	0.261	0.04	0.551	0.461
600	0.244	0.063	0.328	0.430
900	0.249	0.111	0.279	0.397
1200	0.467	0.189	0.405	0.325
1500	2.717	0.291	1.033	5.894
1800	3.45	5.148	22.522	8.190
2100	2.637	3.438	10.895	15.572
2400	1.302	1.397	2.478	2.650
2700	2.131	0.599	0.809	0.814
3000	3.228	0.695	1.731	1.421
3300	4.926	0.66	1.496	1.511
3600	5.724	0.539	0.717	3.660

**Table 4.** Vibration amplitudes across the experimental platform.

#### 3.2. Effect of rotation speed on spindle dynamic balance

When the mechanical spindle runs at a low speed, the spindle can be regarded as a rigid system. After the dynamic balance, the balance effect is relatively reasonable and the effect is relatively stable. However, at high speeds, the spindle system may enter a flexible state. If the spindle is still considered to be a rigid system, the system will have an effect on the dynamic balancing effect after entering a certain speed. Measuring the spindle speed at 3400r/min, 3600r/min, 3800r/min, 4000r/min four different speeds, dynamic balance of the vibration response measurement. The vibration amplitude at different speeds is shown in figure 9.



Figure 9. Vibration amplitude at different speeds.

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It can be seen from the experimental results that, firstly, when the main shaft is not balanced, the vibration is greater at each rotating speed. After 3600r/min dynamic balance, the vibration amplitude is basically unchanged from 3400r/min to 3800r/min and 4000r/min, and the amplitude is increased; after 3800r/min dynamic balance, the speed is reduced or increased, and the amplitude is increased. There are different degrees of improvement; the same, after the 4000 r/ min dynamic balance and then the speed is reduced, the amplitude also has varying degrees of improvement. Changing the rotational speed has an effect on the dynamic balance effect. Changing the spindle rotational speed mode also has a certain influence on the vibration amplitude change of the main shaft. The change rules of the system at 3400r/min and 3600r/min are similar, and the change rules at 3800r/min and 4000r/min are similar.

Changing the rotational speed has an effect on the dynamic balance of the experimental platform in this paper. The reason is that the entire system has crossed the critical rotational speed and is working in a flexible state. It cannot be simply based on the rigid shaft dynamic balance method. The doublesided influence coefficient dynamic balance method of the flexible shaft should be used.

#### 3.3. Effect of test block plus angle on spindle dynamic balance

In the experiment, try to add a weight of 10.0g of the same mass at different angles on the spindle end face. The trial weight angle is added once every 30°, and 12 times during the test. The vibration of the spindle before and after adding the trial weight is measured and the vibration amplitude is obtained. The difference between the difference and the trial plus the mass point angle correspond one to one. The results are shown in figure 10 and figure 11.



Figure 10. Relationship between amplitude difference and phase difference and test weight angle.

As can be seen from figure 10, the amplitude difference measurement changes show a "sinusoidal" change, and the phase difference shows a "cosine curve" change. At a test angle between 45° and 135°, the difference between the amplitude difference and the phase difference varies a lot and then begins to narrow. When the trial angle is between 225° and 315° the amplitude difference, the change in the difference between the value and the phase difference reappears and shows a gradual increase.



Figure 11. Influence factor size vs. angle.

From figure 11, we can see that the size of the influence coefficient changes with different trial angles, and the size of the influence coefficient is reduced to three sizes with different shapes. Circles represent smaller influence coefficients, and quadrilaterals represent larger influence coefficients. The distribution area of the coefficient of influence represented by different shapes has a certain degree of regularity: the distribution of influence coefficient is larger in the area where the difference between the amplitude difference and the phase difference is larger, and the distribution of smaller influence coefficient is the area where the difference between the difference in amplitude and the difference in phase is small. After this, the relationship between the size of the influence coefficient and the difference between the difference between the difference is explored. According to figure 10, a total of four angles, ie, 75°, 315°, 195°, and 255°, in which the difference between the amplitude difference change greatly and are smaller and selected. The test of heavy-moving balance was performed again. Comparison of the vibration before and after the dynamic balance and the balance efficiency are shown in table 5.

Angle	Balanced vibration amplitude/µm	Balanced vibration amplitude/µm	Decrease percentage
75	5.1	1.1	78.43%
195	5.8	1.8	68.98%
255	5.3	1.5	71.69%
315	5.4	1.3	76.92%

Table 5. Effect of balancing after adding test weight in different angles.

The experimental results show that when the test weight is added to two positions of 75° and 315°, the amplitude ratio of vibration is reduced obviously, and the dynamic balance effect is better.

By comparing the final balance effect of the experiment, the following conclusions are obtained: firstly, the larger the difference between the amplitude difference and the phase, the larger the influence coefficient obtained, indicating that the unit mass is most sensitive to the amount of imbalance compensation, and the amplitude difference and phase the smaller the difference is, the smaller the influence coefficient obtained is, indicating that the unit mass is the least sensitive to the amount of imbalance compensation; secondly, the difference between the amplitude difference and the phase difference directly determines the size of the influence coefficient, and indirectly affecting the on-line dynamic balance of the spindle, the greater the influence coefficient, the more effective the amplitude reduction effect.

#### 4. Conclusion

Experimental verification and analysis results show that cross correlation method has the best effect on amplitude and phase extraction of vibration signals after eliminating noise and filtering preprocessing during the operation of the spindle. The vibration signal obtained by the cross correlation algorithm is used as the input of the influence coefficient method. The vibration amplitude is obviously reduced, the balance precision is 89.78%. The method has great speed and accuracy in calculation.

Fundamental theory of regulation of online dynamic balance based on influence coefficient method is studied, and vibration parameters are detected from multi-directions. Spindle amplitude with control method of single plane influence coefficient was reduced to 87.26%, compared with single plane dynamic balance in balancing efficiency and accuracy, the method avoids the greater error caused by the original error accumulation, it improves the efficiency and accuracy and realizes more precise measurement.

After the critical speed of 1800r/min, the spindle is in a flexible working state, bearings supporting stiffness will be reduced to cut down on external influence. With the increase of spindle rotation rate, there will be a downward trend in the balance efficiency of the spindle, but it still maintains more than 80%. The experimental results show that the two parameters of the amplitude and the angle of test block directly determine the influence coefficient and indirectly affect the effect of online dynamic balance. Through the experiment, if the mass block formula for the first trial addition is improved, spindle response will be obvious, it is helpful for on-line control and restraining spindle vibration. The research results of moving strategy of mechanical double balance block balancing device show that the movement path of mass blocks do not cross when moving at the same time and the mobile strategy that mass blocks successively arrive is the most reasonable. The feasibility and accuracy of the move strategy are verified, some problems such as the error and the long balance time in the mass movement process are solved.

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