Experimental Study on Unbalanced Vibration Signal of High Speed Spindle Based on All Phase Fast Fourier Transform

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Abstract—**The spindle system will vibrate due to mass unbalance during high speed operation, which will affect the machining accuracy. In order to compensate the dynamic balance quality of unbalanced vibration, spindle dynamic balance processing can be carried out. In the process of dynamic balance processing, the extraction of unbalanced vibration signal is the key to affect the balance quality.The vibration signal extraction experiment of high-speed spindle was carried out by using all-phase FFT method.The vibration signal extracted by the all-phase FFT method is taken as the input of the influence coefficient method, and the amplitude of vibration is obviously reduced, and the balance precision reaches 65.21%. Compared with the cross-correlation method, the unbalanced vibration is effectively suppressed.The results show that the all-phase FFT method has the characteristics of stability and high balance precision, and can be applied to the vibration signal extraction of high-speed spindle and the vibration signal extraction of rotary subclass.**

Keywords-high speed spindle; vibration signal; feature extraction; all- phase FFT

I. INTRODUCTION

The main machine tool used in the modern processing process is the numerical control machine tool, which is the most basic equipment in machining. As the main component, the spindle of machine tool affects the machining precision, The reason is the vibration caused by the imbalance of the spindle. When the spindle has a large unbalanced mass, in the process of rotation will produce unbalanced centrifugal force, when the unbalanced centrifugal force can not get the external balance, the spindle will produce a strong vibration, with the increase of the speed, the centrifugal force will be more and more large, affecting the machining accuracy of the machine tool .Machine tool spindle can not avoid vibration when working, it needs to balance the centrifugal force produced by the unbalanced mass of the spindle. The key to affect the balance precision is the extraction of unbalanced vibration signal.

At present, how to extract the unbalanced signal of the spindle is the primary problem to be solved for the realization of the spindle dynamic balance on line, and the extraction and processing of rotor vibration signal has always been a hot topic in the field of scientific research at this stage, and some theoretical achievements have been made. Gao[1] reconstructed the signal by wavelet inverse transform to extract the vibration signal characteristics of the motor shaft. Through simulation and experiment Guo Junhua[2], Feng[3] concluded that the whole cycle truncated DFT method has higher extraction precision, but the spectrum leakage and fence effect will occur when DFT processing. Jiang Zhinong [4]and Xu Juan[5] eliminated the influence of phase lag on phase extraction accuracy by signal cross-correlation processing, and the extracted amplitude and phase accuracy were significantly improved compared with the traditional cross-correlation method. Shang Yiqi[6] proved that the all-phase time-shift phase difference method has higher precision. Zhang [7] used the least squares algorithm to fit the fundamental frequency signal, and the traditional fast Fourier transform discrete Fourier. Compared with the transform algorithm, it has a certain theoretical advantage[8].Wang[9] uses a virtual instrument to design a vibration measurement system and effectively track spindle vibration. Wang [10] used the Prony method to extract the amplitude, frequency, phase and other information of the vibration signal. Compared with the fast Fourier transform, the Prony algorithm overcomes the shortcomings of its spectral leakage and low frequency resolution. Dong[11] established a Labview-based spindle vibration detection and analysis system to achieve acquisition, processing and analysis of vibration signals, reducing hardware costs. Mou Yu [12] obtained experimentally obtained all-phase FFT algorithms with high phase extraction accuracy. Wang Zhaohua[13] rigorously proves the phase invariance of all-phase FFT. Guo[14] used correlation analysis to achieve amplitude and phase extraction of vibration signals. Xie[15] proposed an improved wavelet threshold denoising method to process vibration signals. Zhang Shihai[16] proposed a comprehensive method for high-precision unbalanced vibration signal separation based on signal prediction and extension, EMD and correlation analysis of time series model. Li Chuanjiang[17] used the three-time spline interpolation method to obtain the instantaneous frequency of the rotor from the key phase signal, construct an unbalanced signal from the instantaneous frequency, and then use the least squares method to identify the amplitude and phase of the unbalanced signal. Wang zhan [18] verified the accuracy of the cross-correlation algorithm in extracting amplitude and phase by comparing the vibration response of the spindle system under experimental and simulated conditions.

In order to make the extraction of the vibration signal have higher precision, the vibration signal of the spindle is extracted on the basis of the predecessor using the all-phase FFT

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vibration signal processing method, and the effectiveness of the method on the spindle vibration signal extraction is verified by experiments.

II. BASED ON ALL-PHASE FFT VIBRATION SIGNAL PROCESSING METHOD

The all-phase fast Fourier[20] transform method was first proposed by Wang Zhaohua and Hou Zhengxin of Tianjin University in 2003. After continuous development, it has become an important tool in digital signal processing. The all phase FFT is based on the improvement of FFT, the only difference is that they differ in the preprocessing of the signal.

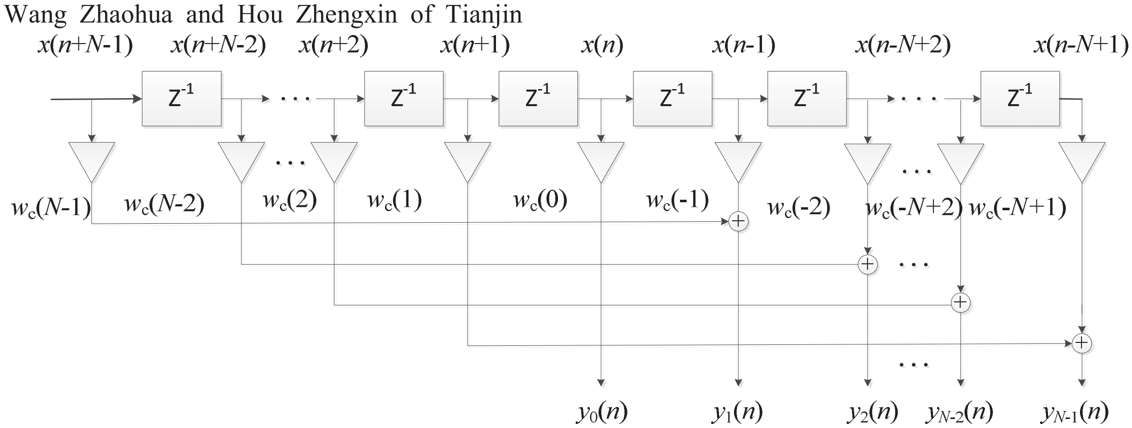

Figure. 1 Flow chart of all-phase data preprocessing

Figure 1 is a unified flow of all-phase data preprocessing It can be seen from the figure that the discrete signal of length (2N-1) is input first, and then the signals of these lengths are weighted by the convolution window w_c, and then each data weighting result is isolated by N delays. The time unit is superimposed and N data is output.

After the preprocessing of the input sequence is performed, the signal needs to be spectrally analyzed, that is, the vibration signal is processed. Spectral analysis yields the amplitude and phase of the vibration signal. Now list the N-point N-dimensional vectors of the time series x(0):

$$\begin{aligned} \mathbf{x}_0 &= \left[x(0), x(1), \cdots, x(N-1)\right]^{\mathrm{T}} \\ \mathbf{x}_1 &= \left[x(-1), x(0), \cdots, x(N-2)\right]^{\mathrm{T}} \\ &\cdots\cdots\cdots \\ \mathbf{x}_{N-1} &= \left[x(-N+1), x(-N+2), \cdots, x(0)\right]^{\mathrm{T}} \end{aligned} \tag{1}$$

Then move each x(0) in x_0 to x_{n-1} to the first position to get another N N-dimensional vectors:

$$\begin{aligned} \mathbf{x}_0' &= \left[x(0), x(1), \cdots, x(N-1)\right]^{\mathrm{T}} \\ \mathbf{x}_1' &= \left[x(0), x(1), \cdots, x(-1)\right]^{\mathrm{T}} \\ &\cdots\cdots\cdots \\ \mathbf{x}_{N-1}' &= \left[x(0), x(-N+1), \cdots, x(-1)\right]^{\mathrm{T}} \end{aligned} \tag{2}$$

Align x(0) and take the average value to get the all-phase data vector:

$$\mathbf{x}_{\mathrm{ap}} = \frac{1}{N}\begin{bmatrix} Nx(0) \\ (N-1)x(1) + x(-N+1) \\ \cdots \\ x(N-1) + (N-1)x(-1) \end{bmatrix} \tag{3}$$

According to the shifting property of DFT, Equation 1 $x_i'(n)$ Discrete Fourier transform $X_i'(k)$ And formula 2 $x_i(n)$ Discrete Fourier transform $X_i'(k)$. There is a very clear relationship between:

$$\begin{aligned} & X_i'(k) = X_i(k) \mathrm{e}^{j\frac{2\pi}{N}ik} \\ & i, k = 0, 1, \cdots, N-1 \end{aligned} \tag{4}$$

For equation 4 $X_i'(k)$. The summation average is the output of the all-phase FFT:

$$\begin{aligned} & X_{\mathrm{ap}}(k) = \frac{1}{N}\sum_{i=0}^{N-1} X_i'(k) = \\ & \frac{1}{N}\sum_{i=0}^{N-1} X_i(k) \mathrm{e}^{j\frac{2\pi}{N}ik} = \\ & \frac{\mathrm{e}^{j\phi_0}}{N^2} \cdot \frac{\sin^2\left[\pi(\beta - k)\right]}{\sin^2\left[\pi(\beta - k)/N\right]} \end{aligned} \tag{5}$$

III. HIGH-SPEED SPINDLE VIBRATION SIGNAL EXTRACTION EXPERIMENT

The experimental platform consists of a motor, a spindle, a computer control unit, a vibration sensor, and a balancing device. The main requirement of this experiment is the displacement of the spindle vibration. Considering the surrounding environment, the vibration frequency and amplitude range, the compliance degree of the supporting instrument and the cost, etc., the eddy current sensor is selected as the displacement measuring sensor of this experiment. The data collector uses National Instruments' (NI) data acquisition system. In the experiment, NI 9239 was used to synchronously collect the signals of three hall elements.

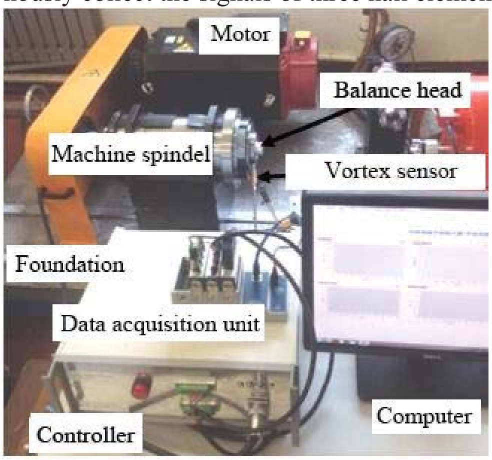

Figure.2 Experimental platform

Vibration signal extraction experiments were performed on high-speed spindles using the all-phase FFT method. The experiment uses labview software to write a all-phase FFT program to extract the amplitude and phase of the fundamental vibration signal of the spindle. When the spindle is between 1000r/min and 3500r/min, the interval is 500r/min. The added unbalanced masses were 16.5 g, 22 g and 27.5.The phase of the amplitude of the spindle is extracted using an all-phase FFT method.

Table I Amplitude and phase extraction of 16.5g unbalanced mass All-Phase FTT

Speed / r / min	**Amplitude / µm**	**Phase / °**
1000	4.68	57.58
1500	9.21	58.00
2000	8.86	59.64
2500	5.01	63.47
3000	8.10	61.66
3500	8.18	56.35

Table II Amplitude and phase extraction of 22g unbalanced mass All-Phase FTT

Speed / r / min	**Amplitude / µm**	**Phase / °**
1000	13.12	59.67
1500	14.98	58.65
2000	20.21	64.82
2500	11.86	62.88
3000	14.53	57.12
3500	13.44	55.24

Table III Amplitude and phase extraction of 27.5g unbalanced mass All-Phase FTT

Speed / r / min	**Amplitude / µm**	**Phase / °**
1000	17.50	62.11
1500	26.10	59.75
2000	13.17	64.88
2500	16.72	56.67
3000	23.35	55.45
3500	23.51	65.54

From Table 1 to Table III, it can be seen that the stability of the unbalanced phase of the all-phase FFT in the extraction of the unbalanced vibration signal of the spindle, although not as stable, still maintains high stability, while the stability effect on the amplitude is not ideal. At 16.5g unbalanced mass, the maximum vibration phase difference is 3.47°, the amplitude difference is 4.63. Under 22g unbalanced mass, the maximum vibration phase difference is 4.82°, the amplitude difference is 8.35, and the imbalance is 27.5g. Under mass, the maximum vibration phase difference is 5.54° and the amplitude difference is 12.93.

IV. Comparison of Spindle Vibration Signal Processing With All-Phase FFT And Cross-Correlation Method

Now compare this method with the built-in on-line dynamic equilibrium method, called cross correlation analysis [20]. The spindle speed is 2000r/min, and the test mass is 8.5g amplitude and phase. Figure 3 and 4 are obtained. As can be seen from Figure 3, Online dynamic balancing device system and full-phase FFT extract the amplitude of spindle vibration signal, the amplitude of vibration shows great randomness, but basically remains in the same range.

The amplitude of all-phase FFT varies with high randomness. However, as can be seen from Fig.4, the all-phase FFT has the advantage of stability in phase spectrum analysis. The phase of the original method is distributed around 30°,and the final average is 32.86°.The phase spectrum analysis of the all-phase FFT is very stable, showing a straight line in almost 50s, and the average phase value is 30.12.

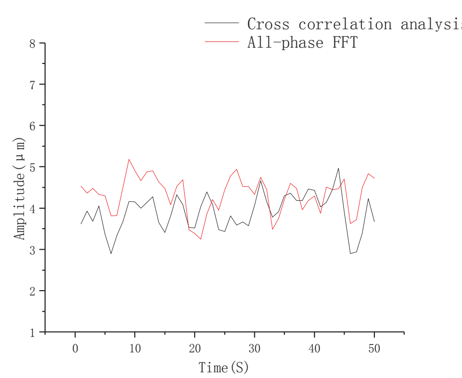

Figure. 3 Amplitude contrast

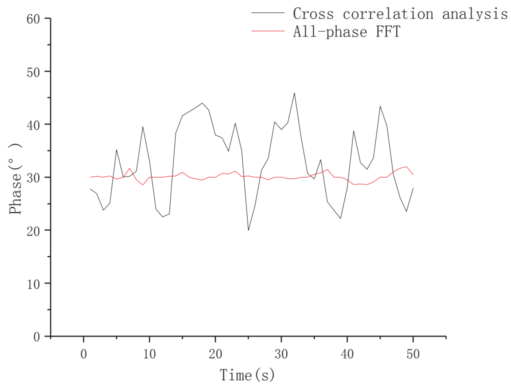

Figure. 4 Phase contrast

The vibration signal extracted by the cross-correlation algorithm and the all-phase FFT method are used to extract the vibration signals respectively as the input of the parameters of the on-line dynamic balance of the influence coefficient method, and the parameters such as the influence coefficient, the correction quality, the residual unbalance, and the balance of the spindle on-line test are obtained. The comparison and experimental data are shown in Figure 5 and Table IV.

Table IV Spindle balancing experiment data

Dynamic balance parameter	**All phase FFT**	**Cross correlation analysis**
Initial imbalance	13.39μm∠30°	14.79μm∠85°
Trial weight	10g∠210°	10g∠265°
Unbalanced amount after aggravation	5.36μm∠85°	5.84μm∠110°
Correction weight	11.9g∠230°	15.1g∠345°
Influence coefficient / μm / (g · mm)	0.0161∠337°	0.014∠260°

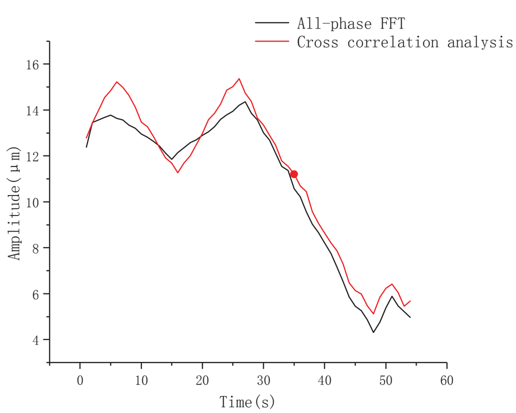

Figure. 5 Amplitude comparison of the two methods

The influence coefficient method requires a calibration front and detection surface on the rotor. First, the initial unbalance vibration is measured to be A, and then the counterweight Q is added. After the measurement, the unbalance vibration value is measured to be B. The influence coefficient $\alpha = (B - A)/Q$ is calculated, and the corrected counterweight is $Q_0 = A/\alpha$.

Table V Amplitude comparison between the two methods

Time/s	**all-phase FFT/μm**	**cross-correlation analysis/μm**
0	12.39	12.79
6	13.64	15.23
12	12.64	12.84
18	12.58	12.01
24	13.79	14.86
30	13.01	13.34
36	10.22	10.69
42	7.16	7.86
48	4.31	5.12
54	4.96	5.68

The influence coefficient method online dynamic balance has shown that the vibration signal extracted by the all-phase FFT algorithm is input as the influence coefficient method, the amplitude of the vibration is obviously reduced, the balance rate is 65.21%, The balance rate is equal to the amplitude before balance minus the amplitude after balance, divided by the amplitude before balance, and the residual balance is lower than the cross-correlation method. Unbalanced vibration is effectively suppressed. It can be seen that the embedded all-phase FFT algorithm program is applied to the dynamic balance software, and each performance parameter meets the design requirements, and the effect is ideal in the single-plane dynamic balancing process, and the test system can be applied to the dynamic balance of other similar working conditions, and Promoted to high-speed spindle double-sided dynamic balance test.

V. CONCLUSION

Simulate the four fundamental frequency signal methods for dealing with spindle vibration, and find that the all-phase FFT has stability advantage in phase spectrum analysis, and the extracted phase value is more accurate than the other three processing methods.

The stability of the unbalanced phase of the all-phase FFT in the extraction of the unbalanced vibration signal of the spindle, although not quite stable, still maintains high stability, and the stability effect on the amplitude is not ideal.

Compared with the cross-correlation method, the all-phase FFT has no advantage over the original method in the amplitude-frequency processing. However, it has the advantage of stability in phase spectrum analysis. The phase spectrum analysis of the all-phase FFT is very stable, showing a straight line in almost 50s, and the average phase value is 30.12.The vibration signal extracted by the all-phase FFT algorithm is input as the influence coefficient method. The amplitude of the vibration is significantly reduced, the balance rate reaches 65.21%, the residual balance is lower than the value obtained by the cross-correlation method, and the unbalanced vibration is effectively suppressed.

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REFERENCES

[1] Gao, R., Pei-Qing, Y. E., Jiang, K. R., & Wen, L. I. (2010). Vibration signal processing of motor spindle based on wavelet singularity. *Journal of Jilin University, 40*(4), 1025-1028.

[2] Guo J H, Wu X, Liu X q, &Yan T Y. Study on the extraction method of amplitude phase of vibration signal in rotor dynamic balance [J]. Machinery & electronics, 2011(10):6-10.

[3] Feng Yingpeng. Research and implementation of vibration signal processing method in high-precision dynamic balance measurement [D]. Shanghai: Shanghai normal university,2013.

[4] Jiang Z N, Feng K, Gao J J. Application of phase compensation filter method in automatic balance system [J]. Vibration.Testing and diagnosis, 2006(3):234-239.

[5] Xu J, Luo Y C, Zhang L,&Guan M. Research on vibration signal extraction method in online dynamic balance [J]. Journal of electronic measurement and instrumentation. 2012,26(11):972-976.

[6] SHANG Yiqi, CAO Yiqing, CHAI Yanli, ZHANG Ningning,&LOU Lifen. Analysis of amplitude and phase calculation method of vibration signal [J].Measurement technology, 2010(4) : 30 -- 32.

[7] Zhang S H , Cai Y J.A new double-face online dynamic balance device and its control system for high speed machine tool spindle[J].Journal of Vibration and Control.2016,22(4):1037-1048

[8] P.Duhamael,M．Vetterli．Fast fourier transforlTl：A tutorial review and a state of the art[J]．Signal Processing,1990,19(4)：259—299．

[9] Wang S L,Ding Y F, Wang L, et al. Vibration Signal Measurement and Analysis of Machine Spindle Based on LabVIEW[J]. Modular Machine Tool & Automatic Manufacturing Technique, 2014.

[10] Wang X. Research on vibration signal processing method in online dynamic balance based on the second generation wavelet [D]. Hefei: hefei university of technology.2014:44-50.

[11] Dong F , Yang J C , Gao T Z , et al. The Research and Design of Virtual Spindle Vibration Test System[J]. Applied Mechanics and Materials, 2014, 556-562:2903-2905.

[12] Mou Y, Pan X, Gao J J,&Wu H Q. Study on real-time phase extraction method of unbalanced vibration signal based on LabVIEW [J]. Industrial instruments and automation devices.2015,5:17-20.

[13] Wang Z H, Huang X D, Yang W. FFT phase measurement method [J]. World science and technology research and development, 2007, 29(4).

[14] Guo F, Ma X M, Xu H J. Design of online dynamic balance measurement system based on LabVIEW [J]. Information technology.2015.

[15] Xie Z J , Song B Y , Zhang Y , et al. Application of an Improved Wavelet Threshold Denoising Method for Vibration Signal Processing[J]. Advanced Materials Research, 2014, 889-890:799-806.

[16] Zhang S ,Wu L, Teng X,Qu C,&Zhou D S . Study on Imbalance Vibration Signal Separation of Motor Spindle Based on EMD Method[C]// International Conference on Digital Manufacturing & Automation. IEEE Computer Society, 2010.

[17] Li C J, Fei M Q, Zhang Z Q. A method for extracting unbalanced signals at non-stationary rotating speeds [J]. Vibration, testing and diagnosis.2016,36(2):390-395.

[18] Wang Z, Zhu F L, Tu W. Study on vibration signal extraction of spindle by cross correlation method [J]. Modular machine tools and automatic processing technology.2018, (2) : 87-93.

[19] Wang Z H, Hou Z X, Su F. Spectrum analysis of all phase FFT [C]// annual meeting of communication theory and signal processing. 2003.

[20] Pan X, Wu H Q, Gao J J, et al. Study on online active balancing system of rotating machinery and target control method[J]. Wseas Transactions on Systems.