Spindle vibration signal extraction method based on improved all phase Fast Fourier Transform

Z Wang 1, SY Du 1* and LC ROŞCA2
1 School of Mechanical Engineering, Shenyang Jianzhu University, China
2 Faculty of Mechanical Engineering, Transilvania University of Brasov, Romania
*ttdusiyuan@gmail.com

Abstract. In the modern processing technology, the machine tool plays an irreplaceable role as the main processing tool, and its machining accuracy directly affects the processing quality of the part. Because the spindle vibration caused by the rotor mass imbalance will seriously affect the machining accuracy of the machine tool, it is necessary to dynamically balance the spindle. The key step of dynamic balancing is to accurately extract the characteristics of the vibration signal, the phase of the vibration signal of the spindle was extracted by the all phase fast Fourier transform, the amplitude of vibration signal was extracted by cross correlation analysis, the results are applied to the influence coefficient method to realize the dynamic balance of spindle vibration. The results show that the vibration signal feature extraction method combined with the results of the two extraction methods has high precision and stability.

1. Introduction
Machine tools as the most basic equipment in the modern processing process, the machining accuracy plays a decisive role in the quality of the product. Among the many reasons that affect the machining accuracy, the machining accuracy is reduced due to the vibration caused by the imbalance of the machine spindle. When the spindle has a large unbalanced mass during operation, unbalanced centrifugal force will be generated. When the unbalanced centrifugal force due to unbalanced mass is not balanced by the outside, the spindle will generate strong vibration. With the increase of the rotational speed, the centrifugal force will become larger and larger, which seriously affects the machining accuracy of the machine tool and will have a great impact on the processing of the parts. Moreover, the machine tool spindle can’t avoid vibration during operation, so it is necessary to balance the centrifugal force generated by the unbalanced mass of the spindle. The key step affecting the balance accuracy is the extraction of the amplitude phase information of the unbalanced vibration signal.

At present, how to extract the unbalanced signal of the main shaft is the primary problem that needs to be solved to realize the on-line dynamic balance of the main shaft. The research on the extraction and processing of the rotor vibration signal has always been a hot topic in the research field at present, and has achieved certain theoretical results. Guo Junhua [1] have found that the signal is truncated by the whole cycle and processed by DFT method with high extraction precision, but the spectrum leakage and fence effect will occur when DFT is processed. Jiang Zhinong [2] and Xu Juan [3] eliminated the influence of phase lag on phase extraction accuracy by cross-correlation processing the signal, and the extracted amplitude and phase were significantly improved compared with the traditional cross-correlation method. Shang Yiqi [4] proved that the all-phase time-shift phase difference method has
higher precision. Zhang Shihai et al. [5] used the least squares algorithm to fit the fundamental frequency signal, which has certain advantages compared with the traditional fast Fourier transform and discrete Fourier transform algorithm [6]. Wang Xu et al. [7] used the Prony method to extract the amplitude and phase information of the vibration signal. Compared with the fast Fourier transform method, the Prony algorithm overcomes the shortcomings of spectrum leakage and low frequency resolution. Mou Yu et al. [8] obtained experimental results that the all-phase FFT algorithm has higher phase extraction accuracy. Wang Zhaohua [9] proved that the all-phase FFT method has the characteristics of phase invariance. Guo Fan et al. [10] used the method of correlation analysis to realize the amplitude and phase extraction of vibration signals. By comparing the vibration response of the spindle system under experimental and simulation conditions, Wang Zhan et al. [11] verified the extraction accuracy of the amplitude and phase of the cross-correlation algorithm. Gao et al. [12] used inverse wavelet transform to reconstruct the signal and extract the vibration signal characteristics of the motor spindle. Dong [13] established the spindle vibration detection and analysis system based on LabVIEW to realize the acquisition, processing and analysis of vibration signals and reduce the hardware cost. Wang [14] used virtual instrument to design the vibration measurement system and could effectively track the vibration of the spindle. Xie [15] proposed an improved wavelet threshold de-noising method to process vibration signals. From the above research results, the all-phase FFT has higher precision in phase extraction and the cross-correlation method has great advantages in amplitude extraction. Therefore, the amplitude and phase of the spindle vibration signal are extracted by the combination of the full phase FFT method and the cross-correlation method. Experimental results show that the method is effective in extracting vibration signal of spindle.

2. Cross correlation method

In the process of signal acquisition, the detection and extraction of vibration signals is very complicated. There is no strict and accurate formula to accurately represent them. In most cases, vibration signal contains fundamental frequency, multiple frequency, sub-multiple frequency, random vibration signal, etc. The expression of the unbalanced vibration signal can be expressed as follows:

\[
x(t) = e_0 + e \sin(\omega t + \phi) + \sum_{i=2}^{n} e_i \sin(i\omega t + \phi_i) + s(t)
\]

In the equation: \(e_0\) is a DC component; \(i\omega\) is for each different signal frequency; \(\phi_i\) is the phase value of each frequency signal; \(s(t)\) is interference signals such as noise; where the fundamental component signals: \(e \sin(\omega t + \phi)\) is the vibration signal that needs to be obtained.

Set the standard sine signal and cosine signal with frequency \(\omega\) and phase 0 as respectively

\[
g(t) = \begin{cases} 
\sin \omega t, & 0 < t < 1 \\
0, & \text{other}
\end{cases}
\quad h(t) = \begin{cases} 
\cos \omega t, & 0 < t < T \\
0, & \text{other}
\end{cases}
\]

Two standard sine and cosine signals \(g(t)\) and \(h(t)\) are cross-correlated with vibration signal \(x(t)\) respectively:

\[
R_{gx}(0) = \int_{-\infty}^{\infty} x(t)g(t)dt = \frac{T e}{2} \sin \phi, \quad t \in [-\infty, +\infty]
\]

\[
R_{gh}(0) = \int_{-\infty}^{\infty} x(t)h(t)dt = \frac{T e}{2} \cos \phi, \quad t \in [-\infty, +\infty]
\]

The amplitude and phase of the obtained fundamental frequency signal are as follows:

\[
e = \frac{\sqrt{R_{gx}(0)^2 + R_{gh}(0)^2}}{T}
\]
\[ \varphi = \arctan \frac{R_{yy}(0)}{R_{xy}(0)}, \quad \varphi \in [0, 2\pi] \]  

The process of extracting the vibration characteristic signal by using the correlation algorithm is actually calculating the average value, and the cross-correlation algorithm can suppress and eliminate the interference component such as the DC component and the noise contained in the vibration signal. The cross-correlation algorithm can ensure the accuracy of extracting information, and does not need to perform all-cycle sampling on the initial vibration signal, and the calculation amount is not large.

3. All phase FFT

The all-phase fast Fourier transform method was first proposed by Wang Zhaohua and Hou Zhengxin of Tianjin University in 2007. 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 pre-processing of the signal.

![Flow chart of all-phase data preprocessing.](image)

Figure 1. Flow chart of all-phase data preprocessing.

Figure 1 is a unified flow of all-phase data preprocessing. First, input the (2N-1) length of the discrete signal, and then use the convolution window \( w_c \) to weight the signals of these lengths, and then separate each data weighting result by \( N \) delay units for superposition, and output \( N \) Data. After the pre-processing 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 \( x(0) \):

\[
x_0 = [x(0), x(1), \cdots, x(N - 1)]^T \\
x_1 = [x(-1), x(0), \cdots, x(N - 2)]^T \\
\cdots \\
x_{N-1} = [x(-N + 1), x(-N + 2), \cdots, x(0)]^T
\]  

Then move each \( x(0) \) in \( x_0 \) to \( x_1 \) to the first place to get another \( N \) N-dimensional vectors:

\[
x_0^\prime = [x(0), x(1), \cdots, x(N - 1)]^T \\
x_1^\prime = [x(0), x(1), \cdots, x(-1)]^T \\
\cdots \\
x_{N-1}^\prime = [x(0), x(-N + 1), \cdots, x(-1)]^T
\]
By aligning $x(0)$ and taking the average, we can get the all-phase data vector:

$$
x_{ap} = \frac{1}{N} \left[ Nx(0), (N - 1)x(1) + x(-N + 1), \ldots, x(N - 1), (N - 1)x(-1) \right]^T
$$

(9)

According to the shifting property of DFT, the pair of the formula $x'(n)$ discrete Fourier transform $X'(k)$. And $x(n)$ discrete fourier transform $X(k)$. There is a very clear relationship between:

$$X'(k) = X(k) e^{\frac{2\pi i k}{N}} \quad i, k = 0, 1, \ldots, N - 1
$$

(10)

For equation (10), $X'(k)$ the summation average is the output of the all phase FFT:

$$X_{ap}(k) = \frac{1}{N} \sum_{i=0}^{N-1} X'(k) = \frac{1}{N} \sum_{i=0}^{N-1} X_i(k) e^{\frac{2\pi i k}{N}} \sin^2 \left[ \frac{\pi (\beta - k)}{N} \right]$$

(11)

From equation (11), it is known that $\phi_0$ is the phase value of full-phase FFT, and $X_{ap}(k)$ is the amplitude of full-phase FFT.

4. Simulation and experiment

Use LabVIEW to write the cross-correlation method, and use the formula node to write the MATLAB all-phase FFT program. The two programs were connected together. The cross-correlation method outputs the vibration signal amplitude and the all-phase FFT output phase. We call this method the improved full phase FFT method.

The vibration signal of the main shaft is mainly composed of the fundamental frequency signal of the main shaft and environmental noise. Ambient noise can be divided into multiplier signals and Gaussian white noise. There is also a DC component of the sensor. Concrete equation (12):

$$x(t) = a_0 + \sum_{i=1}^{n} a_i \sin (i\omega t + \phi_i) + s(t)
$$

(12)

In the equation, $a_0$ is a DC component; $\sum_{i=1}^{n} a_i \sin (i\omega t + \phi_i)$ is the fundamental frequency signal and the multiplied signal, which are expressed as the vibration of the main shaft, are the fundamental frequency signal when $i=1$, and are the multiplied signals when $i>1$. $a_i$ for amplitude, $\phi_i$ for phase $s(t)$ it is a noise signal, including uniform white noise and white Gaussian noise.

The above is a basic mode of the spindle vibration signal, which is included in the signal collected by the sensor. Therefore, it is necessary to filter to obtain a fundamental frequency signal. For the spindle of experiment, the time domain waveform of the simulated vibration signal can be set as: the uniform white noise is the software self-contained, the signal standard deviation of Gaussian white noise is 1, the DC component is 2 $\mu$m, the frequency conversion signal is 25 Hz, the corresponding vibration amplitude value is 5 $\mu$m, the double-frequency vibration signal is 3 $\mu$m, the triple-frequency vibration signal is 2 $\mu$m, and the corresponding initial phases are 30°, 20° and 10°, respectively. The sampling point is 1000, and the sampling frequency is 1000 Hz. The corresponding function is as follows:

$$x(t) = 2 + 5\sin (50\pi t + \pi/6) + 3\sin (100\pi t + \pi/9) + 2\sin (150\pi t + \pi/18) + s(t)
$$

(13)

Vibration signal extraction simulation is performed by two methods: cross-correlation method and improved all-phase FFT. In the measurement, the fundamental frequency of the spindle is 25 Hz, but due to sensor accuracy and system defects, the extracted vibration signal generally does not reach 25 Hz.
Table 1. All-cycle comparison.

|                      | Cross correlation method | Improved all phase FFT |
|----------------------|--------------------------|------------------------|
| Amplitude / μm       | 4.78                     | 4.78                   |
| Phase maximum / °    | 30.71                    | 31.2                   |
| Phase minimum / °    | 27.74                    | 29.94                  |
| Difference / °       | 2.97                     | 1.26                   |

Table 2. Non-all-cycle comparison.

|                      | Cross correlation method | Improved all phase FFT |
|----------------------|--------------------------|------------------------|
| Amplitude / μm       | 4.70                     | 4.70                   |
| Phase maximum / °    | 33.97                    | 31.2                   |
| Phase minimum / °    | 28.01                    | 29.77                  |
| Difference / °       | 5.96                     | 1.43                   |

The extraction results are shown in table 1 and table 2. Shown, it can be seen that the all cycle frequency and the non-all-cycle frequency have a great influence on the signal processing results. It can be seen from the data in the table that the improved all-phase FFT is more accurate than the cross-correlation method in terms of amplitude extraction and phase extraction, and the jitter amplitude is small. Therefore, the following experimental verification can be performed.

5. Experimental verification

The improved all-phase FFT is applied as an input to the dynamic balance system. The dynamic balance system uses the influence coefficient method to perform dynamic balancing, and compares the method with the cross-correlation method as an input. The experimental platform introduces a mechanical spindle driven by a motor, and a balance head is installed inside, and the unbalanced mass is added by a manual method. Use National Instruments’ (NI) data acquisition system with built-in cross-correlation algorithm for dynamic balancing. The experiment uses the NI 9239 to simultaneously acquire the signals of the three Hall elements. The data calculated by the influence coefficient method is dynamically balanced by the controller driving the balance head. The experimental platform is shown in figure 2.

![Experimental platform](image)

**Figure 2.** Experimental platform.
Below is the relevant data of the experiment. In the case of a spindle rotation speed of 3000 r/min, the amplitude and phase obtained by massing 8.5 g·mm were obtained, as shown in figures 3 to 4. It can be seen from figure 3 that the amplitudes of the spindle vibration signals extracted by the improved all phase FFT method and the cross-correlation method, although having large fluctuations, are all in the same range. That is, the improved all phase FFT method is comparable to the cross-correlation method in amplitude processing.

However, it is known from figure 4 that the improved all phase FFT method has the advantage of stability in the phase spectrum analysis of the spindle vibration signal, and the phase distribution of the cross-correlation method is about 35°, and there is a large fluctuation. The phase spectrum distribution of the improved all phase FFT method is very stable, showing a straight line within almost 60s, which shows the advantage in phase extraction.

![Figure 3. 3000 r/min amplitude contrast.](image)

![Figure 4. 3000 r/min phase contrast.](image)

The vibration signal extracted by the improved all phase FFT method and the vibration signal extracted by the cross-correlation method are used as the influence coefficient method for online dynamic balance under the experimental conditions of the speed of 3000 r/min, 4000 r/min and the unbalanced mass of 8.5 g·mm.

The vibration characteristics extracted by the two methods were used as input parameters to test the dynamic balance effect, the experimental data are shown in figure 5 and figure 6.

![Figure 5. 3000 r/min contrast.](image)

![Figure 6. 4000 r/min contrast.](image)

The online dynamic balance experiment shows that the vibration signal extracted by improved full phase FFT method is used as the input of the influence coefficient method, the amplitude of the vibration...
is obviously reduced, the balance rate is close to 70%, and the balance effect is better than the cross-correlation method built into the existing device. The dynamic balance is ideal.

6. Conclusion

Compared with the cross-correlation method, the improved all phase FFT method draws the advantages of the all-phase FFT and cross-correlation method. There is a great advantage in amplitude and phase analysis. In the phase spectrum analysis, there is a straight line within almost 60s, and the average phase value is 29.71.

The vibration signal extracted by the method is used as the input of the influence coefficient method. The amplitude of the vibration is obviously reduced, the balance rate is close to 70%, the residual balance is lower than the residual balance of the cross-correlation method, and the unbalanced vibration is effectively suppressed. It can be seen that the improved all phase FFT method is applied to the dynamic balance software, and the performance parameters meet the design requirements.

The single-plane dynamic balance process is ideal, and the test system can be applied to the dynamic balance of other similar working conditions, and is extended to high speed spindle double-sided dynamic balance test.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (No.51805337; No.51675353; No.51705340), National Natural Science Foundation of Liaoning Provincial (No.20170540746).

References

[1] Junhua G, Xing W, Xiaochin L and Tianyan Y 2011 J. Machinery & electronics 10 pp 6-10
[2] Zhinong J, Kun F and Jinji G 2006 J. journal of vibration measurement & diagnosis 3 pp 234-39
[3] Juan X, Yichao L, Li Z and Meng G 2012 J. Electr. Measur. Instr. 44 pp 972-976
[4] Yiqi S, Yiqing C, Yanli C, Ningning Z and Lifen L 2010 J. Metrology & Measurement Technology 4 pp 30-32
[5] Shihai Z and Yujun C 2016 J. Journal of Vibration and Control 4 pp 1037-1048
[6] Duhamael P and Vetterli M 1990 J. Signal Processing 19 pp 259-299
[7] Xu W 2014 D. Hefei university of technology pp 44-50.
[8] Yu M, Xin P, Jinji G and Haiqi W 2015 J. Industrial Instrumentation & Automation 5 pp 17-20
[9] Zhaohua W, Xiangdong H and Wei Y 2007 J. World Sci-Tech R & D 29 pp 28-32
[10] Fan G, Xuming M and Huajie X 2015 J. Information technology 44 pp 138-140
[11] Zhan W, Fenglong Z and Wei T 2018 J. Modul. Mach. Tool Autom. Manuf. Techn. 2 pp 87-93
[12] Rong G, Peiqing Y, Kerong J and Wen L 2010 J. Journal of Jilin University 40 pp 1025-1028
[13] Fang D, Jiancheng Y and Tianzhu G 2014 J. Applied Mechanics and Materials pp 556-562
[14] Shunli W, Yufeng D, Lin W, Buyun S and Qibing L 2014 J. Modular Machine Tool & Automatic Manufacturing Technique
[15] Zhijie X, Baoyu S, Yang Z and Feng Z 2014 J. Advanced Materials Research pp 799-806