The Application of Rearrangement Spectrogram to the Dynamic Measurement of Rotation Motion Error of Lathe Spindles

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***Abstract* — Rotation precision of lathe spindle is an important indicator to measure the lathe performance. Owing to traditional Fourier transform lacking of locality and Wigner-Ville distribution having serious cross-interference, a method of rearrangement spectrogram was to extract the parameter of integrated error signal, which was picked up by the sensor in dynamic measurement system. Frequency estimation accuracy of eccentricity error caused when installing standard ball was improved by the method of rearrangement spectrogram, and then the eccentricity error was effectively separated by digital filter. The rotation precision on C616 with the proposed method in this paper was compared with DJ-HZ-1 machine tool rotation precision measuring instrument. Experimental results show that the proposed measuring method in this paper can be accurately measured the spindle rotation precision.**

Keywords - rotation precision; rearrangement spectrogram; non-stationary signal; time- frequency analysis

I. INTRODUCTION

Lathe spindle will produce rotation error in the process of turning due to many factors such as flexure deformation, forced deformation, thermal deformation of spindle, geometry precision of journals and bearings, as well as changes in lubricant. The Rotation error in the process of turning will inevitably affect part precision. Some form errors of section profile for parts will occur such as ellipticity, waviness, etc.. Therefore, real-time measurement of the lathe spindle rotation accuracy becomes an important measuring subject [1].

The spindle rotation error is random, which mainly manifests as high frequency noise. Since installation eccentric error and surface shape error of measuring reference exist objectively when measuring the spindle rotation error, the signal collected by sensors often contains some low frequency components. The frequency characteristic of the sampled signal is changed with time, which belongs to non-stationary signal. Usually, time-frequency analysis can analyze non-stationary signal. Classic analysis and processing method for the sampled signal is Fourier transform, which lacks of local information. Fourier transform is unable to reveal certain frequency component appearing at what time and changing over time[2]. Wigner-Ville distribution is quadratic transformation of signal, but it has many cross-terms in the time-frequency[3]. Time-frequency concentration in time-frequency distribution would be improved by rearrangement spectrogram, and this method also can suppress certain cross-term. Therefore, some of the low-frequency signal's frequency in sampled signals could be estimated by time-frequency analysis method of the rearrangement spectrogram.

After analyzing the measuring principle and the rotation error, a method of rearrangement spectrogram was to extract the parameter of integrated error signal, which was picked up by the sensor in dynamic measurement system. Then the eccentricity error caused when installing standard ball is effectively separated by digital filtering, and the least square circle (LSC) method to evaluate the error-motion is used[4].

II. MEASURING PRINCIPLE

When the lathe spindle has rotary movement, actual position of the spindle rotation center in each moment change instantaneously, and unstable rotation center directly affects machining accuracy and surface quality of work pieces. Since the rotation axis is invisible, a high roundness ball is used as base level to reflect the rotation axis when measuring. Moreover, taking into account the impact of the spindle error-motion in the axial component which acts on the processing surface is small, so a displacement sensor could be used to measure error-motion of the sensitive direction [5-6].

The error-motion rotation of lathe spindle is picked up by the eddy current sensor. The sampled signal is firstly amplified and filtered via conditioning circuits, and then sent to the data acquisition card for A/D conversion. Total error signal picked up by the eddy current sensor consist of two parts, which are the eccentricity error caused when installing standard ball and the spindle rotation error. The maximum values for energy distribution of the total error signal $Z_t^{'}$ are obtained by the rearrangement spectrogram. Power spectrum analysis for vector consisted of maximum values is conducted, and the frequency of the eccentric error $e\sin(\omega t+\phi_0)$ is directly read out according to the power spectrum. Then the displacement signal generated by the eccentric error e is removed from the total error signal $Z_t^{'}$.

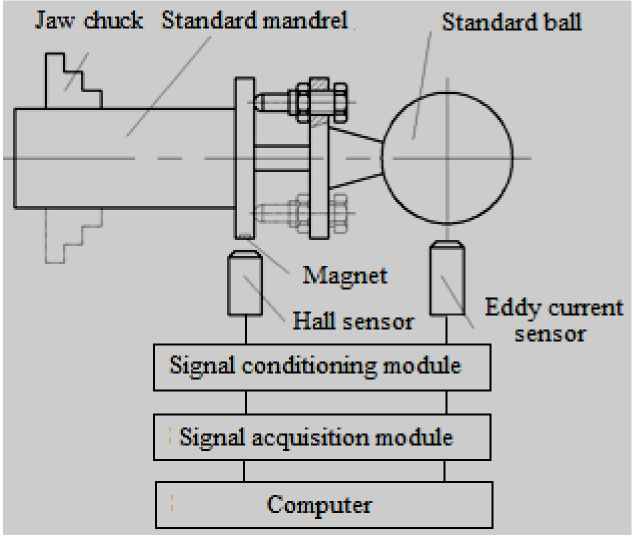

Figure 1. Schematic diagram of measurement system

III. TIME-FREQUENCY ANALYSIS METHOD

A. *Short-time Fourier Transform and Spectrogram*

In order to solve the localized conflict of traditional Fourier transform in processing time and frequency domain, STFT was proposed by Gabor[7]. The STFT goal is to achieve localization in time domain, the signal before the Fourier transform is multiplied by a time window function $\eta(t)$, whose width is very short. Through the moving of $\eta(t)$ on the time axis, the signal is analyzed step by step. STFT of the signal $Z(t)$ can be defined.

$$STFT_Z(t,f)=\int_{-\infty}^{+\infty}Z(t^{'})\eta^{*}(t^{'}-t)e^{-j2\pi ft^{'}}dt^{'} \tag{1}$$

Therefore, Short-time Fourier Transform $STFT_Z(t,f)$ can be understood as Fourier transform of the signal $Z(t^{'})$ near the time point t, that is the local spectrum. Take both sides squared amplitude for STFT.

$$\begin{aligned}S_Z(t,f)&=\left|STFT_Z(t,f)\right|^2\\&=\left|\int_{-\infty}^{+\infty}Z(t^{'})\eta^{*}(t^{'}-t)e^{-j2\pi ft^{'}}dt^{'}\right|^2\end{aligned} \tag{2}$$

Where, $S_Z(t,f)$ is called as spectrogram for $Z(t)$.

B. *Spectrogram Rearrangement*

The initial purpose of rearrangement is to improve the spectrogram effect. According to the previous definition, the spectrogram can be seen as two-dimensional convolution between Wigner-Ville distribution of the signal and Wigner-Ville distribution of the analysis window, that is

$$S_Z(t,f)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}W_Z(s,\xi)W_h(t-s,f-\xi)dsd\xi \tag{3}$$

Where, h is window function, W_h is Wigner-Ville distribution for h. $W_h(t-s,f-\xi)$ constitutes a time-frequency domain near point (t,f) which can be found by equation (4). In this area the weighted average for distribution value of the signal Wigner-Ville is carried out. The rearrangement process is as follows: convert the value at any point (t,f) in spectrogram to another point $(\hat{t},\hat{f})$, This is the focus for energy distribution of the signal around point (t,f), that is:

$$\hat{t}=\frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}sW_Z(s,\xi)W_h(t-s,f-\xi)dsd\xi}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}W_Z(s,\xi)W_h(t-s,f-\xi)dsd\xi} \tag{4}$$

$$\hat{f}=\frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\xi W_Z(s,\xi)W_h(t-s,f-\xi)dsd\xi}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}W_Z(s,\xi)W_h(t-s,f-\xi)dsd\xi} \tag{5}$$

Like this gotten rearrangement spectrogram, the value in any point $(t^{'},f^{'})$ equals to sum of all spectrogram value rearranged to this point, that is:

$$\begin{aligned}&S_Z^{(\gamma)}(t^{'},f^{'})=\\&\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}S_Z(t,f)\delta(t^{'}-\hat{t})\delta(f-\hat{f})dtdf\end{aligned} \tag{6}$$

IV. METHOD MEASURING SYSTEM

A. *Hardware Structure*

Dynamic measurement of the spindle rotation precision of lathe C616 was shown in this paper, Field measuring of the error-motion rotation was shown in Figure 2, Hardware structure of the measuring system consisted of the following measuring objects: computer, lathe C616, reference ball with clamp mechanism, PCI-6024E data acquisition card, OD9000 series eddy current displacement sensor. Above all, the measurement and data processing system with high precision reference ball, eddy current sensor, PCI data acquisition card and measuring software LabWindows/CVI was to dynamically measure the rotation precision of lathe spindle.

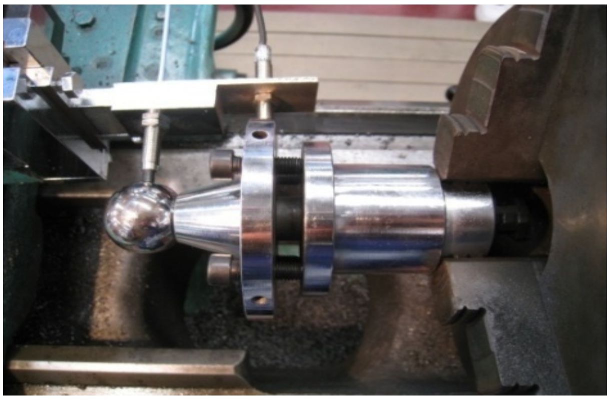

Figure 2.Field measuring of error-motion rotation

B. Measuring soft: LabWindows/CVI.

The error-motion rotation of lathe spindle was measured by the above method, and sampling frequency of the signal was 1024Hz. Original signal of the eddy current sensor output was shown in Figure 3. Spectrogram of the spindle rotation error was shown in Figure 4. Rearrangement spectrogram of the spindle rotation error was shown in Figure 5, and the rearrangement spectrogram had better time-frequency aggregation by comparing Figure 4 and Figure 5. The rearrangement spectrogram was analyzed with power spectrum and shown in Figure 6. The corresponding frequency of eccentricity error caused when installing standard ball was 12.5Hz, and then the error-motion rotation of lathe spindle was obtained by eliminating eccentricity error with low-pass filter. The error-motion rotation of lathe spindle after eliminating eccentricity error was superimposed on the base circle, which had a certain radius, and generated circle image. Moreover, the least square circle (LSC) method was used to evaluate the error-motion.

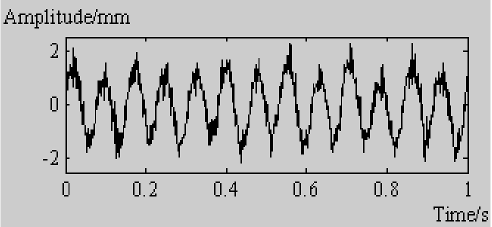

Figure 3. Time-domain diagram of rotation error

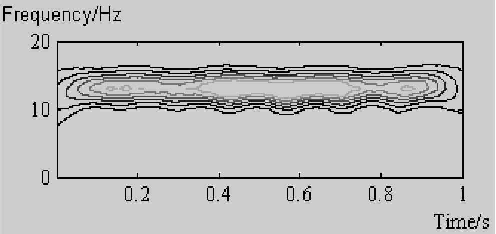

Figure 4. Spectrogram of rotation error

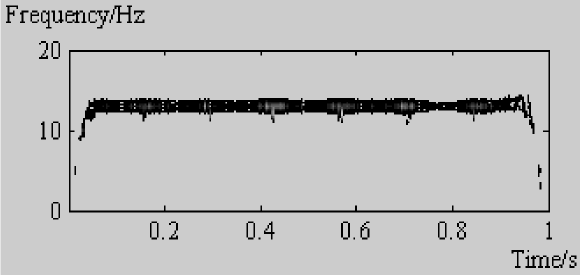

Figure 5. Rearrangement spectrogram of rotation error

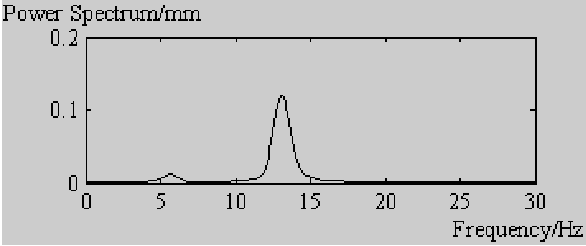

Figure 6.Power spectrum of rearrangement spectrogram

According to error theory, a single sample to evaluate error has larger deviation. The sample number is increased, and the measuring accuracy is correspondingly improved. Depending on the present experiment circumstance, take 10 samples for analysis object. Roundness error values of ten laps spindle rotation accuracy were measured when spindle speed was 750 r/min, and were counted in Table 1. The average of the set of data was 6.28 μm , and the standard deviation of which was 0.42 μm .

Table 1. Count roundness error value（n=750r/min）

Measuring laps	**Roundness error/ μm**	**Measuring laps**	**Roundness error/ μm**
1	6.14	6	6.64
2	6.67	7	6.55
3	5.75	8	6.98
4	5.91	9	5.70
5	6.53	10	5.90

The measuring method in this paper was compared with DJ-HZ-1 machine tool rotation precision measuring instrument, and these two measuring results were in accordance with each other.

V. Conclusion

The rearrangement spectrogram method effectively reduces the cross-interference, and improves the time-frequency aggregation of signal component, and retains high Time-Frequency resolution of Wigner-Ville distribution, which are conducive to extract the parameter of integrated error signal picked up by the sensor. According to non-stationary characteristic of spindle error-motion, the application of rearrangement spectrogram in dynamic measurement for error-motion rotation of lathe spindle was studied in this paper.

Experimental result showed that the rotation on C616 with the proposed method was in accordance with DJ-HZ-1 machine tool rotation precision measuring instrument. In summary, the measuring method was versatile, stable and reliable to complete the measurement of the rotation precision.

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