The State Analysis of Five-axis NC Machine with Large Torque Mechanical Spindle Based on Hilbert Transform

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Abstract. Only five-axis machine with large torque mechanical spindle is capable to complete the process of titanium alloy aerospace structure in general. But mechanical spindle is too complex to locate the fault rapidly when the part shows anomalies or damage, and this reduces high-value machine’s utilization rate as well as brings difficulties in solving part’s quality problems. Pointing at surface quality problems and spindle component’s wearing down that emerge frequently, this paper simulates various parameters in NC (numerically controlled) machining process and monitors spindle states of a five-axis machine with large torque mechanical spindle, then amplitude, time-frequency, and frequency curvature characteristics of the tested signals are obtained by Hilbert Transform and fast identification of key component’s wearing down is realized. The results show that the state analysis method of five-axis NC machine with large torque mechanical spindle based on Hilbert transform presented in this paper has strong engineering application value.

1. Introduction

Five-axis NC (numerically controlled) machine with large torque mechanical spindle is the main source of titanium alloy parts manufacturing, the spindle performance directly determines the processing performance, which in turn affects the final product’s quality [1]. However, in the actual production process, because such machine is equipped with mechanical spindle with complex structure, there is difficulty in diagnosing faults for wearing down and overload, and the final results are reflected on the part surface, which are manifested as tool flapping and ripples. Therefore, timely monitoring of the spindle operating state and effective fault diagnosis will greatly reduce the downtime caused by equipment failure, thereby improving the production efficiency and accuracy of aviation structural components.

The most convenient way to monitor the spindle is to monitor its vibration [2]. The vibration signal contains real-time status information of the power system. Based on vibration data, the most common method is spectrum detection based on Fourier transform. But in reality, the mechanical spindle is a nonlinear time-varying system, which is constantly changing due to the influence of load and equipment state, and since the Fourier integral is limited to the entire time domain, even if a certain frequency component of the signal changes, it cannot find the transformation time and the duration of a certain frequency, the most intuitive result is the frequency aliasing phenomenon after the transformation and the reasonable frequency component of the signal cannot be identified. The essence is that the
fundamental wave selected by the transform is an infinitely long cosine signal, and there is a great limitation on the localization problem of time domain and the frequency domain for the spindle vibration’s unstable signal[3].

Considering the limitations of the Fourier transform in analyzing the spindle state signal, Hilbert transform, is introduced. Based on clear mathematical principles, by converting the measured real-number domain signal into a complex-domain signal, the envelope and instantaneous frequency of the signal can be presented, and the analytic function thus constructed does not contain the negative frequency portion, so it is suitable for analysing spindle status signals[4]. In this paper, the vibration of the large torque mechanical spindle of the five-axis machine is tested for its titanium alloy parts’ surface ripples. The Hilbert transform method is used to analyse the cause of the fault and realize rapid identification of the internal structure’s wearing down of the spindle.

2. Hilbert transform principle
For continuous time signals $x(t)$, the Hilbert transform is defined as follows[5]:

$$\hat{x}(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(t)}{t-\tau} d\tau = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(t-\tau)}{t} d\tau = x(t) \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{\delta(t-\tau)}{t} d\tau$$ (1)

Considering Fourier transform of $\frac{1}{\pi}$:

$$F(j\omega) = -jsign(\omega) = \begin{cases} -j & (\omega > 0) \\ j & (\omega < 0) \end{cases}$$ (2)

For $X(j\omega)$ is $x(t)$’s Fourier transform, according to convolution theorem, then:

$$\hat{x}(j\omega) = F(j\omega)X(j\omega) = -jsign(j\omega)X(j\omega)$$ (3)

Now define the analytical signal for initial $x(t)$ to $z(t)$:

$$z(t) = x(t) + j\hat{x}(t)$$ (4)

Thus,

$$Z(j\omega) = X(j\omega) + j\hat{x}(j\omega) = X(j\omega) + jF(j\omega)X(j\omega) = \begin{cases} 2X(j\omega) & \omega > 0 \\ 0 & \omega < 0 \end{cases}$$ (5)

This shows that the analytical signal consisted of Hilbert transform has only positive frequency, which is very suitable for the analysis of the spindle’s vibration signal.

Then write the analytical signal as an exponential form:

$$z(t) = Aexp(-j\phi)$$ (6)

Let $A$ be the amplitude, and $\phi$ the phase angle, then the original signal can be written as:

$$x(t) = A\cos\phi$$ (7)
Where,
\[ \phi = \arctan(\hat{x}/x) \quad \text{and} \quad A = \sqrt{x^2 + \hat{x}^2} \]  

Therefore, the Hilbert transform of the signal is actually a convolution of amplitude \( A \) and frequency modulated signal \( \cos\phi \).

3. Experiment analysis

3.1 Experimental preparation
Part surface of Zhongjie 1\# NC machine has been frequently corrugated, fortunately, the quality of final product has not been affected. In order to ensure the efficiency and stability of the subsequent processing, the vibration detection test of the spindle head state of the machine is performed to analyse the cause of the problem and identify the fault location. The Zhongjie 1\# five-axis NC machine for machining titanium alloy parts was selected as the experimental object, and the SmartBalancer instrument was used for vibration detection. The instrument is equipped with a three-phase acceleration sensor, which can quickly collect and analyse the vibration signal without disassembling the spindle. In order to facilitate the observation and comparative analysis, and taking into account the structural characteristics of the five-axis mechanical spindle of the machine tool’s long-drive chain, in each experiment, observe from the forward direction of X-axis, and test three parts respectively: directly below the spindle head, left side of the spindle head, right side of the spindle head\(^6\).

![Figure1. Sensor installation diagram](image)

In order to ensure the validity of the measured data and simulate the normal processing state of the machine, each measurement time is consistent, which is 8:30 on Friday morning, and the spindle is preheated for 15 minutes before each experiment. In addition, the spindle speed and the equipped tool were consistent for each experiment, respectively 1500 rpm, and \( \phi20-70R3 \) end mill.

3.2 Experimental data collection and analysis
Since the spindle speed is 1500rpm\(\min\), the sampling frequency is set at 1000HZ. After many experiments, according to the information measured by the vibration sensor, the Hilbert transform principle is used to obtain the analytical signal of the original signal, then the frequency and amplitude of the spectrum line with time. After that, solve the curvature change’s average value of the analytical signal.

3.2.1 Time-frequency signal
Immediately directly below the spindle head, the left side of the spindle head, and the right side of the spindle head, the frequency and amplitude of each part’s analysing signals in four experiments are changed over time, as shown below:
Analyse the spectrogram directly below the spindle head, in the intervals of figure 2(a)'s 6.35s~6.4s, figure 2(b)'s 6.35s~6.4s, figure 2(c)'s 6.25~6.3s, the proportions that the corresponding frequency exceed 200HZ are 94.7%, 95.9%, and 94.3% respectively, and this proportion in figure 2(d) reaches to 97.6% on the whole. It can be found that in these intervals, high frequency concentrate, the amplitudes have obvious high points and even the highest points.
Figure 3. Spectrum distribution on the left side of the spindle head

Analyse the spectrum on the left side of the spindle head, the proportions that frequency exceed 200Hz are 98.6%, 96.4%, 97.7%, 99.3% respectively, with an overall high frequency in each experiment, so more amplitude peak points appeared in the four experiments.

Figure 4. Spectrum distribution on the right side of the spindle head

Analyse the spectrogram on the right side of the spindle head, the intervals that the frequency concentratedly exceed 200Hz are 6.2s~6.25s and 6.35s~6.45s in figure 4(a), and their proportions are 93.4% and 97.5%. Figure 4(b) owns three intervals that high frequency concentrate, and this
phenomenon is more obvious in figure 4(c) and figure 4(d). In the interval where these high frequency occurrences are relatively high, the amplitude also presents corresponding cusps.

According to the results of the above four experiments, in the same period of time, where the high-frequency concentrated, the appearingance frequency of strong amplitudes increases of the part directly below the spindle head, indicating that the accumulation of high-frequency has an adverse effect on the spindle’s operating state. Under the same monitoring state, in general, the interval of the high frequency on the left side of the spindle head is obviously higher than that on the directly below part and the right side part, and the amplitude value of this portion reaches 0.2 mm, which is obviously higher than the right side of the spindle head’s 0.04mm and 0.06mm directly below the spindle head.

Obviously, the amplitude and frequency information of the vibration on the left side of the spindle head is more prominent than the other two parts.

3.2.2 Time-frequency signal curvature

In order to verify the results of the time-frequency signal analysis, according to the above measurement data, the average curvature of the time-frequency discrete signal changes of the four experiments in each part is solved, and the results are as follows:

Figure 5. Curvature diagram of the three parts’ frequency change

According to the curvature diagrams of the above three discrete signals, it is obvious that the order of the singularity’s number of the three curvatures is: directly below the spindle head, the right side of the spindle head, and the left side of the spindle head, which is consistent with the result of that high frequency on the left side is more common and its frequency change is less in time-frequency distribution, which verifies the conclusion of the previous section. Since the number of singular points directly below the spindle head is the largest, it indicates that this part is subjected to the greatest impact,
which is consistent with the general machine phenomenon, and attention should be paid to the maintenance of the connecting parts.

3.3 Experimental result
According to the spindle state detection experiment, after the amplitude, time-frequency signal and its curvature test analysis, it can be judged that the vibration on the left side of the spindle head is abnormal. Considering the mechanical structure of the Zhongjie 1# long-drive chain (as shown in Figure 6), it is possible to locate the mechanical parts directly related to the left side of the spindle head is the bevel gear and their bearing parts. So, it can be judged that under the same processing conditions, the wearing down of the bevel gear and its bearing will be stronger, which is also the main cause of frequent ripples on the surface of parts. It should be paid attention to in daily maintenance.

Figure 6. Spindle structure diagram for Zhongjie 1#

4. Conclusion
The five-axis NC machine with large torque mechanical spindle has complex mechanical structure, which makes fault detection get hard. Under the simulated actual machining conditions, the real number signal of the three parts’ vibration signal of the faulty machine’s spindle head is converted into analytic signal in the complex domain by Hilbert transform, the signal of one dimension is presented as a signal in the two-dimensional complex plane, thereby extracting the frequency and amplitude of the signal. The method overcomes the problem that the traditional Fourier transform cannot perform the horizontal comparison of the frequency of various parts under the same time condition. Through the presentation of the frequency in the time domain, the frequency of each part and the aggregation and distribution can be clearly judged, combining the amplitude change, the mechanical state of the three parts of the spindle head can be analysed and diagnosed.

Further, by solving the variation curvature of the discrete frequency signal, the frequency variation of the state of the mechanical spindle head’s three parts can be quantitatively analysed, and the characteristics of the three parts’ frequency can be clearly compared according to the number, distribution and numerical size of the singular points. This verified the results of the spectrum analysis, and then infer the mechanical state of each part to find the cause of the surface ripple problem.

The results show that the large torque mechanical spindle state analysis method of the five-axis NC machine based on Hilbert transform can quickly identify the wearing down condition of the transmission components in the spindle, thereby improving the quality of parts and improving production efficiency, and has strong engineering application value.

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