Research and application on rapid recognition of CNC machine tools' running state

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Abstract: A rapid recognition of CNC (Computer Numerical Control) machine tools' running state based on time domain characteristic parameters and frequency domain correlation coefficient was proposed. The experiment proved the accuracy and efficiency of the mentioned method, which made the states recognition rate reach 93.33% and the identification efficiency improve 66.67%. In this scenario, a theoretical foundation is established for the condition-based maintenance of CNC machine tools.

1. Introduction
As China gradually develops from a large manufacturing country to a powerful manufacturing country, CNC machine tools are becoming more and more large, high-speed, high-precision and intelligent, which dominate an important position in the manufacturing industries. On the one hand, the CNC machine tools improve production efficiency and product quality; on the other hand, the sudden failure of CNC machine tools seriously affects the on-time parts delivery, which extremely wastes all kinds of production resources and causes huge losses. Therefore, modern advanced manufacturing companies are not satisfied with the breakdown maintenance. It is urgent to improve the reliable operation of CNC machine tools by identifying the running states of the CNC machine tools and implementing the condition-based maintenance [1].

At present, the identification methods of CNC machine tools' running states include traditional methods and intelligent methods. The traditional method is the viewing method, which is checked by well-experienced workers applying visual inspection, hand touch, etc, but it's time-consuming, and the inspection quality is limited by the labor quality and cannot be standardized. The intelligent method collects information by using various advanced instruments, and uses knowledge-based methods such as artificial neural networks, fuzzy theory, and expert systems to identify the running state. The intelligent method is a research hotspot in the field of identification, and also a development tendency, but there are still some shortcomings. The artificial neural network converges slowly and needs a large number of samples for training; the conclusion of the fuzzy theory is not accurate enough; the expert system shows weak recognition ability and poor self-learning ability when it is applied to the CNC machine tool with complex structures. Nowadays, intelligent methods research is focused on top-level design and has not been extensively engineering applied [2-3].
In order to improve the accuracy and efficiency of CNC machine tools' running state recognition, this paper proposes a method based on time domain characteristic parameters and frequency domain correlation coefficient. Firstly, collecting vibration signals under normal, attention and abnormal conditions of CNC machine tools by the overall sensor installation method. Then, through the sensitivity analysis of the time domain characteristic parameters and the frequency domain correlation coefficient, four time domain characteristic parameters and the frequency domain correlation coefficient are selected as rapid identification indicators. Finally, the judgment standards of state recognition is established to complete the rapid recognition model of the CNC machine tool, which can rapidly and efficiently identify the running state of CNC machine tools.

2. Theoretical basis

2.1. Time domain characteristic parameters

The time domain analysis of the vibration signal is carried out by amplitude analysis in the time domain waveform, and the dimensional characteristic parameters (including peak value, peak-peak value, average, absolute average, valid value, variance, skewness and kurtosis) and dimensionless characteristic parameters (including peak factor, pulse factor, margin factor, waveform factor, kurtosis factor) of the signal are calculated by the amplitude probability density function [4].

The amplitude probability density function \( p(x) \) of the signal \( x(t) \) is:

\[
p(x) = \lim_{\Delta x \to 0} \frac{\Delta x}{\Delta x} \int_{x}^{x+\Delta x} f(x) dx = \lim_{\Delta x \to 0} \frac{1}{\Delta x} \left[ \lim_{T \to \infty} \frac{T}{T} \right]
\]

Where \( T_x \) is the total time that the signal \( x(t) \) is in the \((x, x + \Delta x)\) interval.

The amplitude probability density function reflects the distribution pattern of the signal in amplitude, and the probability density functions of different signals are different. The generation and development of the fault will cause a change in the amplitude distribution of the signal, that is, a change in the amplitude probability density function. Generally, if the device is in normal running state, its probability density function curve is close to the normal distribution. When the running state is abnormal, it will be doped into the extra periodic signal to change the original amplitude distribution.

The selection principles of the time domain characteristic parameters: 1 the stability of the time domain characteristic parameters is high under the same states; 2 the sensitivity of the time domain characteristic parameters is high under different states. The dimensional characteristic parameters, such as RMS, are gradually increasing with the occurrence and development of faults, with high stability and low sensitivity. The dimensionless characteristic parameters, such as margin factor, increase significantly in early failures, but if the fault develops to a certain extent, it decreases, with high sensitivity and low stability. Therefore, it is necessary to select both the dimensional characteristic parameters and dimensionless characteristic parameters considering sensitivity and flexibility.

2.2. Frequency domain correlation coefficient

When the state deteriorates or the fault occurs and develops, it often causes a change in the signal frequency structure. In engineering applications, the time domain signal is converted to a frequency domain signal by Fast Fourier Transform (FFT) to obtain a relationship between frequency structure and frequency.

Correlation indicates the extent of similarity between two kinds of signals. The larger the absolute value of the correlation indicates, the stronger the correlation, and vice versa.

The Pearson product-moment correlation coefficient of \( X \) and \( Y \) is the quotient of the covariance of the two variables and the standard deviation product of the two, i.e.

\[
\rho_{xy} = \frac{\text{cov}(XY)}{\delta_x \delta_y} = \frac{E(X-\mu_x)(Y-\mu_y)}{\delta_x \delta_y}
\]
The above is the overall correlation coefficient. Generally, the covariance and standard deviation of the sample calculation are used instead of the covariance and standard deviation of the population. The correlation coefficient formula of the sample is:

\[ r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \]  

(3)

The frequency domain correlation coefficient of the same state is high, and the frequency domain correlation coefficient of different states is low. The correlation analysis between the test signal and the normal state signal can be used as the basis for judging whether the state changes [5-6].

2.3. Rapid recognition model of CNC machine tools' running state

The time domain and frequency domain indicators respectively characterize the running states of the CNC machine tool from different aspects. Therefore, this paper comprehensively selects the time domain characteristic parameters and the frequency domain correlation coefficient to make a rapid identification model of the CNC machine tool's running states. The specific implementation steps are as follows:

- For different monitoring parts, the overall sensor installation method is adopted to collect the vibration signals of the CNC machine tool under normal, attention and abnormal states;
- According to the selection principle of the characteristic indicators, appropriate time domain characteristic parameters and frequency domain correlation coefficient are selected as rapid recognition indicators through the sensitivity analysis.
- Establish the judgment standard of state recognition and complete the rapid recognition model of the CNC machine tools' running state.

3. Engineering application

In order to verify the feasibility of the proposed method, the Y-axis running states of a large horizontal CNC machine tool is rapidly recognition.

3.1. Rapid recognition model establishment

Considering the actual demand of production and processing, the sensor installation method of directly mounting the sensor to the transmission table or column is different from the traditional sensor installation method, disassembling the CNC machine cover and mounting to specific components such as bearings, rolling elements, nut holders, etc, collecting the vibration signals of the CNC machine tool under normal, attention, and abnormal states [7].

The sensitivity analysis of the time domain characteristic parameters is carried out when the Y-axis of the CNC machine tool is under normal, attention and abnormal states, as shown in Fig. 1. Due to limited space, only 3 tests are selected for each state.

Figure 1. The time domain characteristic parameters of the Y-axis under normal, attention, and abnormal states (normalized)
It can be seen from Fig. 1 that the average value, skewness, and waveform factor cannot accurately identify the running states; peak, peak-to-peak, kurtosis, crest factor, pulse factor, and margin factor identify the running states normally; absolute average, root mean square, variance and kurtosis factor can accurately identify the running states and are selected as rapid identification indicators.

Calculate the frequency domain correlation coefficient of the Y-axis under normal, attention, and abnormal states, as shown in Table 1.

| States       | Normal | Attention | Abnormal |
|--------------|--------|-----------|----------|
| Normal       | 0.874  | 0.584     | 0.153    |
| Attention    | /      | 0.891     | 0.511    |
| Abnormal     | /      | /         | 0.929    |

It can be seen from Table 1 that the correlation is very high if the running state does not change, both greater than 0.8, and the correlation coefficient is reduced to less than 0.6 if the running state changes.

According to sensitivity analysis of the time domain characteristic parameters and the frequency domain correlation coefficient, a rapid recognition model of the Y-axis running state is established, and the judgment standard of the state recognition is determined, as shown in Table 2.

| Indicators States | Root mean square | Absolute average | Variance | Kurtosis factor | Frequency domain correlation coefficient |
|-------------------|------------------|------------------|----------|-----------------|------------------------------------------|
| Normal            | <1.5times        | <1.5times        | <2times  | <4times         | >0.6                                     |
| Attention         | 1.5-2.5times     | 1.5-2.5times     | 2-7times | 4-20times       | 0.2-0.6                                  |
| Abnormal          | >2.5times        | >2.5times        | >7times  | >20times        | <0.2                                     |

3.2. Application verification

After establishing the rapid recognition model of the Y-axis running states, a total of 30 tests from April 2019 to June 2019 are carried out to verify the method. The correct recognition rate is 93.33% with 28 correct tests. 2 incorrect tests are caused by the interference of sensors’ signal lines when the data is collected. The axis state recognition takes an average of 0.5 hours, compared with the previous state recognition of taking 1.5 hours, the recognition efficiency is increases by 66.67%.

The root mean square of the vibration signal collected from the Y-axis on May 15th is 1.5 times of the normal state (April 14th), the absolute value 1.5 times, the variance 2.3 times, the kurtosis factor 4 times, and the frequency domain correlation coefficient between the test state and the normal state is 0.286, so the state is rapidly recognized as the attention state. After dismantling and troubleshooting, it was diagnosed that there was a crack in the Y-axis balance cylinder seal ring and immediately replaced it. After the replacement was done on May 19th, the rapid state recognition was performed again, and the four time domain characteristic parameters and the frequency domain correlation coefficient all returned to values of the normal state.

The rapid identification analysis of the Y-axis running states on April 14th, May 15th and May 19th is shown in Figure 2 and Table 3.
Figure 2. The time domain characteristic parameters (normalized) of the Y-axis under normal, attention, and repair states

Table 3. The frequency domain correlation coefficient of the Y-axis under normal, attention, and repair states

| The frequency correlation coefficient | Normal  | Attention | Repair  |
|--------------------------------------|---------|-----------|---------|
| Normal                               | 0.953   | 0.286     | 0.938   |
| Attention                            | /       | 0.948     | 0.284   |
| Repair                               | /       | /         | 0.959   |

Through the application of the above theoretical methods and technical specifications, the rapid recognition of CNC machine tools' running state is proved. In engineering applications, the established rapid recognition model effectively detects the shaking of the Y-axis caused by the crack in the balance cylinder seal ring. The rapid identification of the states guides workers to implement condition-based maintenance, saving maintenance cost and improving production efficiency and quality.

4. Conclusions
- Considering the actual demand of production and processing, a rapid recognition model of the CNC machine tool's running state is established, which overcomes the shortcomings of low accuracy and efficiency of the traditional identification methods.
- The effectiveness and feasibility of the rapid recognition method is verified by the real engineering application. It can identify the running states of CNC machine tools and guide the condition-based maintenance, which has some value in engineering application.

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