Research on power and vibration signal acquisition method and system of machine tool for tool wear monitoring

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Abstract. Tool wear state is a crucial factor in the process of machine tool processing. Tool wear and failure affects the processing quality. Tool replacement in advance affects the production efficiency and increase the production cost. During the machining process, the power and vibration signal often change with the increase of tool wear, which provides a way to monitor tool wear. To meet the needs of tool wear monitoring, this paper presents a system architecture and hardware composition of power and vibration signal acquisition of machine tool, and develops a system to synchronously collect power, vibration signal and process parameters of machine tool. The vibration and power characteristic information recognition method is then discussed corresponding to the process to be monitored from the collected signals. The experimental results show that the system is able to collect and screen the changes of power and vibration signal throughout the whole life cycle of the cutting tool in real-time. The feature information recognition and screening have high efficiency and accuracy, which provides a data basis for tool wear monitoring.

1. Introduction

With the industrial development, manufacturing enterprises put more emphasis on the strict control of the quality in the machining process. As one of the core components in machining and manufacturing process, the condition of the cutting tool highly determines the machining quality\textsuperscript{[1]}. Currently, the widely used method is to set the threshold value of the maximum number of pieces processed by the tool according to the experience data, count the number of pieces processed by the tool during the processing, and replace the blade if the threshold value is reached.

The maximum number of pieces set according to experience often can not accurately reflect the actual processing capacity of the cutting tools. Some cutting tools have not reached the service life when they are processed to the threshold value. At this time, replacing them will cause the waste of cutting tools and increase the processing cost. On the contrary, some cutting tools have been excessively worn before they reach the threshold value, which will cause the surface quality of the processed products to be unqualified and lead to production accidents. Therefore, the traditional monitoring method reduces production efficiency, prolongs the production cycle, and increase the extra cost\textsuperscript{[2]}. Therefore, it is necessary to introduce tool wear monitoring technology.

Tool wear monitoring is mainly divided into direct measurement and indirect measurement. The direct method reflects the change of the tool state by detecting characteristic parameters related to the volume loss of the tool material. Because it is difficult to collect the signal under the actual cutting conditions, it often requires shutdown detection and takes up production hours, so its application prospect is poor\textsuperscript{[2]}. The indirect measurement method is to extract and identify the characteristics of the
tool state by studying the various signals (such as force, temperature, power, vibration, and noise) that are intrinsically related to the tool state in the cutting process, so as to determine the corresponding relationship between the tool state and a certain signal, and indirectly infer the tool wear state by monitoring the signals in the cutting process. Indirect methods mainly include the current or power signal monitoring method\cite{3,4}, Cutting force monitoring method\cite{5,6}, Acoustic Emission (AE) monitoring method\cite{7,8}, Vibration monitoring method\cite{9,10}. For example, Lin Yang built an experimental platform based on force signal acquisition\cite{11}, Hai Li built an experimental platform based on acoustic emission, vibration, and force signals\cite{12}, Drouillet built an experimental platform based on spindle power\cite{13}. In actual production, machine tools often need to carry out a variety of processes. How to collect sensor signals and screen out the corresponding characteristic signals of tool wear state is the main problem in the current research.

The vibration signal is caused by the dynamic component of cutting force and contains information related to the tool wear state. Generally, acceleration sensors are used to collect vibration signals. According to different measurement principles, they can be divided into piezoelectric, piezoresistive, and capacitive modes, among which the most commonly used is the piezoelectric acceleration sensor. When in use, the magnetic force is adsorbed on the surface of the parts to measure\cite{12}. The tool wear in the process of machining causes an increase in cutting force, cutting power, and torque, which leads to the corresponding increase of spindle current and spindle power. Therefore, the power signal can reflect the tool wear state. Current sensors and power sensors are widely used because they are easy to install, not limited by processing conditions, and do not affect the processing process\cite{14}.

In order to meet the needs of tool wear monitoring, this paper presents the power and vibration signal acquisition method and system architecture based on the indirect measurement object of power and vibration signal. Based on the designed software and hardware system, the power signal and vibration signal are collected and the characteristics of the signal to be monitored are screened in real-time, which provides a reference for the study of the change law of power and vibration signal relative to tool wear. The database provides a theoretical basis for on-line monitoring of tool wear.

2. System architecture and composition

The system architecture is shown in Figure 1. The system hardware mainly includes power acquisition equipment, vibration acquisition equipment, and computer host. The power signal is obtained by measuring the current and voltage signal of the spindle motor and input it into the power analyzer; the vibration signal is the vibration signal of the spindle end. After the collected signal is filtered, the analog-to-digital conversion is completed through the data acquisition card. The software designed in this paper completes signal display, analysis, and storage.
2.1. power acquisition equipment

In the process of machining, with the aggravation of tool wear, the change of cutting edge state causes the change of cutting torque, resulting in the change of spindle power. The input power of the spindle can be approximately expressed by the following mathematical model:

\[ P_i(t) = P_u(t) + P_a(t) + P_c(t) \]  

Where \( P_i(t) \) is the total output power of the spindle, \( P_u(t) \) is the no-load power of the machine tool, \( P_a(t) \) is the load loss power, and \( P_c(t) \) is the cutting power of the spindle. Because the machine tool is stable, the processing time and change little, and in the process of batch processing remain stable[15]. Therefore, the power signal source is designed to collect the output power signal of the spindle motor, which is collected by the power sensor installed on the output cable of the spindle motor. The wiring mode and sensor are shown in Figure 2.

The power sensor model is ‘power sensor V5’ of Intelligent Grindoctor Technology(Shenzhen) company. The current collection is a closed-loop current sensor. Based on the principle of magnetic compensation, the accuracy of analog quantity acquisition is 0.5% FS and the current range is 40A. The power sensor’s accuracy is 0.5% FS, the range is 13kW, and the resolution is 1W. Ni company’s USB-6251 data acquisition card is used to collect the analog current signal collected by the power sensor.
The acquisition card's main parameters are 16 channel AI (16 bit, 1.25 MS / s), 2 channel Ao (2.86 MS / s), 24 channel DIO USB Multifunction I/O Device. It offers analog I/O, digital I / O, two 32-bit counters/timers and a digital trigger. The sampling frequency of the power signal in this paper is 5000Hz.

2.2. vibration acquisition equipment
The friction between the workpiece and the worn edge will produce different frequencies of vibration frequencies in the cutting process. Vibration signal is a very sensitive signal to tool wear, which can represent tool wear information. In this paper, a three-axis acceleration sensor J356B18 of American PCB company is selected to measure the spindle's vibration signal, as shown in Figure 3 (a). The sensor can simultaneously collect the vibration signal of the X, Y, and Z axes. As shown in Figure 3 (b), to reduce the interference, on the premise of not affecting the processing, the sensor is installed on the side of the spindle as close as possible to the tool holder to measure the vibration signal in the boring process.

Regarding of vibration signal acquisition, the USB-9234 data acquisition card of Ni company is used to collect the analog current signal collected by the power sensor. The acquisition card can measure signals from integrated electronic piezoelectric (IEPE) and non IEPE sensors. As shown in Figure 3 (c). The NI 9234 is a four-channel dynamic signal acquisition module for making high-accuracy measurements from IEPE sensors. The NI 9234 delivers 102 dB of dynamic range and incorporates Integrated Electronics Piezoelectric (IEPE) signal conditioning at 2 mA constant current for accelerometers and microphones. The four input channels simultaneously acquire rates up to 51.2 kS/s. In addition, the module includes built-in anti-aliasing filters that automatically adjust to your sampling rate. The sampling frequency of the vibration signal in this paper is 12800Hz.

3. Data acquisition system

3.1. system function composition
The power and vibration signal acquisition system proposed in this paper is a synchronous acquisition system for the machine tool's external sensor signal and the information extracted from the machine tool's processing database. The software system is developed based on NI LabVIEW 2017, and the main interface is shown in Figure 4. The power and vibration sensor signals are input to the multi-source signal synchronous acquisition and analysis software of machine tools after analog-to-digital conversion of data acquisition card.
In order to use the real-time NC code to distinguish whether the signal is a processing signal, the system collects the processing information in the database while collecting the sensor signal. According to the process data, the system selects the sensor signal range under the process, which is convenient for later signal processing for a specific process. The output of the file is in "TDMS" format. In order to avoid too large a file, the system is set to automatically close the current file and generate a new write file after a specific time of collection.

The data acquisition system can synchronously collect, display, and save the power and vibration sensor signal and database data. Through parameter configuration, it can realize the following functions: selecting sampling channel, setting sampling frequency and sampling number, saving data according to the specified path, signal waveform display, multiple analysis in time and frequency domain, database list reading, machine tool process information display, etc. The software can expand the sensor input channel according to the demand to meet other signals' subsequent acquisition content.

3.2. Signal screening system

The signal filtering system is a matching executive program based on the acquisition system developed by Python 3.7. The system is divided into primary screening and secondary screening.

During the first screening, the program can monitor the TDMS file generated by the acquisition system in real-time, retrieve whether the process information in the file contains the process to be monitored, save the file to the final folder if it does, and delete the file if it does not. The logic block diagram of one-time screening is shown in Figure 5.
Due to the complexity of the cutting-in and cutting-out process, which cannot reflect the tool wear state well, it should be eliminated, so the screening system needs to carry out the signal's secondary screening. The screening logic is that based on one screening, the mean value of the signal in the middle stable processing region of the power signal is selected as the threshold value of cut in and cut out, and the signal in the middle stable processing region is screened out. The selection of vibration signal is based on the time selected by the power signal. The logic box of secondary selection is shown in Figure 6.

4. Experimental verification

In order to verify the effectiveness of the system, boring experiments are carried out on Heller MCH 350 three-axis NC vertical machining center. The servo drive system of the CNC machining center adopts Siemens 840D system. The local computer has read the machine tool's process information in real-time through the CNC system, including time, current execution code, spindle speed, feed, etc. The read real-time process information can provide the real-time working status of the machine tool.

4.1. Experimental tools

The standard indexable blade produced by Kennametal company of the United States is used in the
The blade model is SPHX07034R21, the blade grade was KCU40, and the composition was PVD tin TiAlN multilayer coating and high toughness matrix. The fixed form of the blade is mechanical screw clamping, and each blade has two cutting edges, as shown in Figure 7.

(a) Experimental tool   (b) Experimental blade      (c) Workpiece model
Figure 7 Tool and workpiece in the experiment

4.2. experimental workpiece and process parameters
The workpiece used in the test is the cylinder body blank cast by HT300, and the schematic diagram of the workpiece is shown in Figure 7(c). The processing object is a 36.7mm tappet hole of a casting blank cylinder body. The processing technology is semi-precision boring, without adding cutting fluid. The cutting speed is \( v = 120 \text{m/min} \), the feed rate is \( f = 0.4 \text{mm/r} \), the back cutting amount is \( AP = 1 \text{mm} \), and the hole depth of each boring is 68mm. Each cylinder needs to process 6 holes, and the service life of each blade is 100 cylinders.

4.3. signal acquisition
Due to the same material and processing technology, the spindle power and vibration signal of CNC machine tools are expected to be periodic in each boring process. From this experiment, the spindle power signal curve and X, y, Z vibration signal curve of six times boring of a cylinder block are intercepted, as shown in Figure 8. The signal presents periodic law, which verifies the accuracy of the data collected by the system.

4.4. signal screening
The system collects all the power signals and vibration signals of the machining center during the tool's whole life cycle. Because the machining center contains multi-tool and process processing contents. It
is necessary to select the signal range to be monitored from all the signals according to the process information. As shown in Figure 9, taking the power signal as an example, the boring power signal selected according to the processed signal is shown.

Figure 9 Power signal screening

It can be seen that the system can correctly select the boring process signal range to be monitored from the processing signals containing multiple processes. The secondary screening of the signal, the screening results shown in Figure 10 in the blue area, shows that the system is excellent to screen out the signal of the stable processing interval.

Figure 10 Signal after the secondary screening

4.5.5 Characteristics of the achieved signal

After the secondary screening of the signal, select the four-second signal interval of smooth processing in each boring process, and observe the macro change trend of power and vibration signal, as shown in Figure 11. It can be seen from the figure that with the increase of tool wear, the power signal shows a significant upward trend, and the amplitude of the vibration signal slightly increases. Through the power and vibration signals collected by experiments, and using the process information to screen out the signal range to be monitored for analysis, it is demonstrated that the system has the characteristics of real-time solid performance and good signal acquisition and screening efficiency.

Figure 11 Power and vibration signal changes with tool wear
5. Conclusions

Aiming to monitor the tool wear condition, this paper proposes a power and vibration signal acquisition method and system. Based on the presented system architecture and hardware composition, it designs and develops a data acquisition system based on power, vibration signal, and machine tool process information. The system can synchronously collect power, vibration signals, and machine tool process parameters, and select the corresponding sensor signal interval from the collected signals. Through the experimental verification of the built platform, the power and vibration signals of the tool throughout the whole life cycle are measured, the vibration and power characteristic information corresponding to the specified process is successfully selected, which verifies the real-time performance and efficiency of the system signal acquisition and analysis. It can provide the primary data for the subsequent online monitoring of tool wear.

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