Sensor System for Monitoring the Cutting Signals of CNC Milling Machine in Real Time

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The development of robust condition monitoring system for a machine tool holder is an important task because the holder has a significant effect on the processing quality. This paper presents the architecture of data acquisition system for detecting cutting acceleration in milling processes in order to develop an on-line condition monitoring system. In this work, a solar-powered wireless sensor system is installed upon the tool holder and is used to monitor the machine tool processing state in real time, thereby improving the processing quality. Accelerometer sensors are employed to estimate tool wear; these sensors monitor the milling signals of the tool holder. The acceleration monitoring data of the high-speed tool holder is wirelessly transmitted to an external information device in real time. As an alternative to sensors that employ wired power transmission, a solar energy transmission system has been developed to provide the required electric power to the sensor system. The experimental results show that the proposed system successfully measures the acceleration signals of the rotational machine tool holder.

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NOMENCLATURE

X_k = 1-D discrete Fourier transform

1. Introduction

Machine tools, which are used for fabricating various machines and processing equipment, can be categorized into two types—metal-cutting machine tools and metal-molding machine tools—according to their functions. Metal-cutting machine tools include lathes, drilling machines, milling machines, grinding machines, and planning machines; metal-molding machine tools include punching machines and shearing machines. A machine tool is composed of several parts. In the case of a drilling machine, milling machine, grinding machine, planning machine, and other machines that employ a rotating cutter, the most important part, i.e., the part that has the most impact on the processing quality, is the machine tool spindle. Therefore, machine tool manufacturers have strict criteria as far as the accuracy of the machine tool spindle is concerned. During the operation of a machine tool, the material characteristics of the processed work-piece, the addition of the cutting fluid, and other practical processing situations may directly affect the processing quality. The working state of the machine tool spindle is practically inspected after processing is completed. If the finished pieces do not meet the accuracy requirement, the machine tool spindle is adjusted or maintained in precision alignment; however, loss of work-piece is generated. In order to solve this problem, some manufacturers of machine tools have proposed that sensing devices such as an accelerometer, a thermometer, or a strain gauge be installed near the machine tool spindle, in order to measure the acceleration frequency, temperature variation, processing output torque, and other working parameters during processing. However, sensing devices cannot be installed adjacent to the cutter because of the generation of cutting waste and the sputtering of cutting fluid near the cutter. Further, the working parameters measured by the sensing devices do not give an accurate reflection of the working state of the cutter, and therefore, the parameters cannot be used for monitoring the processing state in real time or for improving the processing quality. The conventional sensing devices setup performed on an end-milling machine tool is equipped with a commercial wired PCB three-axis accelerometer (model number 356A18). The accelerometer is connected to a commercial TEAC charge amplifier (model number LX-10). The measurements were recorded on a commercial HP35670 spectrum analyzer. However, the cost in these commercial instruments is extremely high.

As a solution to this problem, in [1], it has been shown that complex vibration spectra of rotors and machine tool spindles are primarily influenced by the bearing geometry, out-of-balance assembly, and a multitude of secondary effects due to surface

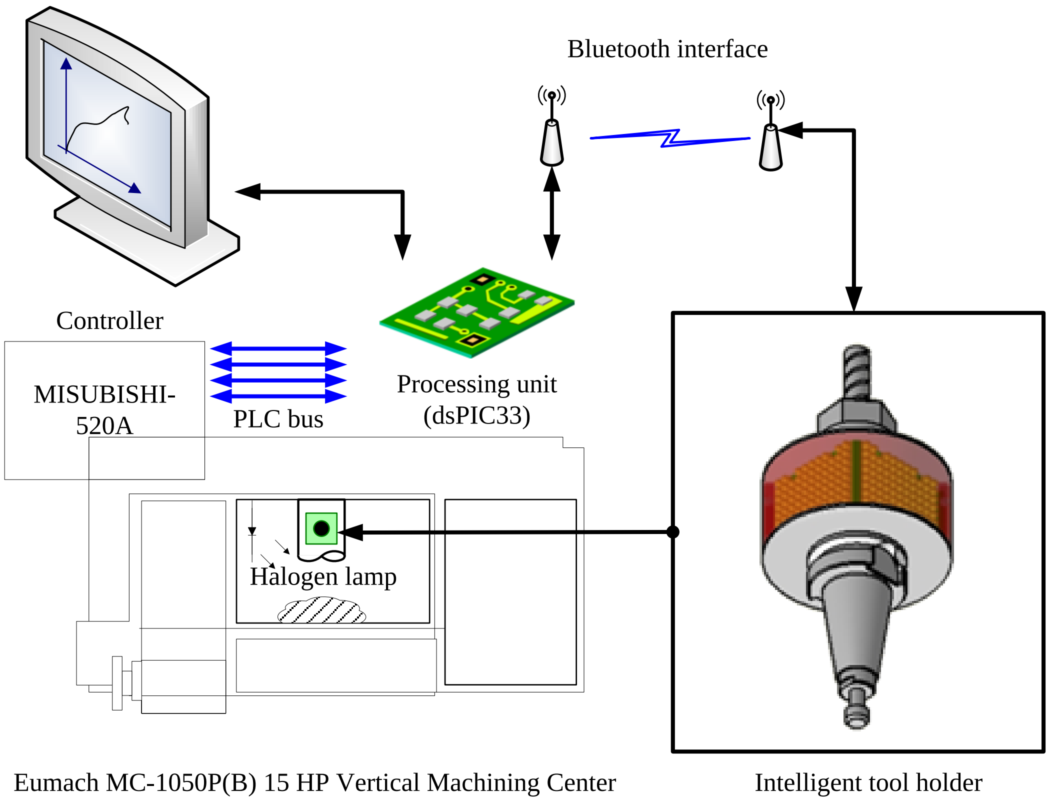


Fig. 1 The proposed low cost sensing system comprises solar power board, a wireless communication module, a FFT processing unit, and an internal sensing device, and is capable of monitoring the working state of the machine tool holder in real time.

anomalies of the interacting bodies. Sensors typically have a finite service life as they employ batteries or wired power systems; therefore, a self-powered system that can be energized by an electromagnetic vibration-powered generator has been proposed in [2,3]. An autonomous machine equipped with a cluster of multi-agent sensors has been proposed in [4]; this device can fully control diverse variables such as the cutting parameters, in-process dimensions of devices, and geometric and form defects. The machine is provided with individual wireless nodes as a result of which it can be placed in locations in which wired sensors cannot be placed. Wireless sensor networks open up new possibilities otherwise not feasible with wired sensors, such as the use of multi-sensor data fusion methods for estimating tool wear. In [5,6] the potential of wireless sensor nodes and networking in manufacturing environments has been investigated. However, the study does not consider the fact that manual maintenance would be necessary to replace the discharged batteries; in addition, most transformers with iron cores are relatively large, because of which these transformers cannot be placed upon the tool holder. Additionally, since the induction coil, sensing chip, and data transmission unit are quite close to each other, the magnetic field generated by the power supply unit directly interferes with the sensing chip or the data transmission unit; as a result, the sensing chip cannot acquire accurate data, and the wireless transmission of the data is affected.

If a sensing device is installed outside the machine tool, the acquired working parameters do not accurately reflect the working state of the cutter; if the sensing device is mounted on the machine tool holder, the magnetic field of the induction coil used for generating electric power directly interferes with the measurement or wireless transmission, and the working parameters of the conventional machine tool spindle cannot be acquired in real time with sufficient accuracy.

This paper presents a novel approach for developing next-generation intelligent sensor systems; the approach involves the integration of a vibration sensor with a solar power board and a wireless communication module. The proposed system comprises the tool holder body, a rotating mandrel, a cutter base, and an internal sensing device, and is capable of monitoring the working state of the machine tool spindle in real time and feedback frequency signal to the machine controller, as shown in Fig. 1.

This paper is organized as follows: The overall real-time monitoring system structure is introduced and analyzed in Section 2. Then, some experimental results are given in Section 3. Finally, conclusions are given in Section 4.

2. Real-Time Monitoring System

The intelligent tool holder structure proposed in this paper is capable of monitoring the working state in real time; the internal inspection device comprises a control substrate and inspection chips. The inspection chips are directly mounted on the rotating center at the bottom of the cutter base, and the working condition of the processing cutter assembled on the cutter base is directly reflected on the cutter base and is measured by the inspection chips; in this process, the chips are unaffected by the centrifugal force on the cutter base and can thus acquire accurate working parameters of the processing cutter. The solar board supplying electric power is mounted on the control substrate, such that the inspection chips or the wireless transmission module does not interfere with the magnetic field of the magnet-coil

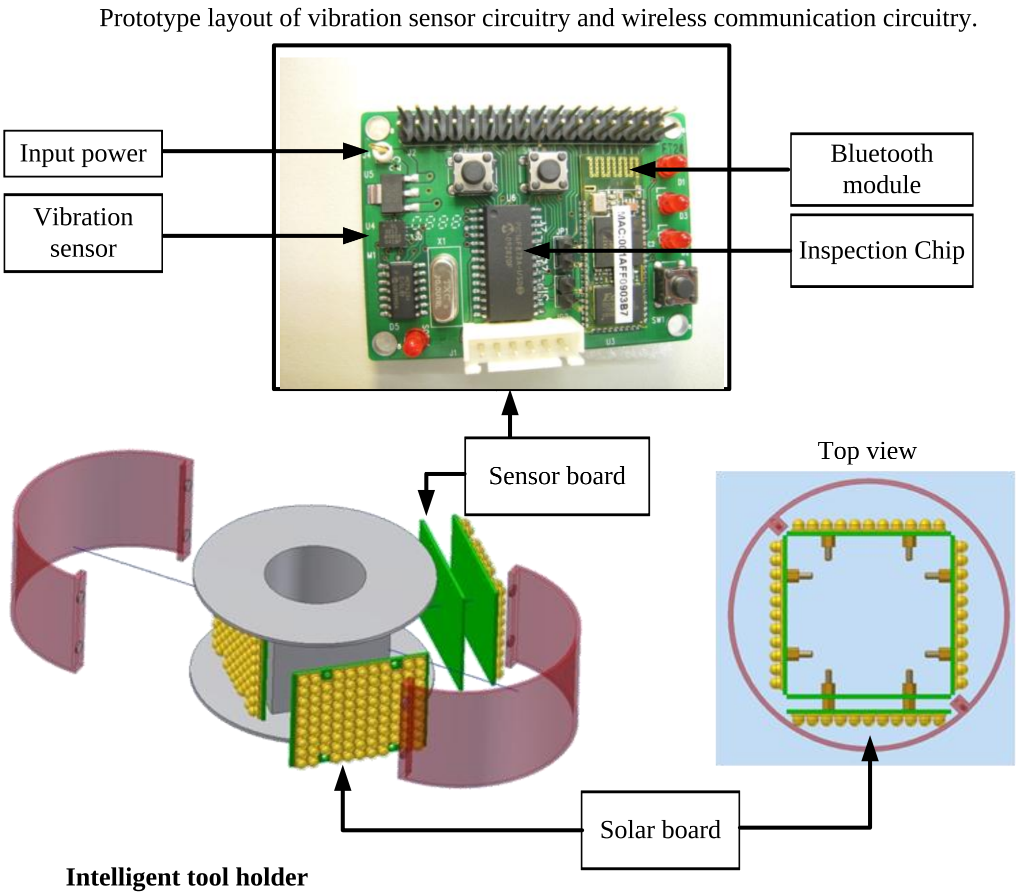


Fig. 2 The system layout of sensor board and solar-powered board.

generator used as the power source. The solar board is activated by the light-emitting arrays. The working parameters are wirelessly transmitted via a Bluetooth interface to an external information device. Thus, the present work presents an optimal design for mounting sensing devices on the machine tool holder, as shown in Fig. 2.

2.1 Tool holder sensing architecture

The machine tool holder structure presented in this study can be used to measure the temperature, vibration frequency, torque, and other working parameters of the machine tool spindle during processing. A low-power accelerometer (Analog Devices ADXL 321) is used as the vibration sensor. The accelerometer operates within ±18 g, and its bandwidth can be adjusted from 0.5 to 2500 Hz using external capacitors. This device can be used in condition monitoring applications wherein a change in machinery vibration often indicates that maintenance is required. The low power consumption of the device, which operates below 350μA at 2.4 V, is an attractive feature, given the low power available within the system.

2.2 Fast Fourier transform

Fast Fourier transform (FFT) is an efficient tool for the analysis of vibration records. The Fastest Fourier Transform in the West (FFTW) [7]—an implementation of the discrete Fourier transform (DFT) that adapts to the hardware in order to maximize performance—is a widely used free-software library applied in various special cases. Let $x_0, \ldots, x_{N-1}$ be an array of n complex numbers; then, the 1-D DFT X_k is given by the summation of exponential (sinusoids) functions, which is taken over the set of all integers N. The time-domain vibration signal was analyzed by FFT.

3. Realization and measurements

The machine tool introduced in the present study can be applied to a drilling machine, milling machine, grinding machine, planning machine, and other machine tools that use a rotating cutter. An external information device receives the working parameters and displays and analyzes data; this feedback on the working state of a processing cutter, which is given to the controllers in real time, helps achieve good processing quality. The proposed condition monitoring system has an additional advantage of accessibility to rotating spindles that would normally be very difficult or impossible to monitor by means of wired sensors, as shown in Fig. 3. The vibration spectrum of the solar-powered system that gives the FFT output of the spindle when excited at different rotational speeds is shown in Fig. 4 Fig. 4(a) shows the spectrum obtained for a fundamental rotational frequency of 9.97 Hz at a rotating speed of 600 rpm. Fig. 4 (b) shows the spectrum obtained for a fundamental rotational frequency of 15 Hz at a rotating speed of 900 rpm. Fig. 4(c) shows the spectrum obtained for a fundamental rotational frequency of 20 Hz at a rotating speed of 1200 rpm.

Demo video clips of the experiment are available on the Web site (http://www.youtube.com/watch?v=-DlxK40p7W0).

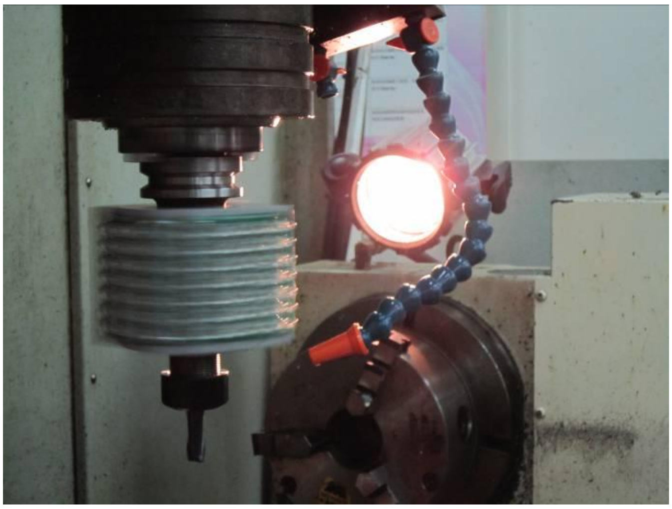
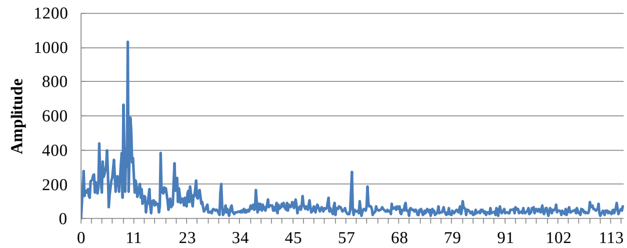
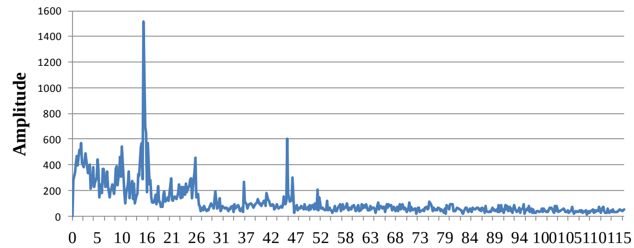


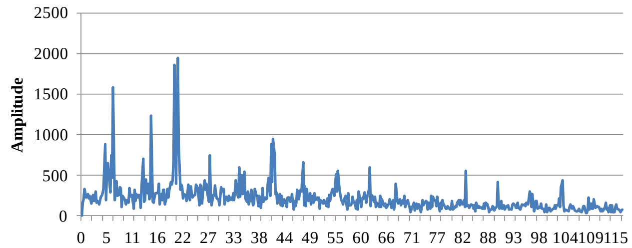
Fig. 3 The proposed sensing devices setup performed on an end-milling machine tool.



(a) RPM = 600



(b) PPM = 900



(c) RPM = 1200

Fig. 4 Acceleration spectrum of tool holder obtained by FFT process.

4. Conclusions

The proposed wireless solar-powered system can monitor the working state of the machine tool holder in real time; the system comprises the spindle body, a rotating mandrel, a cutter base, and an internal inspection device. The cutter base is joined to the rotating mandrel and rotates with the rotating mandrel. The rotating mandrel has a chamber in which the internal inspection device is placed. The inspection chips in the internal inspection device are directly mounted on the cutter base in order to measure the working parameters during processing. The working parameters are transmitted to an external information device via a wireless transmission module in the internal inspection device, thereby accurately providing feedback on the working state of the processing cutter in real time. The experimental results show that real-time acceleration spectrum can be realized at different test rotational speeds.

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