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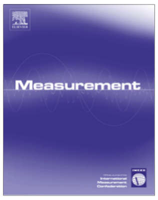

FPGA-based reconfigurable system for tool condition monitoring in high-speed machining process

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ABSTRACT

We present a reconfigurable system to detect and indicate online and in real time, the cutting tool conditions in high-speed face milling. It consists of a data acquisition system (DAS) and a hardware signal processing (HSP) unit. The DAS acquires and digitalizes the cutting vibration signals generated from machining tests performed under different tool conditions and cutting parameters. The HSP unit processes the digitalized vibration signals using reconfigurable IIR band-pass digital filter and statistical techniques, designed and implemented into a single field-programmable gate array (FPGA) and coefficients read-only memories. The system operation is divided into learning and monitoring modes. The tool condition is indicated by an alarm signal, one LED indicator, and a message shown on four-digit seven-segment displays. In all experiments, the system correctly detected the tool condition. The proposed system is fast, compact, reliable, and economical, and no modification of the machine-tool structure is required.

1. Introduction

Cutting tool condition monitoring (TCM) in high-speed machining (HSM) process is one of the main issues of interest in the manufacturing industry. When tool wear or breakage occurs during the machining process and is not detected, it degrades production performance because it affects workpiece quality and production costs. However, few monitoring systems have been developed and reported to detect the tool condition in HSM. These systems are based on the measurement of physical variables related to the cutting tool conditions, such as cutting force [1,2], feed and spindle motor currents [3,4], and vibration [5,6]. Nevertheless, some of these reported systems have limitations for their industrial application, e.g., high costs, difficult installation on the machine tool, or operation with limited characteristics. These limitations are due to the types of measured variables and the employed sensors. For example, cutting force measured by dynamometers. These sensors are mounted between the workpiece and machining table, which makes difficult their place on the machine tool, and limits the maximum workpiece size. Another example is the current signal obtained by monitoring the output servo drivers. These drivers have current sensors with limited bandwidth. In contrast to the aforementioned variables, vibration signal offers better characteristics such as the following: (1) periodic shape that resembles the cutting force, (2) enough information

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regarding tool condition, (3) robustness, (4) reliability, (5) applicability, (6) low-cost, and (7) ease in measurement implementation without requiring any machine tool modification. For this reason, the vibration signal has also been used for TCM in conventional machining [7–9].

Another limitation of the previously reported TCM systems is that they are designed for fixed cutting conditions. However, in the industrial environment, the machining processes are carried out under variable cutting parameters. Therefore, an important characteristic that needs to be considered in the design of TCM systems is its fast and easy adaptation to different cutting parameters set by the operators.

The other limitations of some of these systems are the use of inappropriate technique for their analysis and low processing speed. Some systems are based on the fast Fourier transform (FFT); however, the effectiveness of this signal spectral analysis is limited due to the complexity of the metal cutting process, especially for interrupted milling process with impact phenomenon. In this case, the dynamic signals are nonlinear and non-stationary [10], and the FFT basis cannot identify the transient and nonlinear signals because they present harmonic or inter-modulation distortions [11]. Moreover, this technique requires high power consumption and longer time. Therefore, FFT is not the most appropriate method to process such machining signals. The final limitation of the reported TCM systems is their software or analog implementation, which increases their cost and reduces the performance.

To overcome all the aforementioned drawbacks, we present a reliable and reconfigurable system-on-a-chip (SOC) to detect and indicate online and in real time the tool conditions in HSM. The monitoring system is reconfigured at the cutting parameter set up during the machining process. Vibration signals are obtained by an accelerometer and are digitally processed using a reconfigurable IIR band-pass digital filter (fourth order) and statistical techniques such as the sum of squares and mean value.

The operation of the proposed system is conducted in two modes: learning and monitoring modes. In the learning mode, the system determines the passband of the digital filter, selects a set of filter coefficients, and acquires and processes the data. However, instead of monitoring the tool condition, the processed data are used to set up a healthy-tool threshold. Therefore, the operating level is defined and stored for the monitoring mode. Once the learning process has been completed, the system automatically changes to the monitoring mode.

In this mode, the system acquires, filters, and computes the mean value and compares the data with the set healthy-tool threshold to detect and indicate the tool condition during the high-speed cutting process. The tool condition is indicated by an alarm signal, one LED indicator, and a message shown on four-digit seven-segment displays. These indicators allow intervention during the machining process.

The use of digital filters as a signal processing technique in a TCM system is logical because these filters perform simple mathematical operations, which make them computationally efficient. In addition, digital filters are highly accurate, and their performance is not subject to nonlinearities or changes in temperature or drift of their components with time, in contrast to analog filters.

The proposed TCM system is implemented into a single field-programmable gate array (FPGA) using the VHSIC hardware description language (VHDL), which allows online and real time monitoring owing to the high processing speed and parallel processing of the FPGA. A digital filter design with an FPGA leads to compact implementation because both control and support elements are fitted in the same chip. Moreover, VHDL allows easy and fast modeling of several types of filters by reprogramming or changing the contents of a few internal register. For example, reconfiguration of the passband of a digital filter is performed by changing the set of filter coefficients. This set of coefficients is pre-calculated using any standard digital filter design tool. Then, using meta-programming techniques, the generated set of data is automatically converted to a VHDL code module, which describes a read-only memory (ROM) that contains the set of coefficients.

Finally, the FPGA allows development of scalable digital structures, which can be easily adapted to diverse applications without changing the hardware. On the other hand, the hardware signal processing (HSP) implementation reduces the cost compared with the cost of the reported analog or software TCM systems. The accelerometer and the standard components used for signal conditioning and data acquisition also help to reduce the system costs. Furthermore, this low cost is maintained because the installation system does not require any modification of the machine-tool structure.

2. Vibration analysis

The setting of the band-pass filter was based on the vibration characteristic patterns of the machining tests performed under different cutting tool conditions. These characteristic patterns were obtained from the time–frequency map analysis. For this purpose, vibration signals were processed by the continuous wavelet transform (CWT) method. The time–frequency map analysis demonstrated that the vibration characteristic pattern of the milling process carried out using a healthy cutting tool was different from that generated using a damaged tool. Frequencies between the insert passing frequency (*IPF*) and its harmonics are generated when the cutting tool is defective, whereas this event does not occur when the tool is healthy. A more extended analysis of the vibration characteristic patterns can be found in [12]. Fig. 1 shows the aforementioned result, which shows the 2D contour plot of the CWT time–frequency maps of the vibration signals acquired using tools with different conditions, spindle speed of 7000 rpm, and a cutting tool with three inserts. The vibration maps in Fig. 1 show that healthy cutting tools generate periodic *IPF* and its harmonics as the dominant frequencies (Fig. 1(a)). In contrast, a damaged tool generates additional nonlinear and transient frequencies at nonsynchronous frequencies (Fig. 1(b)–(d)). *IPF* is expressed as follows:

$$IPF = n \times z/60 \tag{1}$$

where n is the spindle speed (rpm) and z is the number of inserts in the cutting tool.