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Abstract

This paper introduces a Tooth Rotation Energy Estimation (TREE) technique and its implementation on a PIC Microcontroller based distributed machine tool condition monitoring system. The technique uses existing machine signals namely; spindle speed and spindle load for the purpose of data acquisition, analysis and decision making thus avoiding the use of any additional sensors. The paper discusses the evolution of this time domain technique, starting from signal acquisition, hardware filtering, the application of moving average for software filtering before going on to explore the signal’s variations for different tool conditions. The acquired data is analysed in terms of the energy per tooth. The strength of an energy index in the acquired signals under various cutting conditions can then be used for fault diagnosis and prognosis. The software and hardware system architectures and the test application on a Kondia B500 vertical axis milling machine are described.

Key Words

E-Monitoring, PIC Micro-controller, Tiny Internet Interface (TINI), Machine Tool, Condition Monitoring, Sweeping filter, CAN, Tooth rotation frequency.

1 Introduction

The application of e-Monitoring techniques in industrial environment has been on a constant rise supported by the recent technological breakthroughs. The monitoring areas in this field generally fall under two major categories namely; process monitoring (i.e. the overall health of the process) and condition monitoring (i.e. monitoring the individual components within the process). Metal cutting is a major operation in industrial manufacturing environment. Of the many different types of machines used for metal cutting operations milling machines are very important. Milling is normally defined as a process of machining flat, curved, or irregular surfaces by feeding the workpiece against a rotating cutter containing a number of cutting edges. The usual milling machine consists of a motor driven spindle, which mounts and revolves the milling cutter, and a reciprocating adjustable worktable, which mounts and feeds the workpiece. The Intelligent Process Monitoring and Management (IPMM) Centre at Cardiff University UK, has been researching techniques for developing tool condition monitoring systems for these rotating cutters in the milling machines and introduced the concept of e-Monitoring [1]. Some of this earlier work in the area of condition monitoring has already been reported and published [2-5].

A Tool Condition Monitoring System (TCMS) is essentially an information flow and processing system in which the information source selection and acquisition (sensors and data collection), information processing and refinement (signal processing and feature extraction), and decision-making based on the refined information (condition identification) are integrated [6]. An effective and time efficient on-line identification of machine tool failure plays a key role in enhanced productivity, better quality and lower costs for unmanned, automated manufacturing systems. The most important success factor for a robust and reliable TCMS is to develop appropriate signal processing techniques to maximize the information utilization of the input signals. The source signals for TCMS generally fall into two categories namely; (1) utilisation of additional sensors and (2) the use of existing machine tool signals. In the past many monitoring techniques have been developed to detect tool breakage and to estimate tool wear by evaluating the most important characteristics of the signals coming from sensors such as dynamometer, accelerometer(s), acoustic emission sensors, thermocouples, and microphones etc and relating them to the predetermined tool conditions. It has been observed that the force measurement is a more reliable method among those for detecting tool breakage. However, the main disadvantage is that each machine tool needs to be fitted with a sensor system, which makes this method very expensive and for some tool systems it is very difficult to install such system [7,8]. However due to the recent advancements in technology and requirements for cost effective TCMS, our research thrust for the design of monitoring and diagnostic systems for industrial environment is shifting from direct sensor based to indirect sensor based approaches. The major reason behind this shift in addition to cost is the increase in relevance of these systems to modern industrial environments. However the major hindrance towards the design of these systems is the reliability of any decision made from the information...
retrieved from a source which may not be directly related to the decision making area [9].

Having identified a suitable signal source, the next step is to decide the analysis methodology and domain for that particular signal for information retrieval. The acquired signals can be analysed in the time or frequency domain or in both for reliable decision making about the tool condition. The Fourier transform is a commonly used signal processing tool in frequency domain for such applications. However this technique has an inherent drawback in that non-stationary transient information in the time domain can not be clearly identified in the frequency domain. As a result it could be very difficult to establish when a particular event (for example, a cutter breakage) takes place from the frequency domain only [10-13]. To overcome this deficiency a windowing technique has been applied to the Fourier transform of a small section of the signal at a time, creating a so-called short-time Fourier transform [14]. The use of short-time Fourier transforms to detect cutter breakage in milling has been reported by Tarng et al [15]. However, the precision of the short-time Fourier transform is still limited and greatly dependent on the size of the window. These signals can also be analysed in the time domain. The most important factor for time domain analysis is that time series modelling and its implementation is a mathematically extensive task and not supported by normal low-cost 8-bit microcontrollers. While extensive research has already been done in this area, no definitive system has been developed for monitoring machines and tools under all conditions. Instead, specialised devices designed to detect particular faults have been produced [9]. The aim of this research work has been to develop an effective time domain analysis technique which uses the existing machine tool signals but remains simple and efficient enough to be implemented on a normal 8-bit microcontroller as a front end monitoring node. The research work has been designed and tested on a Kondia B500 vertical milling machine. Machine tool spindle load and spindle speed signals were chosen for analysis which were directly available from the machine controller thus avoiding the requirement of any additional sensors.

2 A Brief Review of Time Domain Analysis Techniques

In addition to the frequency analysis techniques already reported e.g. [8,16,17] and wavelet transform signal analysis e.g. [13,18] for decision making about the tool condition, there has been extensive research in the field of time domain analysis as well. Tansel and McLaughlin [19] have reported the use of time series based Tooth Period Modelling Technique (TPMT) for the detection of tool breakage. The parameters of a 20th to 24th order AR model were used for this application. The use of a vibration sensor for decision making has been reported as well [20]. Y. Altintas has researched the usage of feed drive current for prediction of cutting forces and subsequently to determine the tool breakage [21]. The average current was sampled by an analogue circuit whose timing at tooth passing interval was obtained by an encoder mounted on the spindle shaft using a PC and used further for decision making. Roth and Pandit have reported the development of multivariate autoregressive models fitting to tri-axial accelerometer signals, for machine tool condition monitoring [22]. The developed algorithm is designed to track the changes in the energy over time for decision making. Kuljancic and Sortino have reported tool wear estimation (TWEM) technique based on the force signal variations and their statistical analysis [23]. Tansel et al have reported two encoding methods to estimate tool wear from the cutting force signal [24]. A dynamometer was used to acquire cutting force signal for analysis and decision making. Lin and Yang have reported a force signal based model for wear monitoring in face milling operations [25]. A relationship between the flank wear and average cutting force coefficients is suggested to estimate the tool wear. The modelling has taken care of the dual motion of cutter rotation and workpiece feeding motion. A dynamometer was used to measure the cutting forces, which are acquired and used to estimate the cutting coefficients.

Although extensive research has been carried out in this area, the requirement of cost effective yet reliable tool condition monitoring system is still there. Most of the techniques discussed above are effective but they use additional sensors and/or are based on PCs. This not only increases the overall cost of the system but also restricts the industrial environment. The system reported in this paper is not only based on simple hardware (based on 8-bit microcontrollers) but also uses existing machine tool signals (spindle speed and load) thus reducing its overall cost and yet being reliable enough to be used in manufacturing industry.

3 Hardware Architecture

The proposed machine tool condition monitoring system is based on three tier architecture as shown in Figure-1. The first layer nodes are based on PIC 18F458 microcontrollers and MAX264 programmable filters. The MAX264 programmable filters are used for necessary band pass filtering of the input signals. The pass band is determined by the microcontroller depending upon the machining parameters “on the fly”. All the control inputs of the filter were connected to the Microcontroller Unit (MCU) providing total control to the developer. The Pulse Width Modulation (PWM) module (built-in the MCU) was used to generate the required clock signal for the filter, thus reducing software overheads. The MAX264 filter has been named as sweeping filter as it can either be used as a simple band pass filter as reported in this application or as a sweeping filter for frequency analysis as reported in an earlier application [4]. The spindle speed and spindle load signals are tapped from the machine controller and
interfaced to an isolation card. This card provides high voltage protection between the machine tool signals and analogue inputs to the system. The isolation card is housed in a signal conditioning card rack fitted into the machine tool Kondia B-500 for research applications and signal distribution. The hardware architectural design details of these boards have already been reported by Jennings et al [26]. The outputs from the isolation card are interfaced to the first tier monitoring nodes. The first tier microcontrollers use 40MHz crystal oscillators. The microcontrollers are linked together using Controller Area Network (CAN) bus using PCA82C50 CAN transceiver. The CAN is a serial interface useful for communicating with other peripherals in noisy environments. The system has been designed based upon extended data frame CAN protocol usage. The same communication medium is used to link the entire first layer of the system to second tier, which is based on a Tiny Internet Interface (TINI) system. The TINI microcontroller is a small computer that executes Java bytecode and has built-in Ethernet networking and interfaces for connecting many different types of hardware [27]. The TINI CPU is the Dallas DS80C390 microprocessor which is descendent of the 8051 microcontroller having six 8-bit I/O ports. TINI has built in serial, parallel, 1-Wire, and CAN ports with extra pins for controlling optional devices. It can address up-to 1MB of RAM and 1MB of Flash ROM. The TINI board also contains an RS232 interface, a real time clock and a unique Ethernet Media Access Control (MAC) address. A simple architecture of the TINI system is shown in Figure 2. It communicates to the rest of the system using the CAN bus and can link the entire system to a central server. Within the overall context of design in this three tier system, TINI is proposed not only as a link medium between front end nodes and Ethernet but also to be used as a middle stage of data processing within the system. Each front end node is responsible for monitoring the health of at least one machine signal. The system has a plug and play capability to add extra front end nodes if required as shown in the Figure-1. In the event of any abnormal situation developing, depending upon the severity of the problem, relevant nodes will be instructed to share the information and a decision made either at tier one or a decision verification requested from tier two if higher computational powers required (data would have already been sent to 2\textsuperscript{nd} tier for independent analysis as soon as abnormality was indicated to save time and to maintain the ability to make real time decisions).
4 Software Considerations

The instruction set of PIC18F458 Microcontroller is based upon 16 bit wide instructions (with the exception of three instructions). It has eight analogue input lines, which can be interfaced to different machine signals, though only one signal can be acquired and converted at one instant. The A/D module allows the conversion of an analogue input signal to a corresponding 10-bit digital number. A number of instructions are available for data manipulation in this device, which is ideal for such applications. The initialisation block of the software in the first tier nodes sets up the micro-controllers’ operating mode and selects and configures the digital and analogue I/O pins. It initialises the CAN activity and does essential handshaking to verify the health of the system at initialisation as well as at regular operating intervals. The starting of data acquisition and processing events is based on existing signals namely Zero Speed Signal (SSTA) and Speed Arrival Signal (SARA) from the machine controller as shown in Figure-3. These signals along with CNC demand signal help the microcontroller to decide about the latest machine parameters. Changing the clock input to the filter can vary the centre frequency of the bandpass filter. The built in Pulse Width Modulation (PWM) module in the microcontroller is used to generate the clock input for the filter.

The data is acquired in segments of one tooth rotation each. During the data acquisition stage of next segment, the processing of previously acquired data is completed. The processing includes software filtering, finding the peak to peak difference in the acquired samples, segmental average and variance (these will be explained in next section). A general flow diagram is shown in Figure-4. The TREE technique is analogous to the one normally used in swept spectrum analysers as far as the calculations for the relative power of a frequency component are concerned. The principle differences are the different domains (time domain for TREE technique and frequency domain for swept spectrum analysers) and the use of voltage controlled oscillators (VCO) which is not required in the use of the TREE technique. The storage space for tooth rotation samples is variable and is calculated by the microcontroller using the actual variable spindle speed and a fixed sampling rate. If there is no mechanism in place for further data analysis and decision making; the data acquired by first tier nodes will either have to be communicated to the server or discarded. In order to prevent data overload and the data becoming obsolete, it should be classified and discarded if it is commensurate with normal machine behaviour. Only selected abnormal data is forwarded for future referencing etc. The research presented in this paper adhers to this principal. While the data for a tooth rotation is being acquired, the calculations of previous acquisition are carried out in parallel and the results are compared against parameter dependent thresholds for decision making.
In the event of abnormal indications, the observant node communicates to other first tier nodes over the CAN bus for verification and depending upon the results from other nodes it can generate a warning/alarm or can send data to TINI board for further analysis/advise. The CAN module of each node is configured to operate/support the extended data frames. The CAN bus in this application is operating at 125Kbits/sec rate. This data rate was selected to strike a balance between the noisy industrial environment and timing requirements to enable the system in calculating results within one tool revolution.

5 Tooth Rotation Energy Estimation (TREE) Technique.

The TREE technique uses existing spindle speed and spindle load signals of the machine. It analyses the variations in these signals under various cutting and cutter conditions for each tooth rotation period in terms of average tooth rotation energy. The machine signals are acquired using PIC microcontroller after necessary filtering as shown in Figure 1. Due to the inherently fast response of NC machines to any parametric or environmental changes it is imperative to select an appropriate sampling rate which could detect these variations without any loss of information and yet be supported by the PIC Microcontroller. An audit of the machine was carried out which revealed that the spindle encoder was designed for generating 12000 pulses/sec. The due consideration to this rate while designing a monitoring system using existing controller signals is extremely important since if the sampling rate of a designed system is much lower, there may be enough time for machine controller to overcome the variations before they were actually acquired and analysed. Having done a detailed analysis of encoder pulse rate, microcontroller’s capabilities and the actual monitoring requirements; machine signals were sampled at 8000 samples/sec (a PIC can support higher sampling rates depending on the clock rate and MCU chosen). The chosen sampling rate delivered the best results considering both available internal memory and the number of required samples at different speeds.

5.1 Implementation and Results

The TREE technique focuses on the average tooth rotation energy and its variations to determine the tool condition. Tests were carried out using a range of machining parameters. The results discussed here are based on a spindle speed of 500 RPM, feed rate of 100mm/minute and 1mm depth of cut using a four teeth cutter on a Kondia B500 vertical axis milling machine. Under the described spindle speed and data sampling rate, 240 data samples/tooth rotation were analysed. Figure 5(a) shows the acquired spindle speed signal for both new and broken cutters. In all 24000 data points are shown consisting of 12000 data points for new and broken cutter each. The signals are interfaced midway to show the variations for both conditions by simulating the tooth breakage. The machining environment noise clearly dominates the signals though these signals have been acquired after first stage of hardware filtering and signal conditioning. Moving average filtering (software) was applied to further filter the data. The span of the moving average is variable for this application design, which depends on spindle speed and number of teeth in the cutter where as the sampling rate is fixed. The moving average of spindle speed signal based on a span of 240 data samples (corresponding to one tooth rotation) was calculated using Matlab software and results are shown in Figure 5(b). The noise has been filtered out very effectively, Figure 5(c) shows the results of moving average filtering using the actual PIC microcontroller based designed system. Figures 6(a)-6(c) show the results from the repetition of same steps apart from the fact that the source signal is spindle load. It can be clearly seen that the variations in the spindle load signal are much higher as compared to the spindle speed signal after breakage of a tooth. The moving average span in this design is variable which corresponds to average tooth rotation energy under different cutting conditions and is calculated on the fly. Figure 6(c) shows the variations in tooth rotation energy for a healthy and broken cutter. These variations in parallel with the spindle speed signal analysis are used to verify each other’s results before making a final decision about the health of the tool. Figures 7(a) & 7(b) show a step further into this research where the average of the data shows the cutter breakage clearly. Similarly Figures 8(a) & 8(b) show the calculations of the variance of the same data and verify the results. The technique is efficient enough to deal with varying cutting parameters e.g. depth of cut. The decrease or increase in the depth of cut affects the spindle load signal and average tooth rotation energy. This can be easily dealt with by considering the fact that (e.g. increased depth of cut) increases the spindle load and average tooth rotation energy but the variations in this energy are not sufficient enough to reach the threshold values which are also changed with the parameter changes. This applies to different cutting parameters thus making it a reliable and robust system.

6 Conclusions and Future Work

A time domain data analysis technique along with its implementation on an 8-bit microcontroller based system and its results for a real world application have been reported. The capabilities of PIC Microcontroller to be implemented as a heart of the first tier monitoring node in the overall system design along with its communication features on the CAN bus have been fully explored. The use of distributed embedded systems for machine tool condition monitoring applications has been verified for its reliable applicability.
Figure 5(a), Acquired Spindle Speed (ASS) Data

Figure 5(b), Moving Average Filtering (MAF) of ASS Data, using Matlab (Floating point calculations)

Figure 5(c), Moving Average Filtering (MAF) of ASS Data, using PIC (Integer calculations)

Figure 6(a), Acquired Spindle Load (ASL) Data

Figure 6(b), Moving Average Filtering (MAF) of ASL Data, using Matlab (Floating point calculations)

Figure 6(c), Moving Average Filtering (MAF) of ASL Data, using PIC (Integer calculations)
Use of the existing machine tool signals have proven fruitful for its future applications. The monitoring system designed for any industrial applications needs to be extra robust and reliable to cater for noisy environments. The milling operation in particular needs extra care as is evident from the acquired signals shown in Figures-5(a) & 6(a). To increase the reliability of the designed systems further there has been an ongoing research at the IPMM Centre to develop a frequency domain analysis technique for the same signals in parallel and has been reported earlier [5]. Further research work is under progress to interface both the time and frequency domain analysis techniques to design a single but reliable and robust tool condition monitoring system based on 8-bit PIC microcontrollers.

8 References


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