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SENSOR FUSION FOR AN INTEGRATED PROCESS AND MACHINE CONDITION MONITORING SYSTEM

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Abstract: This paper describes the implementation of an integrated monitoring system for a CNC machine tool and its machining processes such as drilling, milling, turning and grinding. The monitoring system uses a variety of sensors such as force, torque, vibration, acoustic emission, and temperature to monitor the machining processes and the physical condition of the machine tool. The major aim is to improve the reliability of the machining operations and machine condition so as to ensure high part quality and reduce inspection costs. The paper describes the integrated monitoring systems developed and a case study to describe some of the obtained results. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Working to meet the demands of a global marketplace, it is necessary for manufacturers to fulfil exact requirements. The international competition, increasing requirements for quality, faster paced advances in increasingly complex technology, rapidly expanding options in materials and processes and increased unpredictability of surroundings create an urgent need for implementing new technologies and utilising existing commercial technologies as a vital approach for industrial survival. Condition monitoring of machine tools and machining operations is one of these state-of-the-art technologies to be implemented. It offers a flexible, effective and economical methodology to improve the entire performance of manufacturing systems through: better design; enhanced health and safety standards; minimisation of unproductive time of staff;

improved quality and reliability; minimum environmental pollution; improved availability of machine tools; better customer satisfaction; and maximum profits (Hutton, 1996). Condition monitoring can achieve its goals by two main directions: the first direction is to ensure a good quality of the products by monitoring process conditions. The second is to maintain high productivity by establishing a good maintenance system of the whole machine tool to prevent any operational failure or down-time. Productivity can also be improved by including the necessary inspection and quality control processes within the production stage.

With the use of CNC machines and high speed machining it has become extremely difficult for the machine operator to monitor the ongoing process and provide a fast response to sudden disturbances, e.g. tool fracture. What is needed is an automated machine condition monitoring system that predicts failures before they cause damage or breakdown (Martin, 1994). Therefore, machine condition monitoring systems should be able to track faults such as gradual tool wear and tool fracture, which can offer the highest potential for avoiding unproductive down-time and maintain the greatest quality of the manufactured products. Condition based maintenance strategy can also reduce unnecessary downtime based upon measuring the condition of several critical machine elements during the normal machine tool operation. Then analysis can be done to predict the time to failure for critical machine parts and thus allow maintenance to be planned before the failure of any of the critical elements (Kacprzynski, 2000). The main objective towards maintenance should be maximising efficiency, quality, and the availability of the manufacturing system while reducing the need for maintenance.

From technical aspect, many different types of sensors and signal processing methods are now commercially available. Many ideas have been presented, see for example (Jemielniak, 1999), and numerous approaches have been proposed for condition monitoring. However, machine tools are very complex systems which include electronics, electrical, hydraulic and pneumatic drive systems, mechanical systems, control systems, measurement systems, gears, bearings, ball screws, lubrication systems and coolant systems. Machining processes are also difficult to be monitored due to the high combinations of operating conditions and faults. To fully understand and attempt to control the behaviour of a machine tool and the machining process, effective condition monitoring systems should be developed which guarantee the reliability of the system operations and quality of products (Young, *et al.*, 1994).

This paper describes an integrated machine and process condition monitoring system that uses a variety of sensors and signal processing methods in order to establish a real on-line machine and process condition monitoring system. The paper presents a condition monitoring strategy which is based on an on-line and off-line monitoring sub-systems. The paper focuses on an initial experimental work performed to evaluate the on-line monitoring system of machining processes.

2. CONDITION MONITORING STRATEGY

The proposed condition monitoring strategy includes commercially available equipment along with newly developed systems and software. The main idea is to use the best of available technology for tool setting and checking, part probing etc. and to implement a sensor fusion model to monitor the process and machine health in order to accomplish a comprehensive integrated system.

In order to determine output quality of a machine tool and ascertain its health state, it is necessary to fully understand all of the possible contributing factors. This means having the necessary knowledge of machine health condition in terms of accuracy and repeatability and the state of the process.

Some of these influencing variables are rapidly changing and others remain relatively stable for long periods. Therefore the monitoring strategy involves some high speed continuous on-line monitoring (during the actual machining processes) and some off-line data collection (particular measurements performed when the machine is not on real machining process). Figure 1 shows the complete schematic diagram of the integrated machine and process monitoring system.

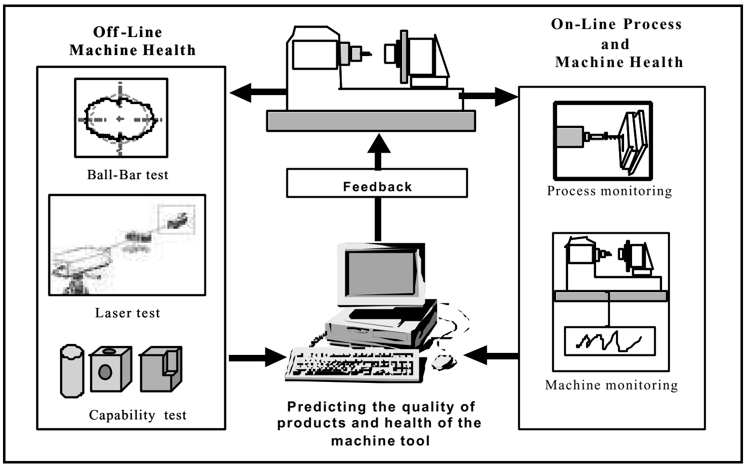

Fig. 1. The machine and process monitoring system

The off-line part of the condition monitoring strategy is concerned with collecting data on the machines behaviour on a long-term basis using standard tests. Off-line monitoring is used to detect the capabilities of the machine in terms of accuracy, repeatability, straightness, squareness, etc. It is used to monitor system performance, and to provide a mechanism which can react to the detected changes before they cause non-conformances in the production process. Three methods can be used for off-line monitoring of the machine health: laser interferometer systems, Ball-bar calibration system and the machining of standard parts. The laser and Ball-bar systems are very efficient method for determining whether a machine is configured and calibrated properly. The output of a Ball-bar is a circular pattern as shown in Figure 1, ideally a perfect circle representing a constant radius from the centre point. The dimensional and motion errors of the machine tool, however, result in deviations from the perfect circle. Machine calibration also can be performed through the analysis of a standard test piece. If problems are found then a suitable measurement system is introduced, and detailed measurements are then taken to recognise the error source. The advantage of such method is that the health of the whole system can be tested. However, if a problem is recognised, the fault may be caused by an error generated from the cutter or the rotating spindle and further analyses are normally needed.

The feedback process to the machine tool, shown in Figure 1, could be in terms of Condition Based Maintenance schedule to solve any machine problems or it could be in terms of operational feedback such as replacing a worn or a broken cutter.

The on-line monitoring consists of sensor fusion of various monitoring signals that relate to the process and to the health of the machine tool. The signals related to the on-line machine health are: the servo motor current of all the axes, the coolant pressure, temperature, and flow rate. The group of signals that mainly involves the monitoring of the machining process consists of cutting forces, torque, vibration, acoustic emission, temperature and spindle load. Figure 2 presents the sensors related to the process. Regarding the type of sensors, more details will be described in the following sections.

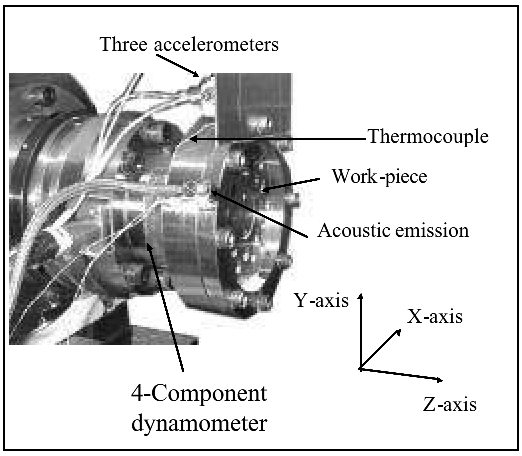

Fig. 2. Sensors installed on the work-piece side of the machine tool.

Sensor fusion has appeared to increase the reliability in the extracted information in some areas by the use of multi-sensors concurrently to monitor a machining. Process parameters such as feed rate, depth of cut, cutting speed, tool geometry, and noise can cause variation in the machining signals. Because of this reason, most of the researchers assume that it is important to integrate more than one sensor or parameter to increase the confidence in the system. Multiple sensors have been beneficially implemented in complex machine condition monitoring systems, such as tool wear monitoring for metal cutting environments, to obtain comprehensive information about the process (Al-Habaibeh, *et al*., 2000). The utilisation of different sensors involves integration and fusion of the sensory signals to extract the key features from the data by removing any existing redundancy.

3. IMPLEMENTATION OF CONDITION MONITORING

The most challenging part to achieve in the above monitoring strategy is the on-line condition monitoring of machining processes. In order to achieve a real on-line condition monitoring system for machining operations such as grinding, drilling, milling, drilling and turning, a fast processing time of signals is needed. In addition sensor fusion is needed to increase the reliability in the system and reduce false alarms. Figure 3 shows a schematic diagram of the complete process monitoring system. Three accelerometers are used to monitor the vibration of the work-piece (Kistler 8704B500) connected to two 4-channel-couplers (Kistler 5134). The acoustic emission signal is monitored using AE sensor (Kistler 8152A) that is connected to AE-Piezotron coupler type (Kistler 5125) which gives the AE signal and the RMS of the AE signal. The force signals are monitored using a 4-component Dynamometer (Kistler 9272). The force dynamometer is connected to a 8-channel charge Amplifier (Kistler 5017B). Spindle Load of the spindle is calibrated and monitored through a direct connection between the CNC machine panel and the monitoring system. The signals are monitored using a data acquisition card (National Instruments AT-MIO-64E-3).

An attempt is also made to measure the heat generated by the drilling process using a thermocouple. The thermocouple is used to measure the work-piece temperature which could present the efficiency of the cooling system as well as the generated heat from the process.

The evaluation of the sensor fusion system is made using a drilling process of a nickel-based alloy. A 10.2mm tin coating k10 solid carbide drill is used for the test. A through-drill coolant of 30 bars is implemented in the experiment. The machining parameters are kept the same during the process: Cutting speed: 25 m/min and Feed rate 0.07 mm/rev (737 RPM, 52 mm/min). During the experimental work, tool wear is measured following every drilled hole.

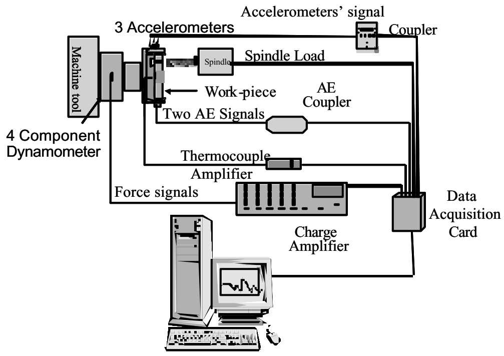

Fig. 3. A schematic diagram of the complete monitoring system.

4. EXPERIMENTAL RESULTS

A total of 38 holes are drilled until the tool is identified by the operator as being significantly worn. The main wear on the drill is found to be flank wear, see Figure 4. The values of flank wear as a function of number of holes drilled is also shown.

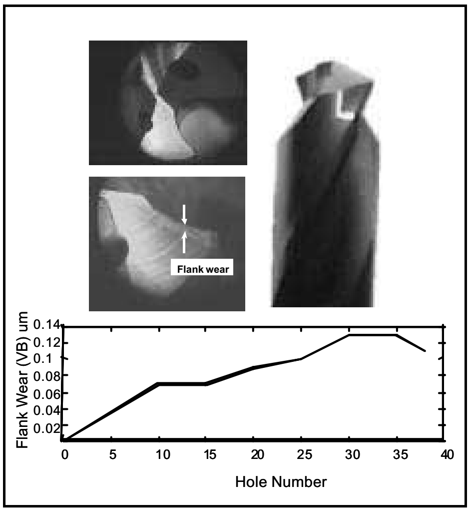

Fig. 4. The measured flank wear and its value following every drilled hole.

Figure 5 shows examples of the monitored signals during the drilling process. The figures present the raw signals for the first hole (fresh drill). It presents the drilling forces in the x-axis (Fx), y-axis (Fy) and z-axis (Fz) using the force dynamometer. The thrust force (Fz) is found the most representative force signal. As shown in the figure, the drilling process starts at elapsed time equals 5 seconds and finishes at 17 seconds.

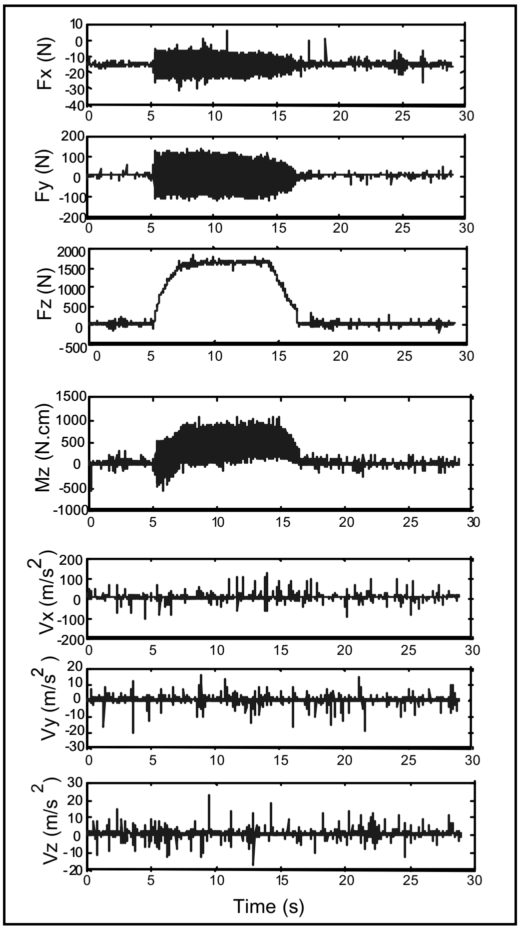

Fig. 5. The three cutting forces , the drilling torque, and three vibration signals.

The drilling torque (Mz), shown in Figure 5, is also measured using the force dynamometer. The torque is measured around the z-axis (feed direction). As it can be noticed, the average value of the torque level increases until it reaches a steady state and then it starts to decrease upon the exit of the drill from the other side of the work-piece.

The vibration signals of the x-axis (Vx), y-axis (Vy) and z-axis (Vz) are not found informative in this experiment as shown in Figure 5. This is expected due to the low sampling rate implemented in this test. As shown in Figure 6, the acoustic emission signal (AE) is found to be inadequate to detect any features in the drilling process due to the low sampling rate. However, the Root-Mean-Square signal obtained directly from the hardware (AE_RMS) is found to be informative about the drilling process. The increase in the AE_RMS level between 5 seconds and 17 seconds is due to the drilling process. However, another increase in the AE_RMS value level is found following the drilling process. This is found due to the noise produced by the coolant when colliding with the work-piece at pressure of 30 bars.

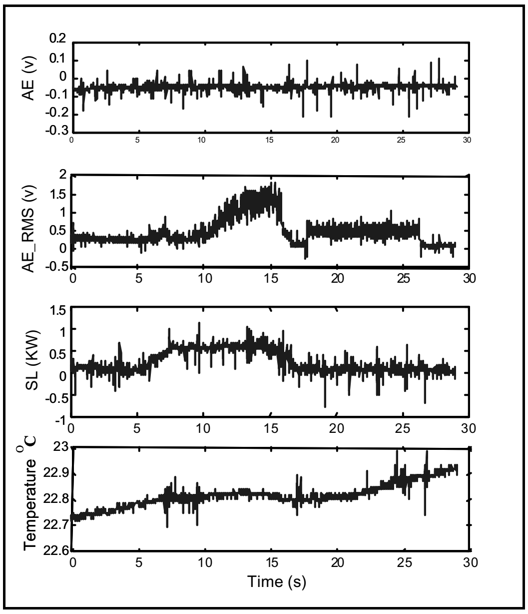

Fig. 6. AE signals, spindle load and work-piece temperature.

The spindle load signals extracted from the machine tool itself (SL) is found to be informative in terms of the drilling process despite the fact that it has a significant level of noise. The work-piece temperature is found to be increasing even before the drilling process. This found due to the increase temperature of the coolant when passing through the pumps. However, the temperature reaches a steady state during the drilling process then it decreases slightly when the drill goes through the work-piece (i.e. more effective cooling). Then the temperature starts to increase again. One reason for that could be due to the produced heat during the drilling process that would require additional time to be transferred to the thermocouple through the work-piece. Also the temperature is expected to increase after stopping the cooling process.

5. ANALYSIS OF SIGNALS

An automated analysis method is used to calculate different statistical values of the signals in order to evaluate the effect of tool wear on the signals. Statistical values such as average, maximum, minimum, power and standard deviations are used as features for analysis. The statistical analysis is performed on the steady state region (i.e. during the drilling stage) for all signals except temperature signals which are analysed through the complete acquisition time. Figures 7 presents some of the main statistical values which are useful in this test. The thrust force, work-piece temperature and spindle load are found most sensitive features to monitor tool wear of the drilling process.

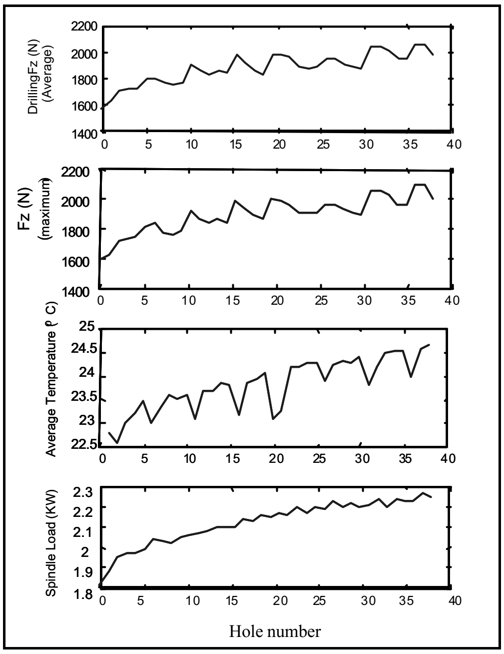

Fig. 7. Sensitive features to tool wear

6. DISCUSSION AND CONCLUSIONS

The described experimental work is an example of a pilot study conducted to evaluate the sensor fusion system for an on-line monitoring system. Some signals are found useful in detecting the gradual tool wear while others are less sensitive. Spindle load, thrust force and drilling torque are among the most sensitive signals that correlate with tool wear. However, this might not be the case for other drilling processes or parameters. Therefore, an understanding of the process signals and parameters is important to design a reliable on-line condition monitoring system. The application of specific threshold value for every signal and an intelligent decision making algorithm might be useful in determining gradual wear in drilling operations.

In this paper an integrated process and machine condition monitoring strategy is described including off-line characterisation of the machine and on-line monitoring of the machine and the process. The Process and Machine Condition Monitoring System is still under development. The application of sensor fusion for monitoring machining processes is described. An example of gradual tool wear monitoring of a drilling operation is presented. More experimental work and data analysis are still needed to evaluate the integrated monitoring system. In particular, the effect of sensory fusion on the monitoring process, the selection of the best combination of sensory signals with the best signal processing methods, the correlation between the machining signals and the methodology to automate a process monitoring system.

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