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A multi-sensor approach to the monitoring of end milling operations

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Abstract

The application of multi-sensor systems for the monitoring of machining processes is becoming more common-place to improve productivity, automation and reliability. The sensors employed in such systems possess signal- and information-ability for enhancing the monitoring and control of machining processes. Although measuring force, power and acoustic emission (AE) signals has been commonly used for the monitoring of turning and drilling operations, their application to the milling process has not been well developed, perhaps due to the complexity of the process. In order to enhance knowledge in this area of applications, a multi-sensor system was developed and installed for the monitoring of end milling operations. The signals acquired and analyzed by the system include force, torque and AE under different machining conditions. The measured signal data was used to perform frequency domain analysis. The results indicate the feasibility of using the frequency peaks of the AE_{RMS} and the torque power spectra for the monitoring of end milling operations.

Keywords: Multi-sensor systems; Monitoring of machining processes; End milling; Power spectra

1. Introduction

An automated and untended work-place with flexibility and efficiency is widely envisioned as an important factory of the future. The requirements of machined components with more stringent surface finish and higher machining accuracy have led to the demand for more precise and better control of automated machining processes. By the implementation of multi-sensor systems for the monitoring and control of metal cutting operations and the machine tools, it is anticipated that significant reduction in machining errors, with better surface finish, can be achieved. This approach is increasingly being used because of the relatively low cost of powerful and high speed microprocessors and the sensing instrumentation has made digital closed-loop control and signal processing systems economical for the applications. A multi-sensor system with various sensors is an important step for accomplishing higher machining precision.

The use of sensors to establish reliable, precise and efficient real-time monitoring and control of machining processes has been an important task for the past few decades, as evidenced by various task forces [1] and surveys [2]. Examples of specifications on sensor systems for machine tools and machining process monitoring can be found in the literature [3]. Comprehensive reviews have been conducted on the methodologies with focus on the sensor requirements and intelligent sensor systems [4]. The studies indicate that the monitoring and control of machining processes is very much dependent on the type of machining process and its process parameters. The fundamental mechanics of the cutting processes and the selection of sensor systems play an important role on the accuracy and reliability of the results.

The objectives of the monitoring of machining processes usually are related to the performance of the machine tool, progression of tool wear, dimensional tolerances, surface roughness and other features of the workpiece, the energy usage, or the chip formation. Over the past four decades, different types of sensors such as dynamometers, acoustic emission (AE) transducers, and accelerometers have been commonly applied to sense a particular characteristic or a combination of characteristics such as tool wear, tool fracture, machine vibration, etc. [5–10]. The majority of the past research of the sensor systems was performed on the measurement and analysis of the involved sensor signals in the time domain only. On the contrary, frequency domain analysis of the signals from force, torque, and AE sensors has been found to be more useful [11].

In the research study reported here, a multi-sensor system was developed and implemented for the monitoring of end

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milling operations [12]. The signals acquired and analyzed by the system include force, torque and AE. Comprehensive experiments were conducted to study the influence of force, torque and AE under different machining conditions. The machining conditions applied in the experiments consisted of different combination of cutting speed, feed rate, radial depth of cut and axial depth of cut. The measured signal data was used to perform frequency domain analysis. The response of the AE_{RMS}, force, torque, power and specific cutting energy were compared. The results indicate the feasibility of using the frequency peaks (FPs) of the AE_{RMS} and the torque power spectra in a multi-sensor system for the monitoring of end milling operations.

2. Experimental equipment and test procedures

The experimental studies involve measurements of the dynamic state of the end milling operations with varying machining parameters. To facilitate acquisition and analysis of the machining process data, a multi-sensor system as shown in Fig. 1 was developed. The sensing system include a rotating cutting force dynamometer, an AE sensor, a multi-channel spectrum analyzer, an IBM compatible 486 computer with analog-to-digital converter, and software for calculating the cutting forces.

The end milling experiments were conducted on a Majak AJV 25/405 CNC vertical machining center with four tooth milling cutters of 20 mm diameter. The machining was carried out on 160 mm long, 55 mm wide, and 42 mm thickness workpieces of AISI 4140 steel. The cutting forces and torque were measured by the rotary dynamometer, Kistler type 9124A and amplified with its built-in integrated charge amplifiers. Kistler type 8152A2 piezotron AE sensor was used to measure AE signals amplified and pre-processed by a AE coupler. After pre-processing, the root-mean-square values of AE under different machining conditions could be obtained and analyzed. A Bruel and Kjaer (B&K) 2035 spectrum analyzer and a 486 IBM compatible computer were used for the graphical display and analysis of the measured data. The time waves of force, torque and AE were used for the analysis. The high speed capability of the spectrum analyzer ensures that the characteristics of the FFT spectra are displayed in real-time without loss of data.

The machining conditions used in the experiments were: cutting speed, V, 17.5–64.0 m/min; feed rate, f, 42–86 mm/min; axial depth of cut, h, 1.0–2.5 mm; and radial depth of cut, b, 5.0–10.0. A tool maker's microscope, Mitutoyo model TM300 was used to observe the cutting edges and to measure the flank wear of the cutter. The characteristics of the AE, dynamic force components and torque were studied in the frequency domain. The frequency spectra of

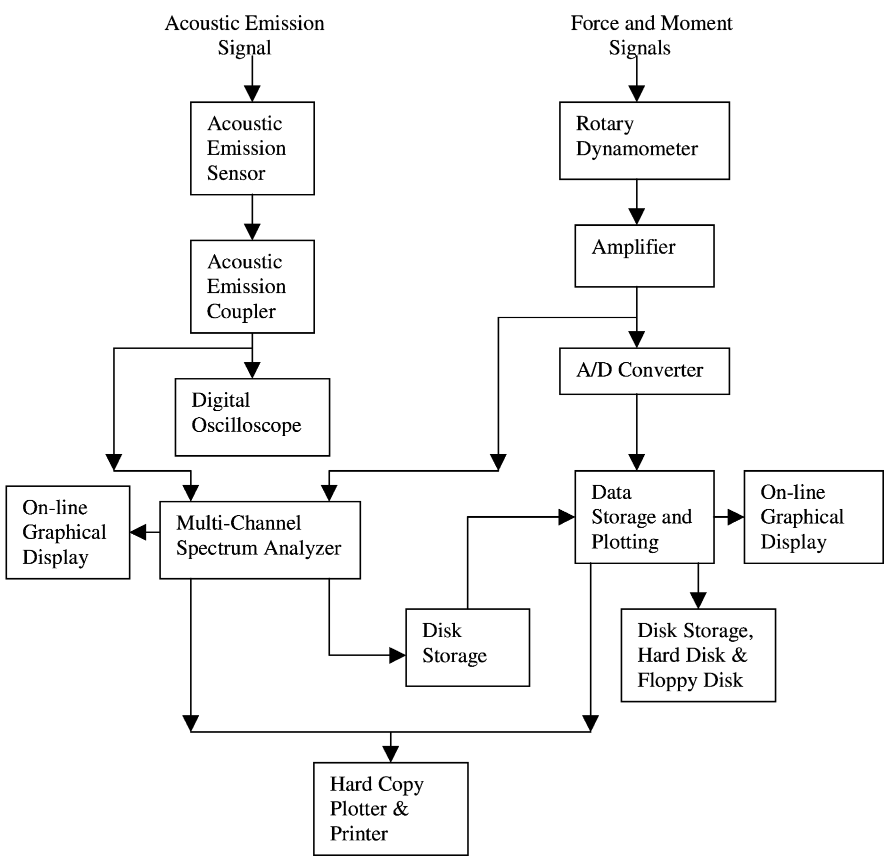

Fig. 1. Schematic diagram of a multi-sensor system for sensor signal acquisition and analysis.

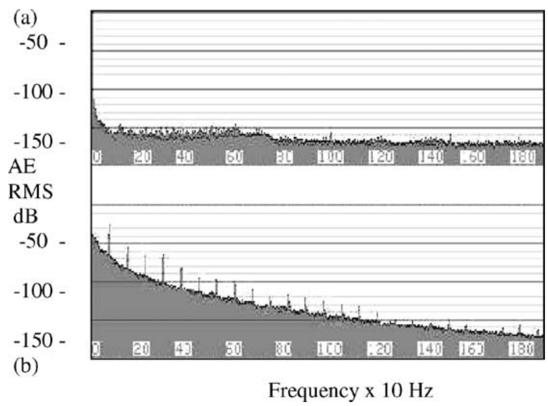

Fig. 2. Power spectra of AE RMS during: (a) air cutting; (b) actual cutting; $V = 64$ m/min; $f = 53$ mm/min; $h = 1.5$ mm.

the signals at no load conditions (air cutting) were obtained in the beginning and later the spectra under different machining conditions were obtained to have clear distinction between the signals due to the actual cutting operations and the ‘background’ signals at no load conditions (air cutting).

3. Results and discussion

3.1. Cutting data analysis

In the milling process, cutting forces and AE are generated due to plastic deformation in the shear zone near the cutting edges of the cutting teeth of the milling cutter, rubbing between the chips and the rake faces of the cutting teeth, rubbing between the workpiece and the flank faces of the cutting teeth, and the loading of the cutting teeth at the entrance to the cutting zone. In the end milling experiments conducted, Figs. 2–4 show the measured power spectra of the AE_{RMS}, the force and the torque that are analyzed in the frequency domain. The signal processing technique of FFT frequency averaging is employed for reducing the noise in the signal measurements. The power spectra indicate the

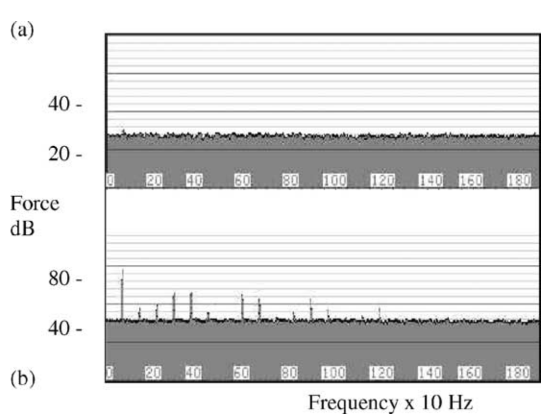

Fig. 3. Power spectra of force during: (a) air cutting; (b) actual cutting; $V = 64$ m/min; $f = 53$ mm/min; $h = 1.5$ mm.

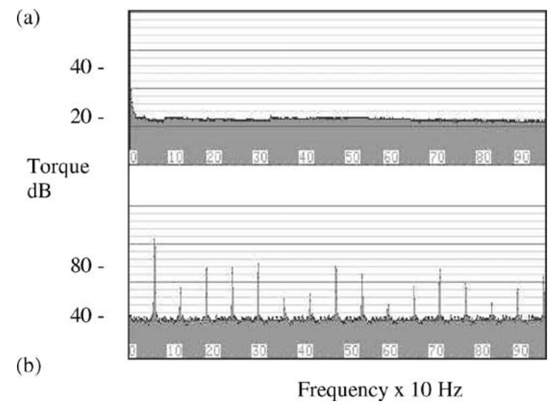

Fig. 4. Power spectra of torque during: (a) air cutting; (b) actual cutting; $V = 64$ m/min; $f = 53$ mm/min; $h = 1.5$ mm.

presence of FPs for actual cutting (plot b) in contrast to no FPs for air cutting (plot a). From the power spectra shown in plot b, a principal or fundamental FP, denoted by FP, is found to exist with decreasing harmonics. Every frequency spectrum for the analysis was the result of an ensemble average of over 800 spectra, each of which obtained from the FFT block of 2048 data given by one cutting condition. By doing this, the noise components in the sensor signals can be considerably reduced. The background noise levels in the AE signals were checked by air cutting tests with the same cutting conditions as that used to obtain AE signals in actual cutting tests.

3.2. Monitoring of the cutting parameters

The monitoring and control of machining processes is very much dependent on the type of machining process and its process parameters. With the material properties of the cutting tool and workpiece, the geometry of cutting and the cutting speed, the models developed on the mechanics of the cutting processes provide outputs related to the size and shape of the deformation zones in which plastic deformation occurs in the work and chip materials. The cutting forces during the machining process can be determined according to the stress distributions. The cutting force models developed are not accurate and the available data is largely base on experimental evidence. Therefore, for the monitoring and control of the machining processes, the use of measured cutting forces has been widely reported in the literature [13]. Measurement of the cutting forces can provide information on the machining conditions, which can be used to monitor dimensional accuracy and surface finish of the workpieces, and wear of the cutting tools.

The sensors used for monitoring of the machining processes may of direct or indirect measuring system. Owing to the limitations of single sensor instrumentation, there is an increasing effort to use combinations of different sensors or transducers to monitor various variables. An important capability of a multi-sensor system is the selection of a few reliable characteristic features from the large amount of

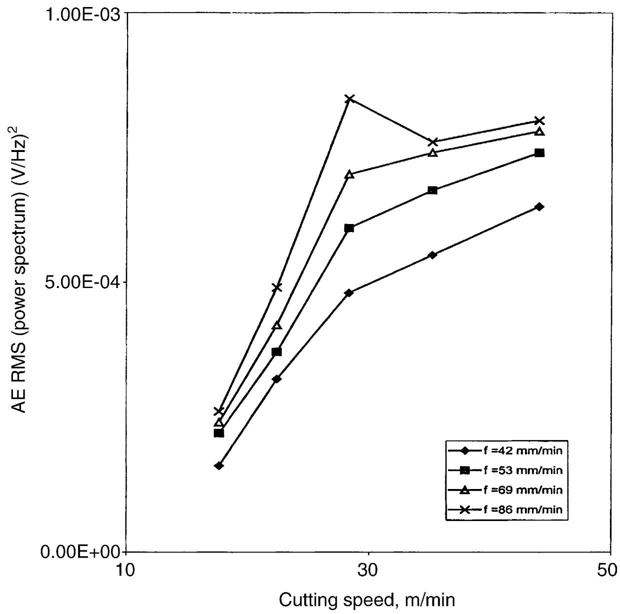

Fig. 5. Effect of cutting speed on the AE RMS (power spectrum) at different feed rates (*f*: feed rate).

signal data, which could be used for learning and decision making to implement a suitable monitoring and control methodology [14].

For monitoring of the cutting parameters, cutting speed was used for studying the signal characteristics. Several factors are involved in the material removal process due to change of cutting speed that affect the process conditions as represented by the signal characteristics shown in Figs. 5–7. With increasing cutting speed, the metal removal process involve four fundamental factors, namely: (i) increase in chip

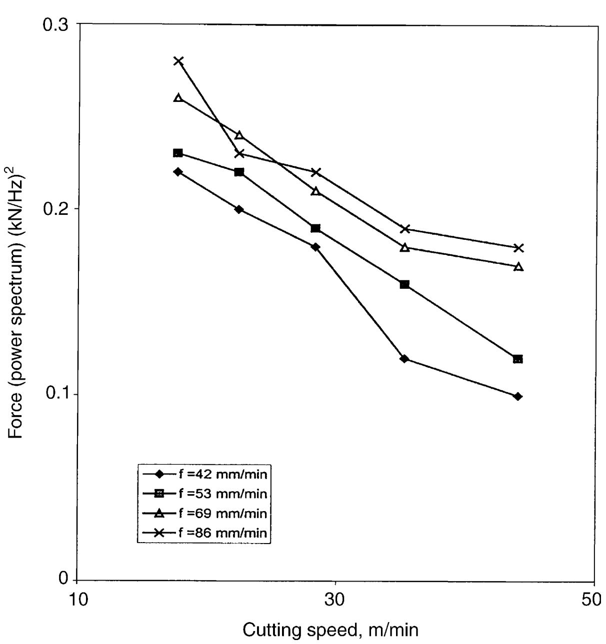

Fig. 6. Effect of cutting speed on the force (power spectrum) at different feed rates (*f*: feed rate).

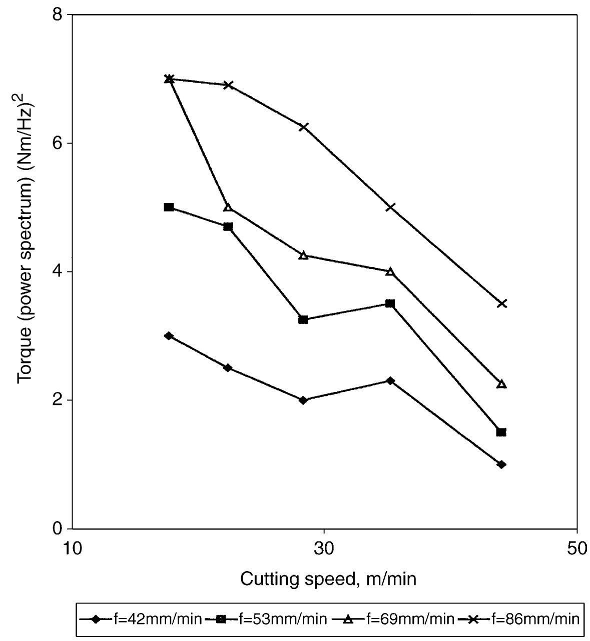

Fig. 7. Effect of cutting speed on torque (power spectrum) at different feed rates (*f*: feed rate).

velocity, (ii) increase in shear strain rate, (iii) increase in the rate of chip generation with respect to time, and (iv) decrease in feed per tooth relative to the cutting speed. The first three factors contribute to the increase in the generation of AE signals at the peripheral edges of the cutter. For the fourth factor, the friction coefficient at the tool–chip interface will tend to increase while the shear angle of the shear zone will tend to decrease. However, a smaller coefficient of friction and a greater shear angle will result when the cutting speed is increased contributing to decrease in the cutting force. Thus, from the power spectrum FP values, Fig. 5 shows that AE_{RMS} values increase with increasing cutting speed. But, the force FP values in Fig. 6 show that the cutting force values decrease with increasing cutting speed. As expected, the torque FP values shown in Fig. 7 vary similar to the force values due to the fact that the spindle torque is the product of the tangential cutting force and the radius of the milling cutter.

With prescribed rotation of the cutting tool, the main factor affecting the chip thickness is the feed rate. Both the shear angle of the shear zone and the material removal rate increase with increasing feed rate. Thus, the AE activity at the peripheral edges of the cutter will increase due to these changes. Similarly, the force and torque components show increase with the feed rate since the feed per tooth is increased. Similar trends are observed with radial and axial depths of cut as both these parameters tend to increase the metal removal rate.

3.3. Tool wear monitoring

The measurement of tool wear can be done by direct or indirect methods. In direct method, tool wear is measured

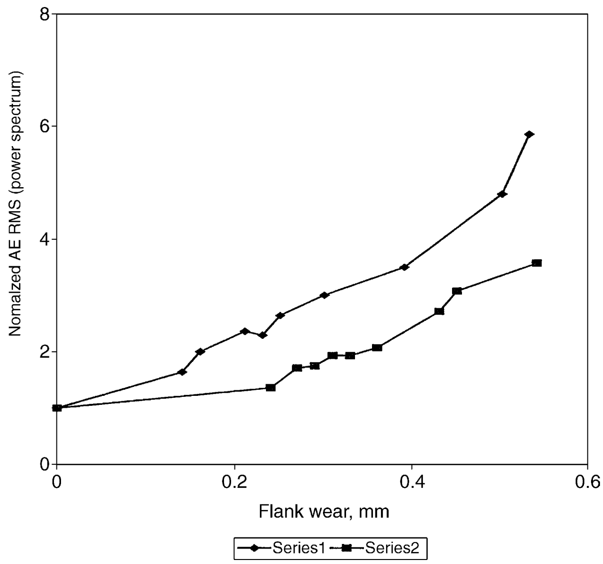

Fig. 8. Normalized AE RMS (power spectrum) vs. flank wear. Series 1: $V = 44$ m/min; $f = 86$ mm/min; $h = 2.5$ mm. Series 2: $V = 17.6$ m/min; $f = 42$ mm/min; $h = 1.0$ mm.

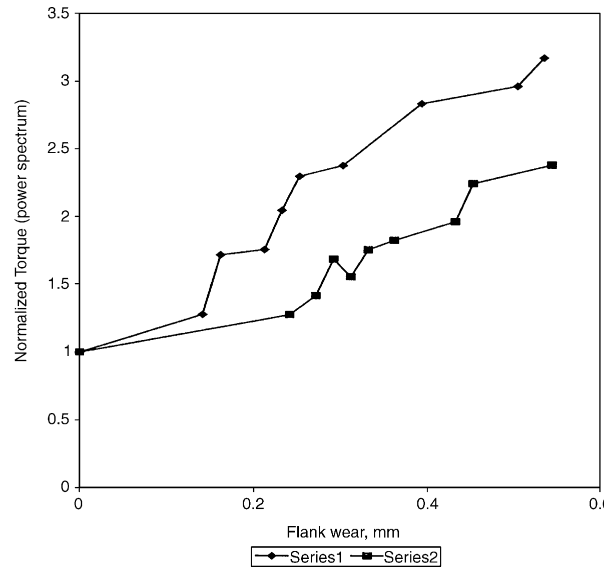

Fig. 10. Normalized torque (power spectrum) vs. flank wear. Series 1: $V = 44$ m/min; $f = 86$ mm/min; $h = 2.5$ mm. Series 2: $V = 17.6$ m/min; $f = 42$ mm/min; $h = 1.0$ mm.

over a period of time for an amount of material removed. On the contrary, the indirect method is based on a certain relationship linking tool wear and some process parameters.

In the experiments reported here, the variations of FP of AE_{RMS}, force and torque with measured flank wear are shown in Figs. 8–10. The FP values of the AE, force and torque are normalized with the respective data measured in the cutting experiments with a new cutting tool. All the variables show an increasing tendency with increasing flank wear of the cutting tool. From the figures, it can be seen that the FP of the AE_{RMS} and torque are more sensitive to the variation of the flank wear than the force. Further, it can be observed that the FP of the AE_{RMS} has the highest sensitivity towards the flank wear among the variables studied. In addition to the above three sensor signal variables, the FPs of both the power consumption and specific cutting energy can also be derived from the power spectrum of the torque signal [12].

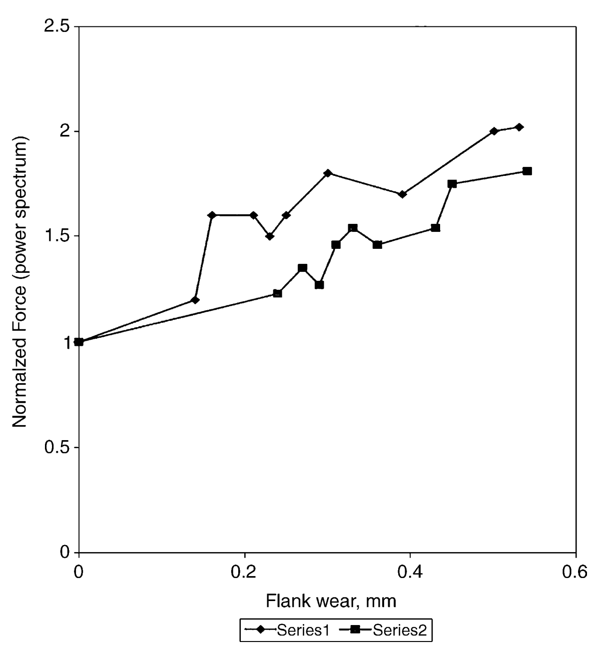

Fig. 9. Normalized force (power spectrum) vs. flank wear. Series 1: $V = 44$ m/min; $f = 42$ mm/min; $h = 2.5$ mm. Series 2: $V = 17.6$ m/min; $f = 42$ mm/min; $h = 1.0$ mm.

3.4. Evaluation of the monitored cutting process parameters

The multi-sensor system used combines the capabilities of AE, force and torque monitoring methods for the end milling operations. A summary of the variations of the cutting process parameters under different cutting conditions is shown in Table 1.

The arrow symbols denote the tendency of variation of the above cutting process parameters with changing machining conditions. The upward arrow indicates that the monitored parameter increases with an increase in that cutting vari-

Table 1
The tendency of variation of the monitored process parameters under different machining conditions

Investigated parameters	Cutting speed	Feed rate	Axial depth of cut	Radial depth of cut	Tool wear
FP of AE RMS	↑	↑	↑	↑	↑
FP of torque	↓	↑	↑	↑	↑
FP of force	↓	↑	↑	↑	↑

able while the other cutting conditions are kept constant. Similarly, a downward arrow implies that the monitored parameter decreases with an increase in that cutting condition while the other cutting conditions are kept constant.

4. Conclusions

The multi-sensor system developed and used in this investigation combines the capability of AE methodology, and force and torque methodology for the monitoring of end milling operations. An important point of consideration is that under different cutting conditions, a time series of signal from a single source may not be able to provide sufficient information required to make reliable decisions with high degree of certainty on the state of machining processes. Multi-sensor systems remove the above drawback since loss of sensitivity in one sensor domain can be offset by information from other sensors within the system, thus allowing high decision making capability over a wide range of process conditions to be possible. With information from the force, moment and AE signals acquired during the machining processes, the frequency characteristics of the cutting activity determined, and these will provide a means of monitoring the machining process.

In the end milling operations, the characteristic FPs derived from the measured frequency spectra of AE, force and torque signals could provide a reliable means of monitoring the process conditions. In the investigation of the influence of the flank wear of the cutting tool on the FP of AE_{RMS}, force and torque, it was observed that the FP of AE_{RMS} is more sensitive to growth of tool wear. Thus, this would lead to the development of progressive tool wear monitoring on-line. To sum up, the multi-sensor system installed in the present investigation is relatively inexpensive, easy to implement and operate for the monitoring of machining processes.

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