A Comparative Study of Using Spindle Motor Power and Eddy Current for the Detection of Tool Conditions in Milling Processes

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***Abstract*— This paper investigates the use of the power of the driving motor of a CNC spindle in comparison to two perpendicular eddy current sensors for the detection of tool wear in milling processes. Monitoring the power through the current profile is a low cost system which has been utilised in this study as an attempt to detect the fluctuation in the motor load as a result of the conditions of the cutting tool. Eddy current sensors are dedicated sensors that are installed on the spindle to measure the vibration of the rotating spindle in two axes. Experimental work has been conducted using fresh and worn tools to investigate the effect of tool conditions on the two sensory systems. Time domain features are utilised to compare between the two sensors in relation to this application. The results indicate that Eddy current sensors are found to be more successful and sensitive, in general, than the power of the motor in detecting the changes of the cutting tools during the machining operation. However, the kurtosis value of the power of the spindle has been found to be successful in predicting the tool conditions with high sensitivity.**

***Keywords*— Condition Monitoring; Motor power; eddy current sensor; Tool wear; Linear regression method.**

I. INTRODUCTION

Faults in machining processes can lead, not only to high repair expenses, but also to extraordinary financial losses due to unexpected downtime. Therefore, it is important to develop a reliable and inexpensive intelligent monitoring system. To provide reliable condition monitoring systems, research studies have used a wide range of the sensitivity measuring methods and sensors with different experimental work to create a successful monitoring system to detect tool wear and faults [1]. Unfortunately, the performance of monitoring systems is still far behind the expectations due to its high cost/performance ratio [2].

Online monitoring of the tool wear condition is important in order to improve the quality of the unmanned manufacturing systems employing milling and cutting processes. Early replacement of a workable tool or late replacement of a worn tool may cause time and/or production loss. Furthermore, due to complex structure of tool wear mechanism, unpredictable breakages may occur at any time that might also lead to catastrophic failure affecting other components in the system. By employing effective tool wear condition-monitoring techniques, not only such failures can be avoided but also maximum utility can be obtained from the tools.

Commonly used parameters in indirect methods are cutting forces, vibration, acoustic emission, current, power and temperature. Besides the method used, the parameter choice is also very important to design an effective condition-monitoring system. A parameter that works well for one method might not be the appropriate choice for others. Hence, diagnosing mechanisms depending on a single sensor may not be able to make reliable results for the condition of the tool. Therefore, it is preferable to employ multiple sensors instead of a single sensor to observe the same process is detected the tool wear status [3]. In this paper, two types of the monitoring sensors, eddy current and power sensors will be used to detect the condition of the tool during the manufacturing process. The power of the motor can be considered relatively low cost and 'non-invasive' signal in comparison to other sensors. Therefore, the paper will compare the power of the spindle to eddy current sensors in order to compare the difference using time domain features.

II. MONITORING SENSORS

In previous research by the authors, several sensors have been used including force, vibration, strain, Acoustic emission and microphone. It has been reported that vibration and strain sensors are most sensitive for the changes of tool condition [4]. In this paper, eddy current and power sensor have been utilised in an attempt to detect the faults of the cutting tool in milling operation using time domain features. Eddy current sensors are characterised by the difficulty of the mounting process of the sensors on the machine itself [5]. This sensor operates with magnetic fields where a driver creates an alternating current in the sensing coil in the end of the probe. This creates an alternating magnetic field with induces small currents in the target material; these currents are called eddy currents. The eddy currents create an opposing magnetic field that resists the field being generated by the probe coil [6]. The interaction of the magnetic fields is dependent on the distance between the probe and the target as shown in *Fig.* 1. As the distance changes, the electronics sense the change in the field interaction and produce a voltage output which is proportional to the change in distance between the probe and target.

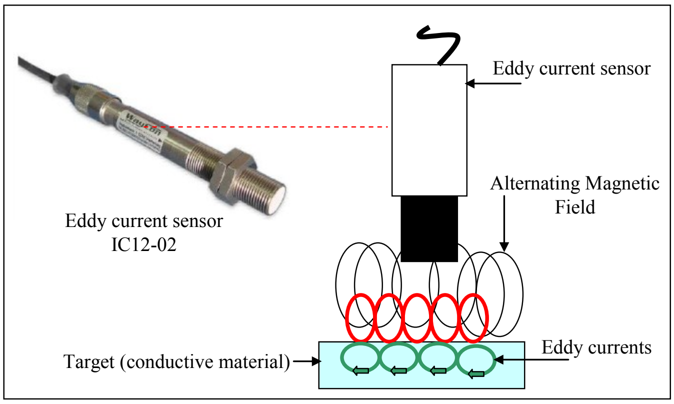


Fig. 1. The basic theory of eddy current sensor.

In order to overcome the disadvantages of commercial dynamometers, many researchers have used the power sensor to estimate cutting force in cutting process as presented in references [7-10]. In summary, the power (current) sensor is less expensive, more durable and flexible, and also very simple to install. Using the motor current to detect the tool condition, based on the amount of used current, monitoring system should be fully developed. Power sensor will monitor the load on the motor that is driving a machine or process and give valuable information since this motor could reflect the changes of the machining condition by the change of load on the motor.

The major advantage of the motor related parameters to detect malfunctions in the cutting process is that the measurement apparatus dose not disturbs the machining and the power sensing use the motor itself as an indirect sensor of cutting force [11]. The operating principle of this sensor is in a hall effect-based current sensor wher the magnetic flux, proportional to the primary current, is concentrated in gapped magnetic core containing the hall effect device as shown in *Fig*. 2. The primary current is measured without electrical contact with the primary circuit providing galvanic isolation. The output signal of the Hall device is then further amplified by additional internal signal conditioning circuitry to provide an output voltage proportional to the primary current [12].

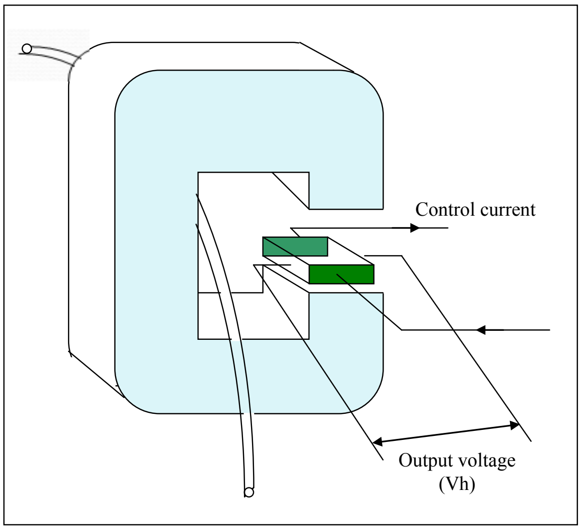


Fig. 2. The principle of the power sensor.

III. EXPERIMENTAL SETUP

As discussed previously, the installation of the eddy current sensors could be a complex task. A specially designed fixturing system to capture the vibration of the spindle has been designed as shown in *Fig*. 3.

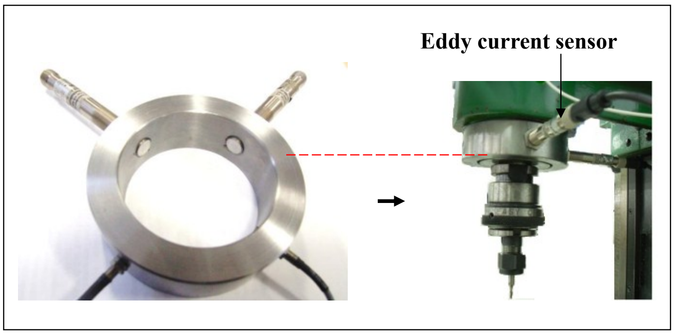


Fig. 3. A specially designed fixture to insert the Eddy current sensors.

As illustrated in *Fig*. 4, the experimental work of the condition monitoring system of this study is performed on a milling CNC machine type (DENFORD) using aluminium workpiece (aluminium AA6262). Two Eddy current sensors (IC12-02) are installed in x, y axes, and then connected to power supply (PDA 3502 A). Power sensor (IP-151) is connected directly to the data acquisition system as analogue input. The signals are monitored using data acquisition card NI PCI-6071E from National Instruments using special data acquisition software written using the National Instrument CVI programming package and a computer. Matlab software is used for the complete analysis of this research. The milling process is carried out at the conditions shown in the Table 1.

TABLE I: THE MACHINING PARAMETERS FOR THE MONITORING SYSTEM.

Machining condition	Specification
Feed rate	220 mm/min
Depth of cut	0.25 mm
Coolant type	No coolant (Dry)
Spindle speed	2500 rpm
Diameter of tool	4mm
Material of Tool	Solid carbide (End mill solid carbide)
Type of Tool	End mill tool (4 flutes, uncoated)

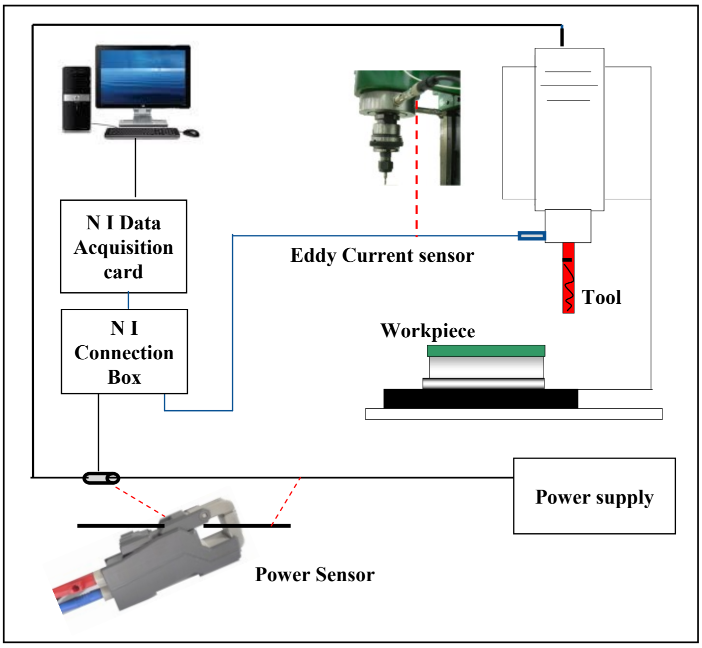


Fig. 4. Schematic diagram of experimental setup.

IV. THE SELECTION OF THE MOST SENSITIVE FEATURES

Reference [13] has suggested a novel approach for the selection of the most sensitive features using an automated method. The approach, named ASPS (Automated Sensor and Signal Processing Selection) depends on automatic generation and evaluation of features to select the most suitable sensor. The approach helps in reducing the cost and development time. In this study, the approach (ASPS) is implemented for rapid design of condition monitoring systems for machining operations. This research builds on the ASPS approach to investigate further combination of techniques and parameters. Where the sensitivity "sensory characteristic features" is extracted for each sensory signal obtained. These features are related to cutting tool conditions using a wide range of signal analysis and simplification techniques. The tool condition monitoring system proposed in this study consists of five components: (1) multi-sensors data acquisition system, (2) signal processing, (3) feature extraction, (4) feature selection, and (5) determine which feature is more sensitive of the changes in the machining operation. Further details are available in [13-15].

V. RESULTS AND DISCUSSION

The tests started with a fresh tool and finished with completely worn tool as shown in *Fig.* 5. The raw signals for the tool are collected from the sensors with sampling rate of 40K sample/second as illustrated in *Fig*. 6. Because the milling process has complex machining signals, it has been found difficult to predict the most sensitive signals and signal processing methods to tool wear directly from raw data. Therefore, signal processing and analysis is needed to extract the important information from the signals (i.e. Sensory Characteristic Features (SCFs)).

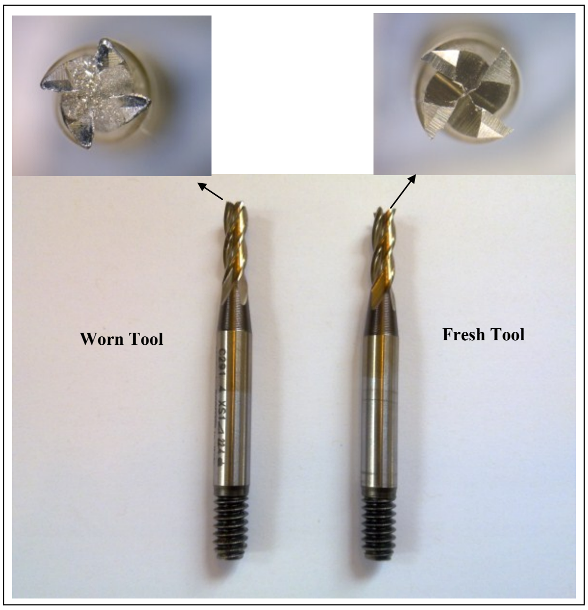


Fig. 5. The two states of the milling tool (fresh and worn tool).

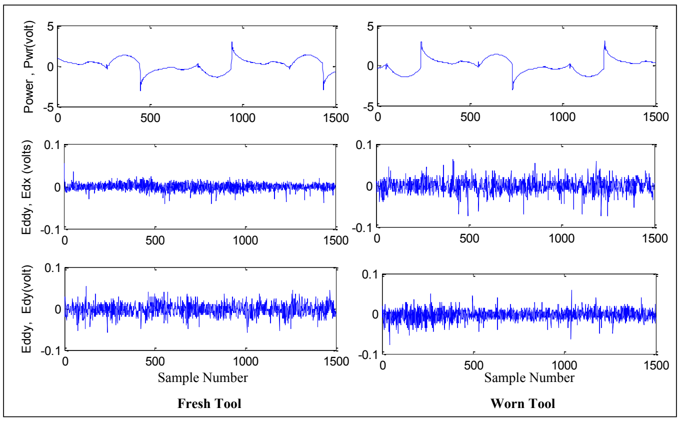


Fig. 6. Eample of the raw signals of the machining process for both conditions(fresh and worn tool.

The raw signals are processed using several time domain signal-processing methods to extract the Sensory Characteristic Features (SCFs). The signal processing methods used are maximum (max), minimum (min), standard deviations (*std*), the average (μ), the range, the skew, kurtosis value (*K*) and power. The 8 signal processing methods are used to process the 3 sensory signals to construct an Association Matrix ASM of (3 × 8) which allows the investigation of 24 sensory characteristic features (SCFs) for the design of the monitoring system. The SCFs are arranged according to their sensitivities to tool wear based on the absolute slope of the linear regression method as shown in *Fig*. 7. Figure 7 presents examples of high, medium and low-sensitivity SCFs to tool wear. The values of the sensitivity are arranged in the Association Matrix (ASM) to classify the Sensor Characteristic Features (SCF) according to their sensitivity as shown in *Fig.* 8.a. From the graphical presentation in *Fig.* 8.b, it is clear that the eddy current sensors in x-axis and y-axis have higher sensitivity to detect the changes of the tool status from the fresh to worn tool. Meanwhile, the power sensor is less effectiveness to sense the tool wear progress.

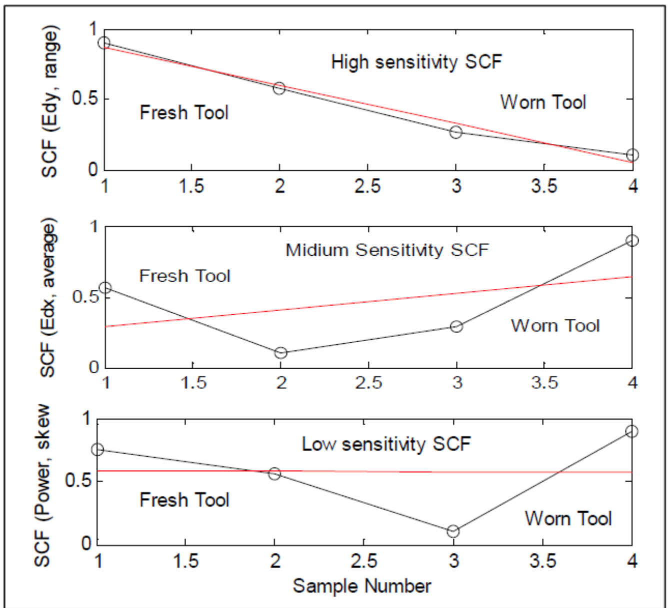
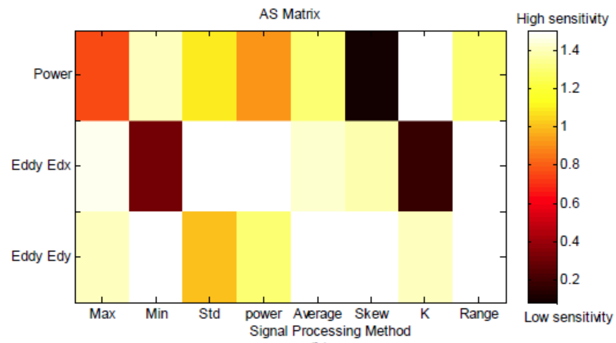


Fig. 7. Eample of low, medium and high sensitivity SCF.

Sensors	*Signal processing methods*							
	Max	**Min**	**Std**	**Power**	**Range**	**Skew**	**Kurtosis**	**Range**
Power	0.769	1.411	1.098	0.907	1.302	0.080	1.504	1.297
Eddy Edx	1.480	0.316	1.503	1.503	1.425	1.390	0.167	1.485
Eddy Edy	1.398	1.490	1.012	1.299	1.505	1.502	1.414	1.506

(a)



(b)

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Fig. 8. The Associated matrix of the system (a) agraphical presentation of the sensitivity (b).

However, from *Fig*. 8 it is clear that using the kurtosis value (K) of the power of the spindle gives sensitive results in comparison to other sensors followed by the minimum value. However, over all the eddy current sensor is found to have a much higher sensitivity using other type of features.

VI. CONCLUSION

Implementing tool-wear monitoring systems is an effective way to prevent damage in machine tools, cutting tools and work-pieces during manufacturing processes. If the cost/performance ratio of the monitoring system is too high, it may not be acceptable for the application in industry.

In this paper, a new investigation has been presented for the estimation of the sensitivity of eddy current sensor and the power sensor to monitor tool conditions. The ASPS approach [13-15] has been tested using time domain features. The results indicate that the kurtosis value (*K*) of the power of the spindle is a sensitive feature to be sued to monitor the tool conditions. However, it has been found that eddy current, in general, is more sensitive to tool conditions. Further research will be conducted using a wider range of features to compare between the two sensors further.

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