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Tool Wear Condition Monitoring using Slip Ring and Accelerometer System in Milling AISI P20 Tool Steel

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ABSTRACT

Vibration is among the common tool parameters used in tool condition monitoring (TCM). TCM plays a crucial role as the control and management of processes. There is an increased need to produce machines that are more efficient and that incur minimum maintenance costs. Tool failure and wear greatly reduce the cost while constantly maintaining the quality of production. Various monitoring systems have been developed by past researchers aimed at better configurability and flexibility. In this work, a simple and reliable method for data transmission in rotating machines using a slip ring and accelerometer system was applied and tested. During the testing, the vibrations at the tool tip were measured using an accelerometer. The results showed that the vibrations increased by an increase in the tool wear. However, in relation to several cutting parameters, the vibrations increased when the feed rate was high but decreased when a lower value of the axial depth of cut, ae, was used. In conclusion, the relationship between tool wear evolution and vibration signals can be established using the cutting tool vibration signals.

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Introduction

Rapid modernization has increased the need to produce better machines with higher efficiency and that require minimum cost of maintenance. A tool condition monitoring system plays a crucial role in the control and management of processes [1]. Efficient monitoring can greatly reduce the cost while constantly maintaining the quality of production. An automated monitoring system will also reduce the cost of hiring personnel to monitor the production line. Meanwhile reduced work force in this industry will also lead to less possibility of accidents occurring during the handling of high speed machining processes [2].

There are two approaches in tool condition monitoring: direct and indirect intervention. Direct intervention involves the taking of immediate measurements from the cutting tool, while indirect intervention requires the use of a sensor system, where wear will be estimated from physical parameters appearing during the machining process such as the cutting force, vibrations, acoustic emissions and temperature [3]. An indirect tool condition monitoring can be described as a system consisting of four processes starting with sensory data acquisition, signal processing, features extraction and cognitive decision making [4].

In addition, indirect measurements require data from sensors to be transferred to the data receivers. The data transmission is known to depend greatly on possible relative motions with respect to the environment [5]. In milling machines, the spindle rotates at a high speed, and this motion presents several challenges in obtaining an accurate transfer of data.

Milling is a machining process characterized by interrupted cutting therefore is more susceptible to problems including vibration between cutting tool and workpiece fixation. Vibration, also known as chatter mainly occurs due to limitations in cutting tool, holding tool, machine, workpiece or the fixture and is also due to the proximity between their natural frequency harmonics and the frequency of tool entry on the workpiece [6].

In addition to the cutting force measurements which are among the main parameters for TCM, vibrations also appear to be the key information in understanding cutting processes, optimizing cutting operation and evaluating the presence of instabilities that could affect the effectiveness of the cutting processes. Vibration plays a major role in the quality of the surface that is generated, and this can be accurately predicted by the vibrational displacements at the tool tip, measured in acceleration units, during the operation [7].

Vibration needs to be controlled to improve efficiency because it directly influences the workpiece surface quality. Surface generation can be monitored by accurately predict the vibrational displacements at the tool tip during machining operation. In addition, vibration measurements are also referred to as displacement, velocity or acceleration measurements.

There are also other factors influencing tool vibration, such as entering angle. According to Armando [6], it is found that a lower entering angle may provide a more stable cutting and prevent microchipping although larger resulting cutting forces are exerted. This will still result in longer tool life since most of this load is associated with low frequencies, at which the behavior of the tool is like a rigid body [6].

In today's research world where flexibility and configurability are being sought after, obtaining a robust estimation of the cutting forces and tool vibration through indirect sensor measurements can be difficult since few processes and tool-related quantities are linked to cutting forces [7].

In this study, a new method of data signal transmission in TCM for milling using slip rings was introduced. Slip ring has been used in various applications such as power and data transmission for rotating equipment like wind turbines, railway tractions and military vehicles. Its simplicity makes it preferred while taking account its performance-related and economic aspects. Slip rings are mechanical units used to carry electrical signals through a rotating parts of the spindle to the static components. It is mounted on a rotating part of a machine and enables the transfer of electrical signals via a fixed brush pressing against the metal rings. Metal rings are connected to both ends of the armature winding. Electrical connection is provided through the rotating assembly. Electric is conducted through the stationary brush to the metal ring as the metal ring turns. In short, this paper aimed to investigate the relationship between the tool wear evolution and the vibration signals in milling process.

Methodology

Experimental Set Up

The experimental runs were performed using a Spinner VC450 CNC milling machine under dry cutting conditions. No coolant is used when cutting to accelerate damage to cutting tool. A single tool insert of coated tungsten carbide was used to mill AISI P20 tool steel in the experiments.

The vibration monitoring strategy involved using a single-axis accelerometer to measure the tool vibration in direction of the cutting feed which is revealed to be more sensitive to wear than that of other force components [8]. The accelerometer was fixed on the tool holder to carry out measurement. The data transmission system using slip ring was fastened on the milling spindle. Additional fasteners have been designed to hold it in place as unnecessary rotation of the slip ring will affect the accuracy of vibration measurement. The use of slip ring in this study improves mechanical performance and simplify system operation by eliminating damage-prone wires dangling from movable joints. The slip ring system is as illustrated in Figure 1.

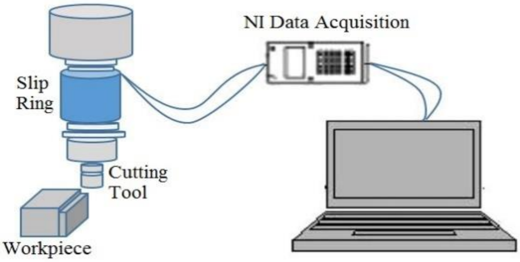

Figure 1: Illustration of experimental set-up

Vibration data from the accelerometer transmitting through the slip ring system was then acquired using a data acquisition device NI DaQ 9234. An interactive, data-logging software NI Signal Express was partnered with the device to acquire and present the data signals with no programming required.

Experimental Procedure

Eight experimental runs were carried out, as shown in Table 1. NI DaQ was used to acquire the vibration signals at a sampling rate of 5 kHz. In Table 1, a_e is referred to axial depth of cut, while a_p is referred to radial depth of cut.

Table 1: Experimental runs with a constant cutting speed and varying feed rates and depths of cut

Run	Cutting Speed (m/min)	Feed Rate (mm/min)	a_e (mm)	a_p (mm)
1	375	298	0.4	1
2	375	298	0.6	1
3	375	597	0.4	1
4	375	597	0.6	1

By using Matlab software, the vibration raw signals generated were gathered in the time domain form and then, it was converted to frequency domain by Fast Fourier Transform (FFT). A low-pass filter is applied to allow signals with a frequency lower than the cut-off frequency and eliminate signals with higher frequencies.

Six cutting tools with different wear values of low, medium and high, ranging from VB=0.045 mm to 0.247 mm were used for every test run. The tool wear was reached when the flank wear was 0.3 mm, based on ISO 3685-1993 but in this experiment, cutting tools was only tested until near-wear. During each set of runs, one parameter was kept constant while the other parameters were varied. Two distinct main cutting speeds and feed rates, comprised of a low and a high range, were chosen to study their effects on the vibration data obtained. Meanwhile, the depth of cut was also varied between 0.4 mm and 0.6 mm to study its effect on tool vibration.

In order to further investigate the relation between vibration and tool wear, the processed signal is then analysed by using the Integrated Kurtosis-based Algorithm for Z-filter (I-kaz). Rizal [9] presented a study of the performance of I-kaz technique to detect flank wear width using cutting force signal.

After each set of experiment, the flank wear was measured optically using a digital microscope. Among all the types of wear, flank wear is found to have a great effect on surface quality although a cutting tool may fail due to several conditions such as flank wear, crater wear, notch wear, built-up-edge (BUE), frittering, thermal crack, fracture, plastic deformation and breakage [10]. The cutting operation was interrupted after each run to remove the tool from its holder in order to measure the flank wear.

Finally, the correlation between the machining signal and the obtained flank wear data is developed based on the findings.

Results and Data Analysis

The experimental results revealed a trend in the vibration signals in response to the increased flank wear in the cutting tool. Vibration signals extracted in time and frequency domain of one of the experiments are shown in Figure 2 and 3. It is observed that there is increase in amplitude of the peak frequencies when the wear increases. Signals coming from noise are also observed and are due to non-homogeneity of the tool in addition to the vibrations from various sensors, errors in measurement and other unaccounted factors [11].

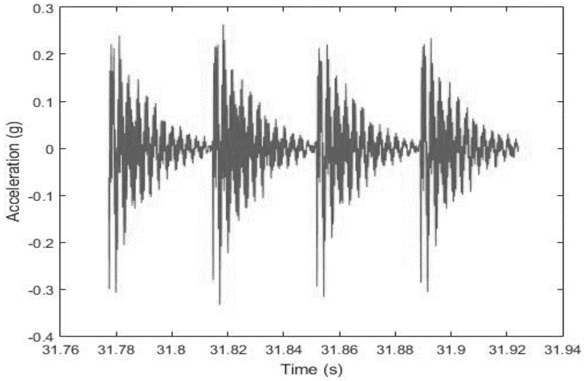

Figure 2: Waveform graph

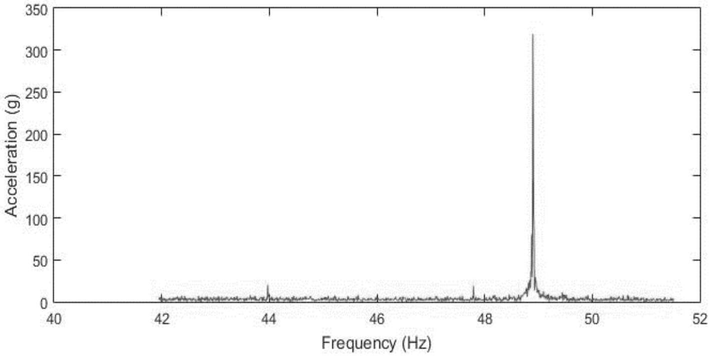

Figure 3: Spectrum graph

The rate at which the teeth of the cutting tool pass by a fixed position is called the tooth passing frequency (TPF). TPF varies with the number of teeth of the cutter and the rotation velocity based on the Equation 1 [3]:

$$TPF = \frac{n\,x\,N_T}{60} \qquad (1)$$

Where,

n = spindle rotating frequency (RPM)
N_T = number of teeth of the cutting tool

TPF is useful for researchers to observe the frequency trend in higher vibration phase. In milling, Orhan [8] mentioned that vibration that resulted from the interaction between tool and workpiece has characteristic frequencies with multiplies of the TPF. In addition, vibration readings with high TPF corresponds to existence of loud noise which is a result of chatter. It is found that TPFs calculated from the machining parameters from each experimental sets are equal to TPFs obtained from the spectrum graph with an average error of 1.47%.

The I-kaz result analysis revealed that the method can be applied to determine tool wear progression in milling. I-kaz coefficient is used to mathematically determine the changes in signals amplitude and frequency of tool vibrations. As a result, a higher value of I-kaz coefficient is found corresponding to an increased flank wear of the cutting tool as shown in Figure 4.

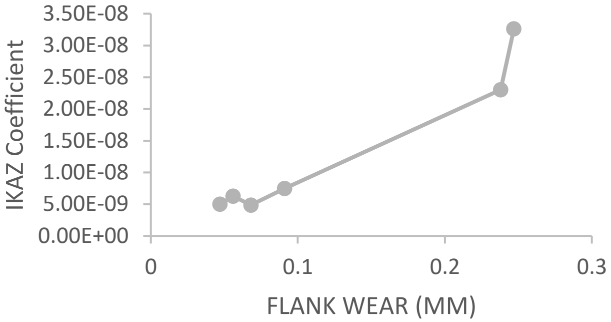

Figure 4: I-kaz analysis shows that I-kaz coefficient increases with increasing wear

To further investigate the relationship with other parameters, the cutting speed was kept constant while the feed rate and axial depth of cut were manipulated. The milling process has been found to be highly intermittent and unstable at high speeds and low radial depths of cut [12]. Due to this phenomenon, researchers have suggested that mill operators should further increase the feed rate to reduce chatter so as to prevent the machine from operating in the range of feeds that excite the harmonics. However, as observed from the experiment, when the oscillations have reached the stable phase, the feed rate could also be decreased to lower the vibrations. Figure 5 below shows the results of the vibration signals, represented in acceleration units (g), against flank wear at two different feed rates of 159 and 318 mm/min and at a constant cutting speed of 200 m/min and axial depth of cut of 0.6 mm. At a higher feed rate, the acceleration was found to be slightly larger, being more significant at a higher tool wear. This could be explained in terms of the relationship between tool chatter and harmonics.

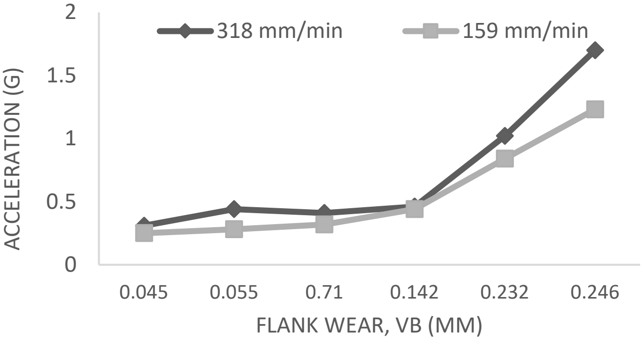

Figure 5: Vibration signals against flank wear at different feed rates of 159 mm/min and 318 mm/min

On the other hand, Figure 6 below shows the trend of acceleration when the axial depth of cut was manipulated at the same cutting speed and feed rate of 159 mm/min. It was found that the acceleration produced was lower when the depth of cut was high, unlike the trend that was observed when the feed rate was increased. Hamdan [13] stated that by decreasing the depth of cut, less material has to be cut per tooth per revolution, thus requiring a lower amount of energy.

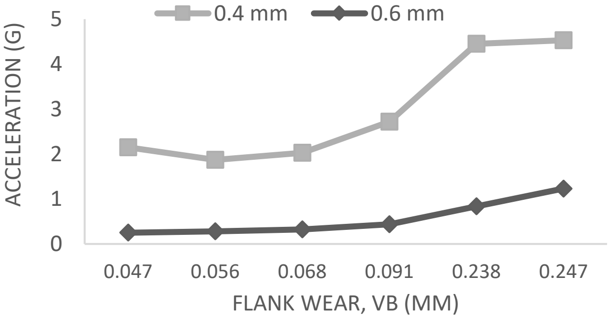

Figure 6: Vibration signals against flank wear at different axial depths of cut of 0.4 and 0.6 mm

In addition, the amplitude of resulting vibrations is also mainly influenced by the combination of the testing parameters as they are highly correlated with each other. Ghani et. al presented a study which shows that the combination of parameters comprising of low feed rate, low depth of cut and high cutting speed is optimal for low resultant cutting force and good surface finish based on Taguchi optimization methodology [14].

Overall, it was found that the vibration signals increased when the tool wear increased in both conditions. The tool tip vibrated at its maximum acceleration when Vb reached 0.248 and 0.247 mm, as shown in Figures 5 and 6, respectively. This proved that the tool chatter was more significant when the tool reached its wear limit [15].

Conclusion

When tool wear increases, the tool tip vibrates at a higher acceleration. However, in response to increased axial depths of cut and feed rates, the vibration signals behave differently. At higher feed rates, the vibration signals are higher, while at higher axial depths of cut, the acceleration decreases. This phenomenon can be explained based on several factors including the area of surface contact, the dynamic interaction of the cutting process, and the tool structure.

In conclusion, tool vibration analysis can be used to establish a relationship between the tool wear evolution and the vibration signals and has been proven to produce reliable results. Slip ring transmission system has also been found to be able to transmit vibration signals with good accuracies.

References

[1] P. Oborski, "Developments in integration of advanced monitoring systems," Int. J. Adv. Manuf. Technol., vol. 75, no. 9–12, pp. 1613–1632, (2014).

[2] M. A. Elbestawi, "Tool Condition Monitoring in Machining - Neural Networks," *Technology*, vol. 220, pp. 5–16, (2006).

[3] M. Kious, A. Ouahabi, M. Boudraa, R. Serra, and A. Cheknane, "Detection process approach of tool wear in high speed milling," *Measurement*, vol. 43, no. 10, pp. 1439–1446, Dec. (2010).

[4] R. Teti, K. Jemielniak, G. O'Donnell, and D. Dornfeld, "Advanced monitoring of machining operations," *CIRP Ann. - Manuf. Technol.*, vol. 59, no. 2, pp. 717–739, (2010).

[5] Lei Tang, K.C. Wang, and Yong Huang, "Performance Evaluation and Reliable Implementation of Data Transmission for Wireless Sensors on Rotating Mechanical Structures," *Struct. Heal. Monit.*, vol. 8, no. 2, pp. 113–124, (2009).

[6] A. Ítalo Sette Antonialli, A. Eduardo Diniz, and R. Pederiva, "Vibration analysis of cutting force in titanium alloy milling," *Int. J. Mach. Tools Manuf.*, vol. 50, no. 1, pp. 65–74, (2010).

[7] M. Salehi, P. Albertelli, M. Goletti, F. Ripamonti, G. Tomasini, and M. Monno, "Indirect Model Based Estimation of Cutting Force and Tool Tip Vibrational Behavior in Milling Machines by Sensor

Fusion," *Procedia CIRP*, vol. 33, pp. 239–244, (2015).

[8] S. Orhan, A. O. Er, N. Camuşcu, and E. Aslan, "Tool wear evaluation by vibration analysis during end milling of AISI D3 cold work tool steel with 35 HRC hardness," *NDT E Int.*, vol. 40, no. 2, pp. 121–126, (2007).

[9] M. Rizal, J. A. Ghani, M. Z. Nuawi, and C. H. C. Haron, "I-kaz (TM)-Based Analysis of Cutting Force Signals for Tool Condition Monitoring in Turning Process," *Noise, Vib. Comf.*, vol. 471, (2014).

[10] M. S. H. Bhuiyan and I. A. Choudhury, *Comprehensive Materials Processing*. Elsevier, (2014).

[11] P. Bhattacharyya, D. Sengupta, and S. Mukhopadhyay, "Cutting force-based real-time estimation of tool wear in face milling using a combination of signal processing techniques," *Mech. Syst. Signal Process.*, vol. 21, no. 6, pp. 2665–2683, (2007).

[12] Y. Altintas, G. Stepan, D. Merdol, and Z. Dombovari, "Chatter stability of milling in frequency and discrete time domain," *CIRP J. Manuf. Sci. Technol.*, vol. 1, no. 1, pp. 35–44, (2008).

[13] A. Hamdan, A. A. D. Sarhan, and M. Hamdi, "An optimization method of the machining parameters in high-speed machining of stainless steel using coated carbide tool for best surface finish," pp. 81–91, (2012).

[14] J. A. Ghani, I. A. Choudhury, and H. H. Hassan, "Application of Taguchi method in the optimization of end milling parameters," *J. Mater. Process. Technol.*, vol. 145, no. 1, pp. 84–92, (2004).

[15] E. Kuljanic and M. Sortino, "TWEM, a method based on cutting forces—monitoring tool wear in face milling," *Int. J. Mach. Tools Manuf.*, vol. 45, no. 1, pp. 29–34, Jan. (2005).