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A Flute Tracking System for Monitoring the Wear of Cutting Tools in Milling Operations

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***Abstract*—**Monitoring of tool wear in milling operations is essential for achieving the desired dimensional accuracy and surface finish of a machined workpiece. Although there are numerous statistical models and artificial intelligence techniques available for monitoring the wear of cutting tools, these techniques cannot pin point which cutting edge of the tool, or which insert in the case of indexable tooling, is worn or broken. Currently, the task of monitoring the wear on the tool cutting edges is carried out by the operator who performs a manual inspection, causing undesirable stoppages of machine tools and consequently resulting in costs incurred from lost productivity. The present study is concerned with the development of a flute tracking system to segment signals related to each physical flute of a cutter with three flutes used in an end milling operation. The purpose of the system is to monitor the cutting condition for individual flutes separately in order to determine their progressive wear rates and to predict imminent tool failure. The results of this study clearly show that signals associated with each flute can be effectively segmented using the proposed flute tracking system. Furthermore, the results illustrate that by segmenting the sensor signal by flutes it is possible to investigate the wear in each physical cutting edge of the cutting tool. These findings are significant in that they facilitate the online condition monitoring of a cutting tool for each specific flute without the need for operators/engineers to perform manual inspections of the tool.

***Keywords*—**Tool condition monitoring, tool wear prediction, milling operation, flute tracking.

I. INTRODUCTION

IN milling operations, the principal factors that define the quality of parts are dimensional accuracy and surface finish [1]. There are several constraints that limit the improvement of part dimensional accuracy and surface finish such as the progressive tool wear and the tool breakage [2]. Therefore, a need to develop tool condition monitoring (TCM) techniques is essential to ensure robustness of metal cutting processes. There are several TCM techniques available in the literature. These techniques typically fall into two categories: direct and indirect approaches. In the direct approach, the actual physical quantity of interest such as the tool wear is directly measured. Examples of direct measurements are the deployment of cameras for visual inspection, radioactive isotopes and laser beams. Although direct measurements have a high degree of accuracy in terms of the tool wear measurement, they are deployed only in research laboratories. This limitation is partly due to access problems during machining and the use of cutting fluids. In contrast to the working principle of the direct approach; the indirect approach measures the physical quantity via empirically determined correlation [3]. Generally speaking, indirect methods are more cost effective than direct ones. This makes them more suitable for practical applications. The most widely reported indirect methods for TCM are those that involve sensing cutting forces [4], [5] acoustic emissions [6], [7] and vibrations [8], [9]. Lan and Naerheim [10] used cutting force measurements along with an adaptive signal processing scheme to detect the fracture and chipping of a cutting tool with two flutes in a milling operation. Altintas and Yellowley [7] detected the tool breakage of an end milling cutter by developing cutting force models. Tan and Tomizuka [5] developed a statistical model based on Root Mean Square (RMS) features extracted from cutting force measurement to detect the tool breakage of a four flutes cutter used in an end milling operation. Acoustic emission (AE) sensing has also been extensively used for TCM in milling operations. Srinivasa Pai and Ramakrishna Rao [6] investigated the sensitivity of the RMS of an AE signal to the condition of a cutter with multiple inserts used in face milling operations. The authors claimed that the RMS of an AE signal is very sensitive to the tool wear. Giriraj et al. [11] used an AE sensor along with an artificial network to detect the progressive tool wear of a cutter with two flutes used in an end milling operation. Diei and Dornfeld [7] investigated the effects of wear in cutter *inserts* on the AE signal *in a face milling operation.* The authors concluded that the AE signal correlates closely with the tool flank wear. Vibration is another parameter that has been the focus of considerable attention for TCM. This is partly due to the strong correlation between the tool condition and vibration signals. For example, Suprock et al. [9] proposed a cost effective method to capture the vibration generated during a milling process using a low cost vibration sensor integrated into the tool holder. They claimed that there is a strong correlation between the captured vibration signal and the tool breakage. Zhang and Chen [12] developed a tool monitoring approach based on using vibration signals and a pattern recognition system to detect the tool wear of an end milling cutter with multiple flutes. The authors concluded that vibration signals can be effectively used for real-time TCM in machining applications. It is also well known that the tool wear is a major cause of unscheduled stoppages in the machining environment resulting in machine tool downtime which is costly in terms of time lost. Some researchers estimate that the amount of machine tool downtime due to the cutter

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wear or breakage is around 6.8% [13], while others put the figure closer to 20% [14]. Machine down time is partly attributed to the time taken by the operator/engineer to perform manual inspections of the cutting tool edges or inserts in the case of indexable tooling after a predefined machining time in order to determine their conditions. The manufacturing costs may also be higher than necessary when the tools are changed before the end of their useful life or after a significant damage is caused to the workpiece.

Although it is possible to detect the wear of cutting tools used in milling operations through applying complicated algorithms such as statistical models and artificial intelligence techniques as illustrated in the above literature, these algorithms cannot pin point exactly which cutting edge of the tool, or which insert in the case of indexable tooling is worn or broken. If these techniques are to be implemented in practical situations, the role of the operator/ engineer will still be needed to perform manual inspections of the tool cutting edges to determine which cutting edge is worn resulting in a significant increase in the costs associated with the machine down time. Thus, there is a great need to develop techniques capable of monitoring the wear on individual cutting edges of the tool independently.

The present study is concerned with the development of a flute tracking system to segment signals related to each physical flute of a three flute cutter used in an end milling operation. The purpose of the system is to monitor the cutting condition for individual flutes separately in order to determine their wear rates and to predict imminent tool failure. As far as we are aware, there is no technique currently available to achieve this objective. This is probably because the benefits of monitoring the wear on individual flutes have not been fully realized in a relevant area. The proposed system consists of i) a non-contact displacement sensor (eddy current sensor), fitted on the milling head and ii) a notch attached to the tool holder. The sensor used for tool condition monitoring purposes is a tri-axial piezoelectric (PCB) accelerometer. This sensor was fitted beneath the workpiece to measure the vibration generated during the cutting process. The results of this study clearly show that vibration signal associated with each flute can be effectively segmented using the proposed flute tracking system. Furthermore, the results also show that by segmenting the vibration signal by flutes it is possible to investigate the wear on each physical cutting edge of the cutting tool. These findings are significant in that they facilitate the online condition monitoring of a cutting tool for each specific flute without the need for operators/engineers to perform manual inspections of the tool thereby reducing the costs of manufacturing through minimizing the machine down time.

The rest of this paper is organized as follows. Section II describes the experimental set up considered in the present study to demonstrate the effectiveness of the proposed flute tracking system in segmenting the vibration signal by flutes. Section III presents the results obtained from experimental results along with a detailed discussion. Finally, Section IV provides a summary of the work conducted in this paper.

II. EXPERIMENTAL SET UP

To demonstrate the effectiveness of the flute tracking system in segmenting the vibration signal by flutes, experimental tests were carried out on a Mori Seiki NMV8000 milling machine where a Sandvik CoroMill Plura 1620 solid carbide square shoulder end mill (1P330-1600-XA 1620) with 16 mm diameter and 3 flutes was used to machine a Titanium Ti-6Al-4V workpiece with the coolant turned off to protect the electronics used inside the machine tool. In these experimental tests, a simple climb milling operation involving 8mm axial depth of cut along the edge of the workpiece was deployed as shown in Fig. 1. The cutting speed, spindle speed, feed rate radial and the radial depth of cut were kept constant throughout the cuts. The cutting parameters used in the experimental tests are summarized in Table I. It is worth pointing out that this simple cutting operation and the cutting parameters were carefully selected to ensure the cutting process is discontinuous where only one flute is in contact with the workpiece, to aid splitting the raw signals into sections that correspond to each flute pass. This is explained in detail in the next section.

Fig. 1 Cutting path used in the experimental tests

TABLE I
MACHINING PARAMETERS USED IN THE EXPERIMENTAL TESTS

Parameter	Value
Radial depth of cut A_e	1
Axial depth of cut A_p	3
Cutting speed V_c	80mm/min
Feed per tooth f_z	859 mm/min

To monitor the cutting process, a data acquisition (DAq) system developed by the Advanced Manufacturing Research Centre (AMRC) was used. This system comprises of two elements: a sensor plate mounted beneath the machined workpiece and an enclosure housing the additional electronics required for the sensor plate to function (National Instruments (NI) DAq modules, power supplies, etc.). The sensor plate incorporates a number of sensors to capture the signals emitted during the cutting process including a 604B31 tri-axial accelerometer with 5KHz frequency range that measure the cutting vibration. The enclosure contains the National Instruments (NI) DAq modules and the corresponding power supplies to acquire data from 604B31 tri-axial accelerometer as well as the other sensors incorporated in the sensor plate. Note in this experimental study, only the vibration measured by the tri-axial accelerometer will be used to monitor the cutting process. The experimental set up of the DAq system inside the machine tool is illustrated in Fig. 2.

To track the vibration signal observed in each flute throughout the cuts, a flute tracking system was developed. This system consists of i) a Sensonic non-contact displacement sensor (eddy current probe) with a 10mm distance range fitted on the milling head and ii) a notch attached to the tool holder and aligned with one of the flutes in the cutter as shown in Fig. 3. The basic working principle of the flute tracking system is as follows. Each time the tool completes a full rotation, the non-contact displacement senses the distance to the top tip of the notch. Since the notch is aligned to one flute as shown in Fig. 3, the signals relating to this particular flute can be tracked throughout the cuts. Consequently, by using this tracked flute as a reference, the other two flutes can easily be identified throughout the cuts.

In this study, the vibration and eddy current signals were sampled at 51200 KHz using National Instrument (NI) 9232 DAQ module. A Compat DAQ chassis (CDAQ) with 8 slots (9188) was used to host 9232 DAQ module via one of its slots. The DAQ module has 3 A/D channels (all being of 24 bits resolution) to perform the discretization of sensor measurements. Following the sampling and discretization of the sensor signals, the data was passed to the computer through an Ethernet port. A virtual instrument based on LabVIEW software was developed to read and store the discretised time-sampled data captured by NI DAQ hardware in the computer local disk in LabVIEW file format (TDMS format). A schematic diagram of the experimental set up is shown in Fig. 4.

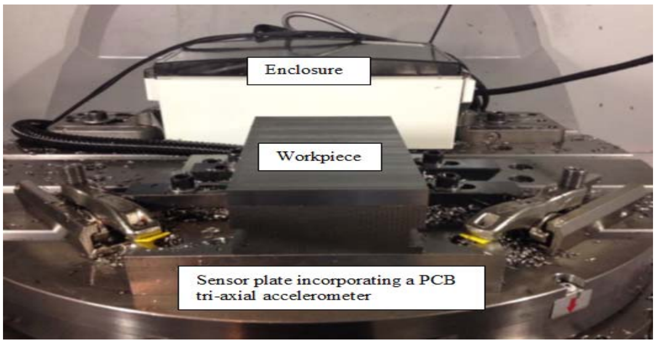


Fig. 2 Experimental set up of the DAq system inside the machine tool

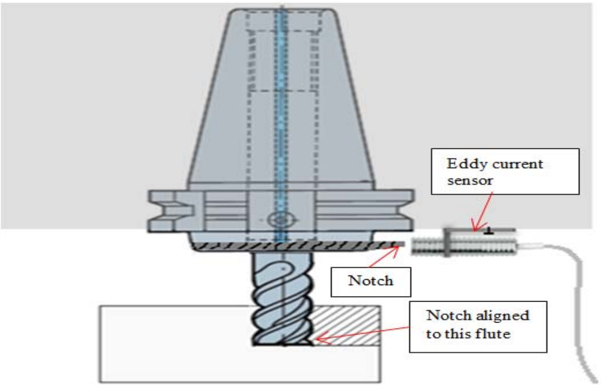


Fig. 3 Experimental set up of teeth tracking system

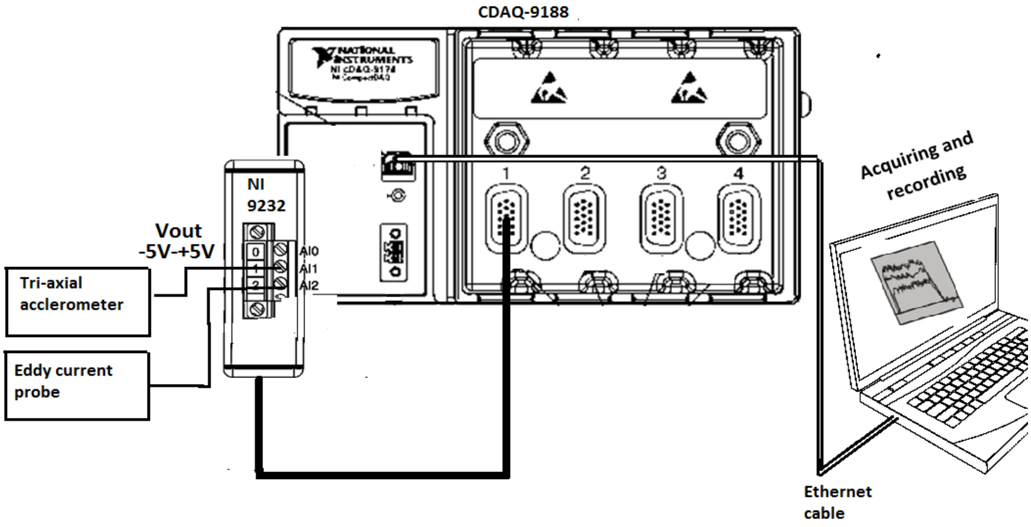
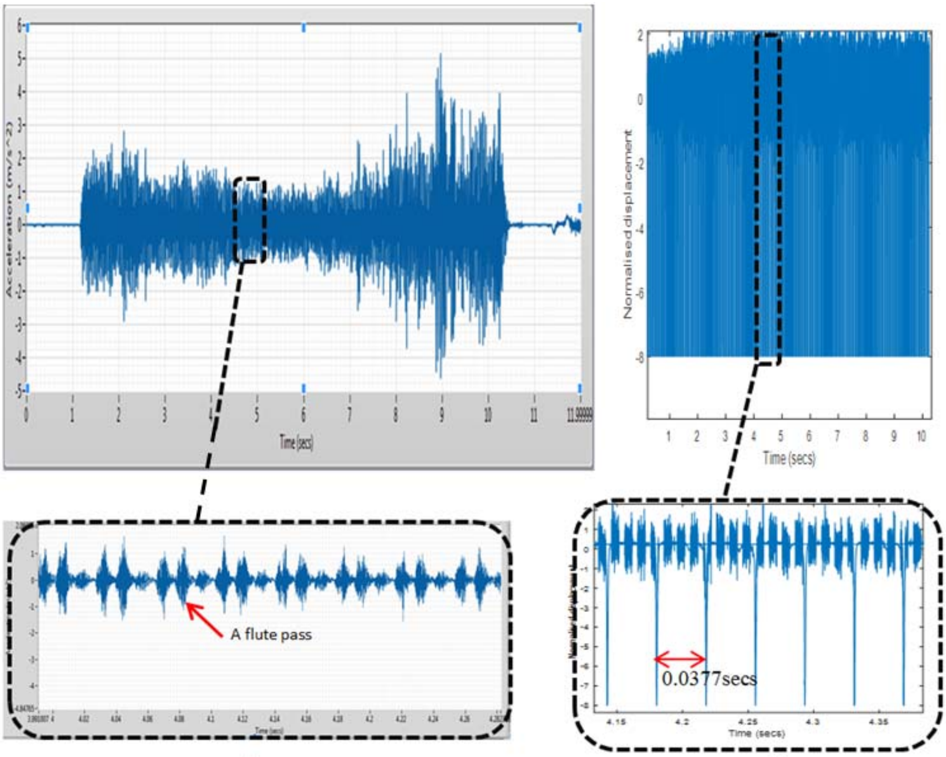


Fig. 4 A schematic diagram of data acquisition hardware

III. EXPERIMENT RESULTS AND DISCUSSIONS

In order to experimentally illustrate the effectiveness of the flute tracking system in segmenting the vibration signals relating to each flute, two cutting trials were initially performed along the path illustrated in Fig. 1 and using the cutting parameters shown in Table I. Figs. 5, 6 show the vibration signal along the X-axis (feed direction) measured by 604B31 tri-axial accelerometer and the displacement of the notch captured by the eddy current probe in these two cutting trials.



a) b)

Fig. 5 The results obtained in cut #1: (a) Flute passes observed in the acceleration signal along the X-axis (b) Displacement measured by the eddy current sensor

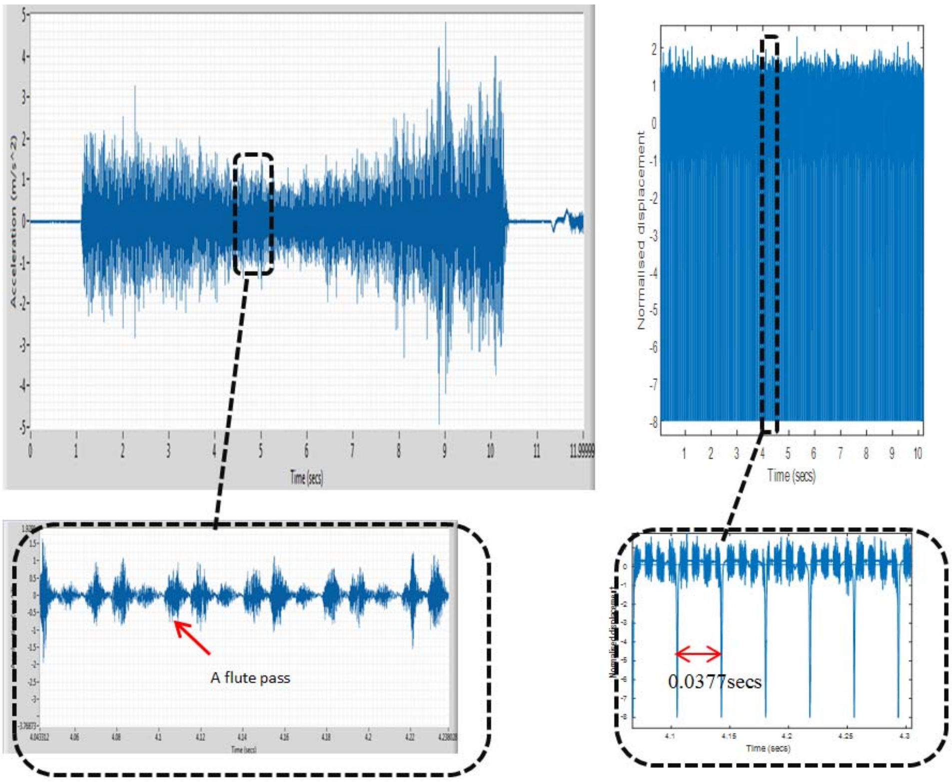


Fig. 6 The results obtained in cut #2: (a) Flute passes observed in the acceleration signal (b) Displacement measured by the eddy current sensor

It can be seen from Figs. 5 (a) and 6 (a) that due to the discontinuous nature of the cutting process (only one flute is in contact with the workpiece at one time), each flute pass can be identified and observed in the accelerometer signal in cuts #1 and #2. Although it is possible to track the three flues of the cutter in cut #1 by assigning flute passes observed in the acceleration signal to individual flutes of the cutting tool, it is extremely difficult if not impossible to keep track of these flutes in cut #2. This in turns makes the task of monitoring the wear on individual flutes throughout the cuts an impossible one to achieve in practice. It can be observed from Figs. 5 (b) and 6 (b) that the displacement results fluctuate significantly between the valleys. These fluctuations in the sensor signal are basically external noises introduced during machining and they are probably caused by the rattling of the senor at the attachment point when the cutting tool is in contact with the workpiece. It can be also noticed from Figs. 5 (b) and 6 (b) that the valleys in the displacement results occur at 0.0377secs intervals which is the time needed for the cutting tool to complete one full rotation with the selected spindle speed (1592 RPM) for the experimental tests as depicted in Table I. This result was anticipated, as the eddy current probe measures the distance to the top tip of the notch only when the notch attached to the tool holder is aligned with the eddy current sensor. This obviously occurs after the cutting tool completes one full revolution. The displacement measurements are therefore taken at regular intervals (one complete rotation), thus creating valleys in the results. It is also worth pointing out that the flute tracking system is essentially a tachometer as it measures the spindle speed as discussed above.

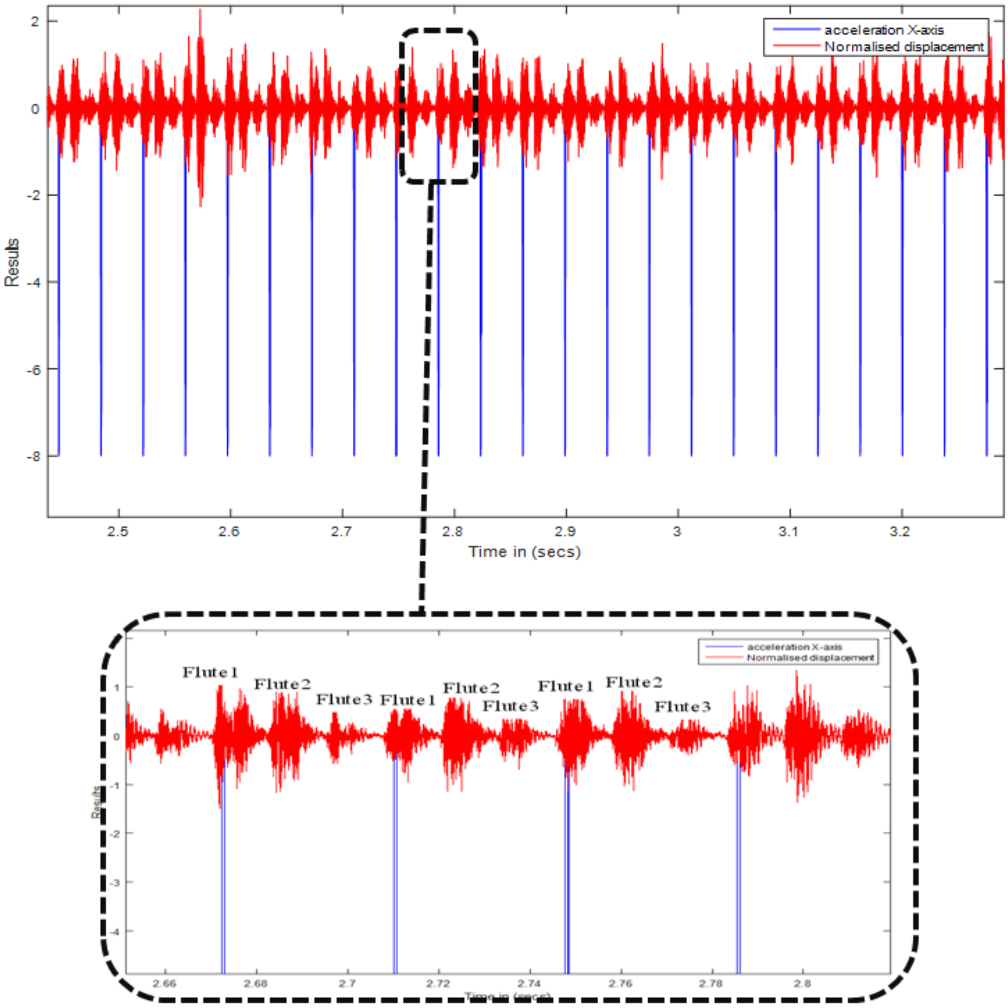


Fig. 7 The segmentation of acceleration signal by flute using teeth tracking system in cut #1

As mentioned in Section II, the notch was deliberately designed to be aligned to one of the cutter flutes to aid tracking of this particular flute throughout the cuts. Hence, by using this tracked flute as a reference, the other two flutes can easily be identified throughout the cuts. To demonstrate this concept, the flute tracking system was used to segment the acceleration signal by flutes in the two cuts shown in Figs. 5 and 6. The results are shown in Figs. 7 and 8 which clearly confirm that the flute tracking system is capable of identifying each physical flute of the cutting tool in these two cuts. Thus, by segmenting the vibration signal by flutes, it is therefore possible to monitor the wear in the individual flutes separately throughout the cuts.

To illustrate this idea, 382 additional cutting tests were performed along the same tool path and using the same cutting parameters as depicted in Table I. The RMS of the acceleration signal in each cut was then calculated for individual flutes of the cutting tool to monitor their progressive wear throughout the cuts. The acceleration results along the X-axis (feed direction) together with microscopic images of the tool at cuts #170 and #200 are shown in Fig. 9. It can be observed from this figure that from cuts #1 to #200, the RMS of the acceleration signal in flute 1 is higher than those in flutes 2 and 3. This might be explained by the fact that the cutting process is not uniform for all the flutes, with flute 1 engaging more with the workpiece and removing more material in one revolution than the other two flutes. Moreover, it can be seen from this figure that when flutes 2 and 3 were broken at cut #200, there was a sudden rise in the RMS signal of flute 1. This increase in the RMS value of flute 1 can be attributed to the higher contact between the workpiece and the tool which occurred to compensate for the loss of contact by the other two flutes. Hence, the rise in the RMS of flute 1 provides a strong indication that the other flutes of the cutting tool were damaged. Similar behaviour was also observed in the average power of X-axis acceleration over a range of frequency [10, 5000Hz] as shown in Fig. 10.

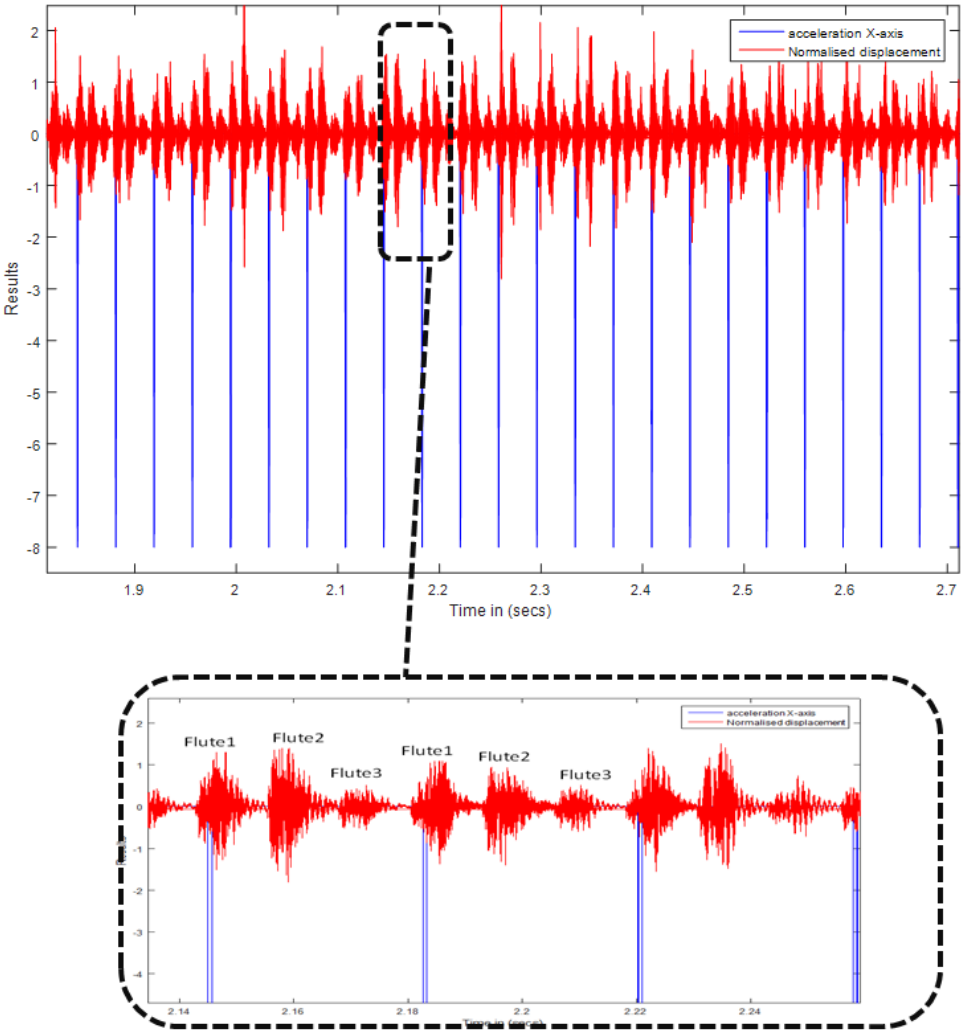


Fig. 8 The segmentation of acceleration signal by flute using teeth tracking system in cut #2

In this study, a flute tracking system has been proposed to segment vibration signal by flutes. To demonstrate this concept, the system was deployed on a simple climb milling operation where a solid carbide cutting tool with three flutes was used to machine a Titanium Ti-6Al-4V workpiece. This system, however, is more applicable to other types of milling operations such as face milling, where cutting tools with indexable inserts, as shown in Fig. 11, are typically used. The proposed system could in such machining operations help operators/engineers to reduce the manufacturing costs associated with machine down time. The authors are currently working on applying the system to other types of milling operations including face milling operation and the results of this work will be reported in future publications.

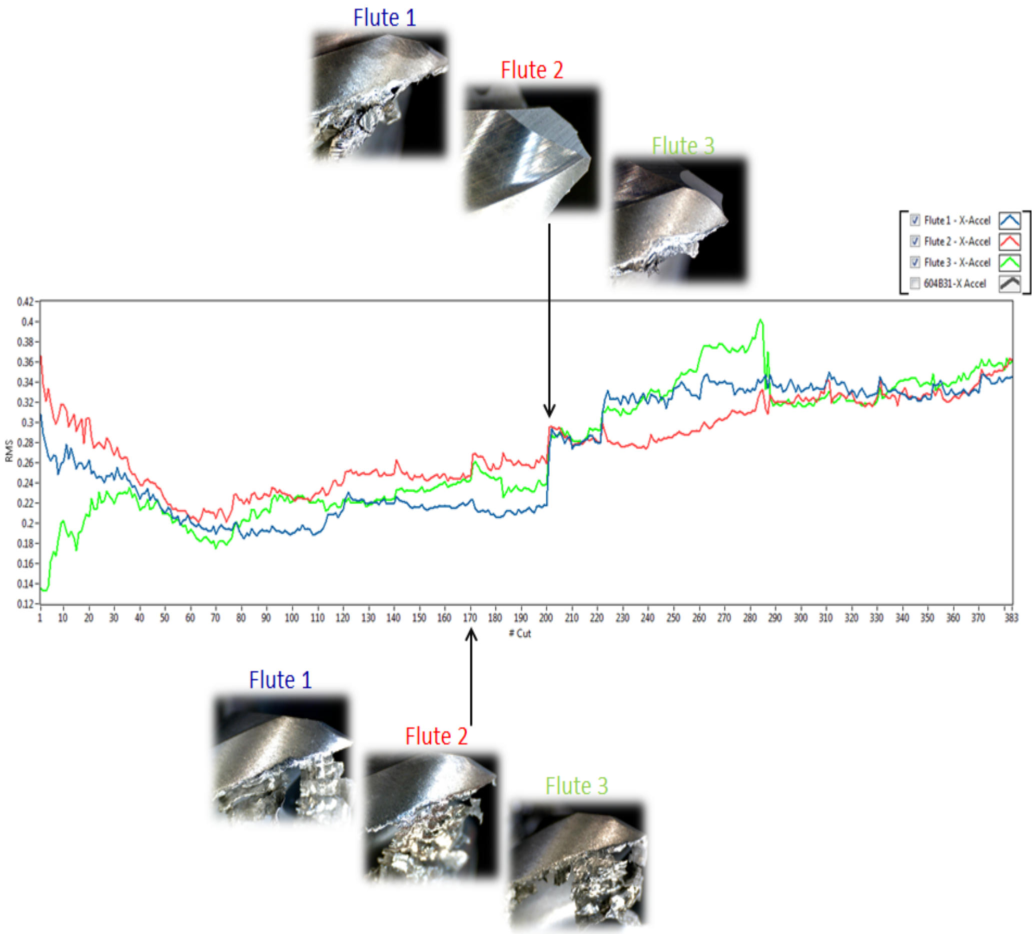


Fig. 9 RMS of X-axis acceleration signal by flute and microscopic image of flutes in cuts #170 and #200

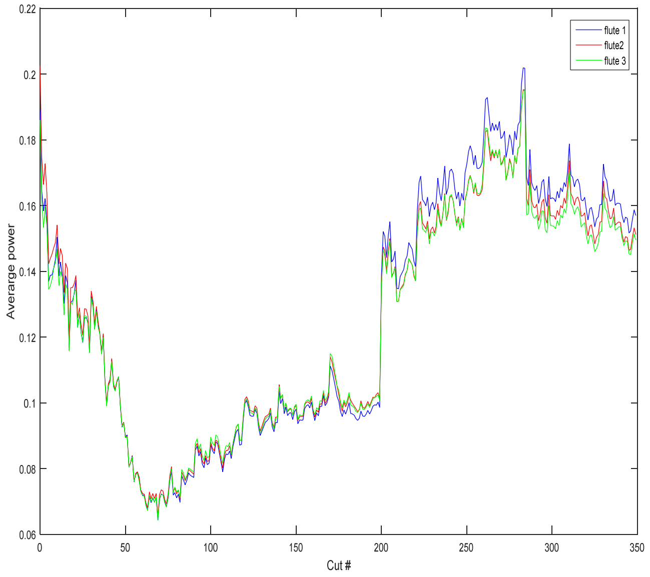


Fig. 10 Average power of X-axis acceleration over a range of frequency [10, 5000Hz]

Fig. 11 A cutting tool with indexable inserts used in face milling operations

It is also important to point out that the main focus of the present study is not to detect the wear in cutting tool flutes using statistical tools such as RMS and average power of acceleration signal as demonstrated above. Instead, the main objective of this study is to illustrate how the flute tracking system can be used to segment sensor signals by flutes in order to aid the monitoring of the wear on individual cutting tool flutes separately. It is therefore worth considering in future studies using the proposed system together with advanced process monitoring techniques such as artificial neural techniques and statistical models to detect the wear of cutting tool flutes, or inserts in the case of indexable tooling. The authors are currently working on this and the results will be also reported in future publications.

Finally, as mentioned earlier that the flute tracking system is essentially a tachometer as it accurately measures the spindle speed. Since most machine tools are equipped with tachometers to measure and control the spindle speed, thus there might be opportunities to use these readily available tachometers to track the cutting edges of cutting tools. This is an issue which, as far as we are aware of, has not been considered by machine tool manufactures yet. However, our discussions with experts in machine tool manufactures indicate that the flute tracking system could be realized in practice by modifying the design of tachometers used inside the spindle housing.

IV. CONCLUSIONS

In this paper, a flute tracking system has been proposed to segment vibration signals relating to each physical cutting edge of a cutting tool to aid the monitoring of their wear separately. The cutting tool considered in this study was a solid carbide tool with three flutes. The tool was used to profile mill a Titanium 6-4 workpiece. The proposed flute tracking system consists of i) an eddy current sensor fitted on the milling head and ii) a notch attached to the tool holder and aligned with one of the flutes. The results showed that, by using the position of the notch as a reference, the vibration signal relating to each flute can be successfully segmented. RMS and the average power signal over a range of frequencies of the vibration signal observed in each flute were also calculated to correlate the vibration to the progressive wear of the flutes. Analysis of the vibration signal and the condition of the flutes demonstrated that the RMS signal and the average power are sensitive to the wear on each cutting edge. These results therefore confirm that, by segmenting the vibration signal by flute, it is possible to investigate the wear in each individual cutting edge of the cutting tool. The result of this will allow an engineer to identify the level of wear on each flute to support a diagnosis on tool wear mechanism. In the case of indexable tooling, an engineer can identify and replace individual cutting edges without manual inspection of the whole tool. Consequently, this system has the potential to reduce the cost of manufacturing by reducing machine down time. Furthermore, this system will support the diagnosis of tool wear mechanisms – an important insight when looking to either manually or automatically optimize the cutting parameters.

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