Wavelet-based Analysis of Force Signals for Monitoring and Prediction of Cutting Performance in High-speed Milling Processes

L.Y. Zhai, M.J. Er, X. Li, O.P. Gan, and L. San

Abstract—**Effective monitoring and prediction of cutting performance degradation is a critical issue in realizing automatic high-yield manufacturing systems. This paper reported a wavelet-based cutting force analysis approach to monitor and predict cutting performance degradation in high-speed milling processes. Experiments on high-speed milling process were conducted and the cutting force signals were analyzed using wavelet transform techniques. The proposed approach is able to discover the correlations between the cutting force features and cutting performance variations, which will enable the establishment of an intelligent monitoring and prediction system for automatic high-speed milling processes.**

Index Terms— **cutting force, surface roughness, tool wear, wavelet analysis**

I. INTRODUCTION

HIGH-speed milling process is one of the most important means for metal removal machining in modern manufacturing industry. Due to the complexity of the machining process, evaluation of the cutting performance in high-speed milling operations usually can only be carried out indirectly by examining the characteristics of various signals acquired during the cutting process [1]. The advance of multi-sensor fusion technologies has encouraged many studies on the correlation between the cutting performance degradation and the corresponding characteristics of various signals such as the cutting force signals, vibration and acoustic emission signals [2]-[5]. For example, reference [6] presented a comprehensive review of critical methods using sensor signals for tool wear monitoring in metal cutting operations. Among these signals, the knowledge of cutting forces is of great importance in evaluation of a cutting process performance because it constitutes a key basis to understand the kinematics and dynamics of the machine tool and the machining process [7]. Cutting force has been regarded as one of the most useful responses to monitor and predict cutting performance degradations due to its easy-to-measure and easy-to-manipulate features, as well as its strong correlation with tool wear propagation, which is the most critical factor determining the work piece surface quality [3], [6], [8], [9]. It has been reported in some research work that the dynamic components of cutting forces are able to provide very detailed information for tool wear and tool failure monitoring [10], [11]. For example, reference [12] developed an online tool condition monitoring system based on cutting force measurement. The ratio of cutting force components have been found as a better indicator of the tool wear. Reference [13] described an experimental and analytical method using three mutually perpendicular components of cutting forces to analyze the relationships between the measured signals and the accrued tool wear. More recently, reference [14] presented a model-based monitoring and failure detection approach for ball-nose end milling process, in which a mechanistic force model has been established for high-speed milling on hardened Stavax steel with 6mm micro-grain tungsten carbide 2-flute ball nose end mill. References [15] and [16] reported a statistical analysis for detection cutting tool wear based on regression model, in which their study presented a new method for detecting the cutting tool wear based on the measured cutting force signals. On the other hand, along with the development of sensory technologies, new techniques to analyze the dynamic features of the acquired signals need to be developed so as to monitor and evaluate the cutting performance more effectively. In such a context, wavelet-based analysis has become one of the most promising means to delineate the details of cutting performance and tool wear degradation due to the localized features of the analyzed result [17].

This paper presented a wavelet based cutting force analysis approach to evaluate cutting performance in high-speed milling processes. The main objective of this research is to correlate the cutting performance to the easy-to-measure force signals using wavelet transform techniques. In the proposed approach, cutting forces are decomposed into detailed levels under different scales, taking advantage of wavelet transforms in multi-resolution analysis. Based on the features of decomposed force signals, relationships between the cutting performance and the detailed level cutting force

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L. Y. Zhai is with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798. (phone: 0065-67906355; fax: 0065- 68968757; e-mail: lyzhai@ntu.edu.sg).

M. J. Er is with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798 (e-mail: emjer@ntu.edu.sg).

X. Li is with Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075 (e-mail: xli@SIMTech.a-star.edu.sg).

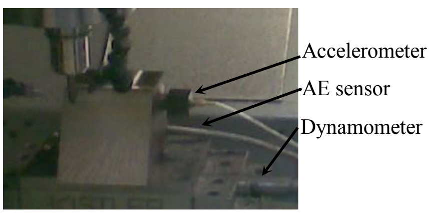
O.P. Gan is with Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075 (e-mail: opgan@SIMTech.a-star.edu.sg).

L. San is with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798 (e-mail: sanlinn@ntu.edu.sg).

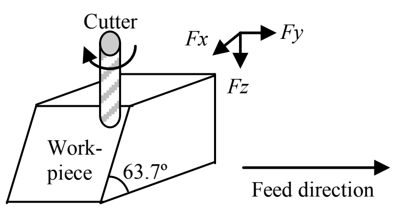
components are discovered, which can be used to detect and predict cutting performance degradation in high-speed milling processes. The remainder of the paper is organized as follows. Section 2 presents a brief review of related works. Section 3 introduces the experiment set-up of a high-speed dry-milling process. A multi-sensor data acquisition system is also introduced in this section. Section 4 elaborates the proposed wavelet-based analysis of cutting force data and conclusions are summarized in Section 5.

II. Experiment Setup and Method

The experiment conducted in this study employed a multi-sensory system to measure and acquire signals of cutting force, vibration and acoustics. Destructive tests using 6mm 2-flute ball-nose end mills were carried out on a Titanium (Ti6Al4V) work piece by a 3-Axis Röders high-speed milling machine. An 8-channel data acquisition system was set up with Kistler multi-sensor system composed of a 3-component dynamometer, a 3-component accelerometer, and an acoustic emission sensor. The machine tool employed is 3-Axis Röders Tech RFM760 high-speed milling machine with a variable spindle speed of up to 42,000 rpm, a maximum power of 14 kW, and a variable feed-rate of up to 30m/min. The work piece is a block of solid Ti6Al4V material with both width and height of 78 mm. The surface to be machined is inclined at the angle of 63.7 degrees, which is set to obtain a ratio of 2 between the axial and radial depths of cut. The cutting conditions were fixed as follows: spindle speed of 10400rpm, feed per tooth of 0.04 mm/tooth, axial depths of cut of 0.2 mm and a radial depth of cut of 0.1 mm. Cutting force components (Fx, Fy, and Fz) were acquired using Kistler quartz 3-component platform dynamometer (type 9254) connected with Kistler amplifiers (type 5070A). As a complement and in order to judge the force signals collected, 3-component vibration and AE signals were also collected at the same time through the 8-channel data acquisition system. Figure 1(a) shows the data acquisition system of the experiment and Figure 1(b) shows the work-piece orientation and force components.



(a) Data acquisition system



(b) Cutting force components

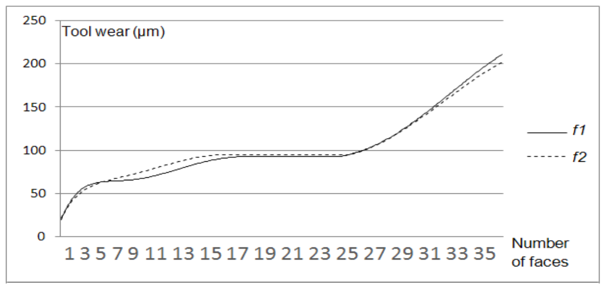
Fig. 1. Data acquisition system and cutting force components

In the destructive test, the milling process was stopped every time after a face (i.e. a layer of material removed from the work piece) was finished for the purpose of measuring tool wear and work piece surface roughness. Tool wear was measured using a Leica microscope with a resolution of 0.001 mm and surface roughness was measured by a Mitutoyo portable surface roughness tester (Surftest SJ-201). The average roughness (R_a) values were measured in the four equally divided regions of the work piece surface, which were called quadrants 1 to 4 in the anti-clockwise direction. In each region five R_a values were read and the average of these readings was recorded as the final R_a value. Surface roughness measurements were carried out in both vertical (perpendicular to the cutting direction) and horizontal directions.

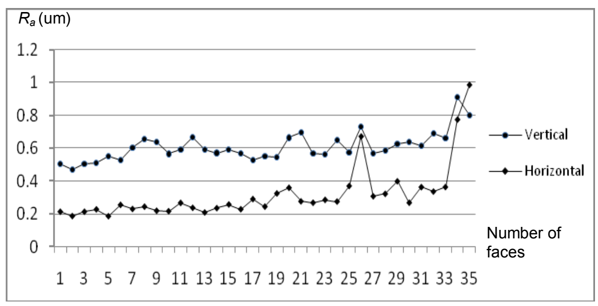
III. Wavelet-based Analysis of Cutting Forces

A. Cutting Force Analysis

Wavelet transforms are an effective means to analyze non-stationary time series signals and they can provide detailed level information about the analyzed signals under various scales. The objective of this study is to develop a wavelet-based cutting force approach to detection and prediction of cutting performance degradations in high-speed milling processes. Preliminary studies conducted in this research have found that the dynamic Fy force component (i.e. cutting force in the feed direction) was more sensitive to the changes in tool wear and surface roughness compared to the other two axes. Therefore, the Fy force component was analyzed in detail using wavelet transform techniques and its relationship with cutting performance degradations was examined.



(a) Tool wear



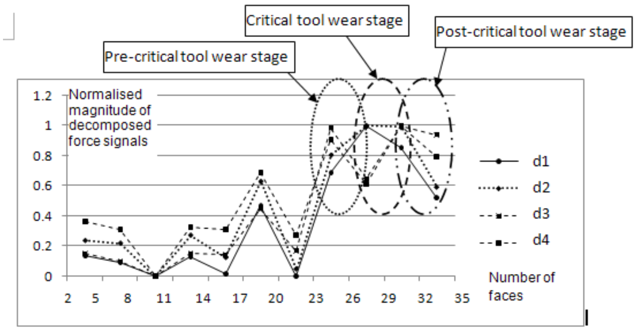
(b) Surface roughness of work piece

Fig. 2. Tool wear and work piece surface roughness

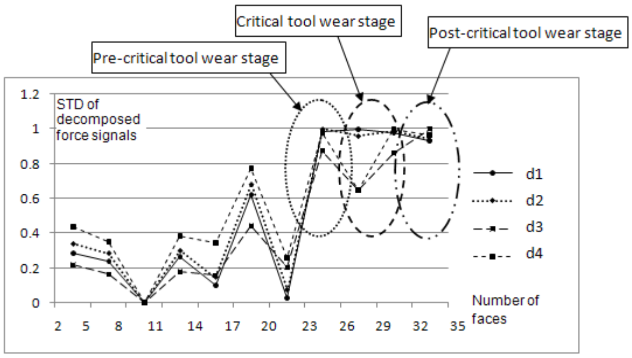
In the destructive test, the new cutter reached its life limit after it cut 35 faces of the work piece. Preliminary analysis of the tool wear has found that the cutter degradation follows a nonlinear manner, namely the tool wear develops relatively fast in the first several faces and then gradually converges into a steady tool wear speed until the tool wear propagates quickly and finally fails (Figure 2(a)). The above nonlinear pattern of cutter degradation process tallies well with the changes of work piece surface roughness. Figure 2(b) shows the average vertical and horizontal surface roughness values measured from the 1st face to the 35th face in the destructive test. In Figure 2(b), it is clear that both vertical and horizontal surface roughness values increase in the first several faces and then gradually converge at a stable level until the 26th face where both vertical and horizontal roughness values increase to a new level. This is in fact the first occurrence of the important symptom of severe cutter degradation. After this first "heart attack" the cutter failed after cutting another 8 faces. The above analysis between the tool wear propagation and the surface roughness progress reveals that they are closely associated with each other.

As mentioned earlier, the objective of this study is to use the easy-to-measure force signals to monitor and predict the cutter degradation and work piece surface roughness. Therefore, it is necessary to examine the characteristics of the force signals while the tool wear propagates. In this study, discrete wavelet transforms were performed to decompose cutting force signals under different scales. More specifically, cutting force signals were analyzed using Daubechies wavelet (db3, level 4). Based on the decomposed force components, the maximum magnitude and standard deviation (STD) of each component under different scales were extracted as the features of cutting force signals. The results have shown that the maximum magnitude and STD of each detailed level component (denoted by d1 to d4 respectively) increase with the propagation of tool wear, as shown in Figure 3(a) and Figure 3(b).

Further investigations into Figure 3(a) and Figure 3(b) have discovered more interesting findings. In Figure 3(a), it is obvious that the magnitude of each component achieves its maximum limit when the first "heart attack" of the cutter occurs at the 26th face, where both vertical and horizontal roughness values increase remarkably (see Figure 2(b)). However, it should be noted that before the magnitude values hit their maximum limits, which is called the "critical tool wear stage" in this study, there is an obvious ramp-up trend in the magnitudes of the cutting force components. This trend of increase of cutting force components is called the "pre-critical tool wear stage" in this study. On the contrary, after the "critical tool wear stage", there is a trend of decrease in the cutting force magnitudes, which is called the "post-critical tool wear stage". Similar patterns can be observed in Figure 3(b). Obviously, using wavelet transform techniques, the three stages of tool wear can be easily identified by examining the features of cutting force signals. This is a very important finding as it will set up a basis for establishing a force-based tool wear monitoring and prediction model in high-speed milling processes.



(a) Normalized magnitude of the detailed level components



(b) Normalized STD of the detail level components

Fig. 3. Identification of tool wear stages

Another interesting finding from Figure 3(a) and Figure 3(b) is that the first and second detailed level components (denoted by d1 and d2 respectively) share similar increase patterns with each other when the tool wear propagates. Similarly, the third and fourth detailed level components (i.e. d3 and d4) also share similar increase patterns with each other. Comparisons among the detailed level force components in Figure 3(a) and Figure 3(b) also find that the high frequency components (i.e. d1 and d2) are more sensitive to the tool wear propagation compared to the lower frequency components (i.e. d3 and d4). As a result, dynamic fluctuations of the high frequency cutting force components of a wavelet analysis can be used to detect and predict the cutting performance degradation in a high-speed milling process.

B. Result Validation

In order to validate the results discussed above, another destructive test was conducted in this study. In the new test, the cutter was selected from the same cutter family without coating in order to expedite the test process. Tool wear of the cutter was measured after every 100 lines of cutting and the cutter reached its limit of tool life after 2100 lines. Figure 4 presents the tool wear propagation with the increase of cuts. As shown in the figure, tool wear started to increase rapidly after 1600 lines of cutting and hit the limit of 200 μm after another 500 cuts. Such a tool wear progress is also well reflected in the results of wavelet analysis of the cutting forces. Figure 5 presents the normalized magnitude and STD of decomposed force signals using db3 wavelet analysis. Apparently, both the magnitude and STD showed an obvious rapid increase following the rapid increase in tool wear around 1600-1700 lines of cutting. From that time until the end of the tool life, the magnitude and STD exhibit very similar patterns as shown in Figure 3, where there is a quick ramp-up at the pre-critical tool wear stage, followed by a vertex at the critical tool wear stage, and a quick ramp-down at the post-critical tool wear stage. Further destructive tests using more cutters have also found consistent results as depicted in Figure 5, which has successfully verified the repeatability and validity of the research findings obtained in this research.

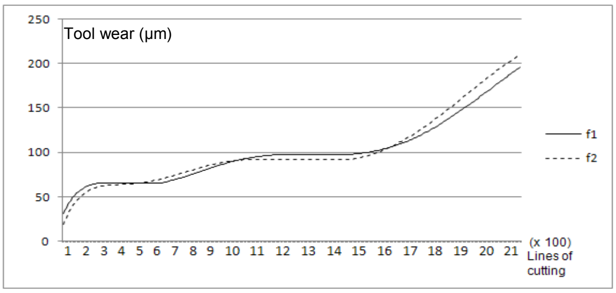
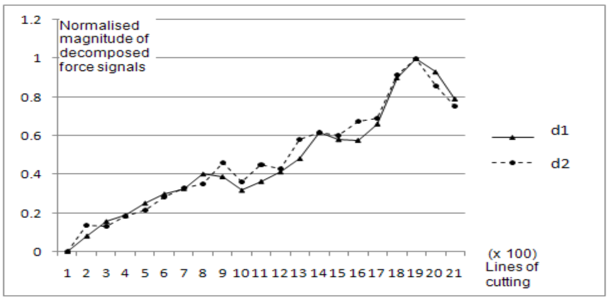
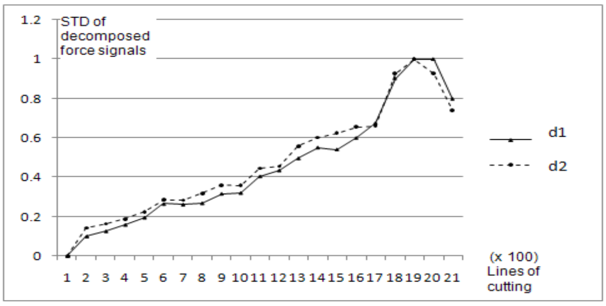


Fig. 4. Tool wear propagation with increase of cuts



(a) Normalized magnitude



(b) Normalized STD

Fig. 5. Normalized magnitude and STD of decomposed force signals

IV. CONCLUSION

Wavelet transforms are a powerful tool to analyze time-varying non-stationary signals. It provides a multi-resolution analysis which can supply localised detail features of the signal in both time and frequency domain. In this study, cutting force signals were analysed using db3 (level 4) wavelets and the features of force signals are extracted to monitor and predict cutting performance degradations in a high-speed milling process. The results have shown that the magnitude and STD of the high frequency components of cutting force signals have a strong correlation to the propagation of tool wear. As a result, the relationships between cutting force signals and cutting performance degradation discovered in this study will enable the establishment of a force-based monitoring and prediction system to detect the status of tool wear and surface degradation in high-speed milling processes.

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L. Y. Zhai received his PhD and M.Eng (both in Mechanical Engineering) from Nanyang Technological University of Singapore in 2010 and 2000, respectively. His B.Eng degree in Mechanical Engineering was awarded by Xi'an Jiaotong University (China) in 1994. He has been actively engaged in several funded research projects in manufacturing system modeling and optimisation in the past ten years. His publication includes more than 20 refereed international journal papers, book chapters and international conference papers. His main research interests include prognostic and health management, fuzzy logic and rough sets, knowledge discovery and intelligent systems.