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Procedia CIRP 46 (2016) 508 – 511

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7th HPC 2016 – CIRP Conference on High Performance Cutting

Tri-axial time-frequency analysis for tool failures detection in deep twist drilling process

M.H.S Harun [a], M.F. Ghazali[b] and A.R. Yusoff[a,*]

[a]Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia
[b]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600, Pekan, Pahang, Malaysia

* Corresponding author. Tel.: +609-424-5873; fax: +609-424-5888. *E-mail address:* razlan@ump.edu.my

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Abstract

Premature tool failure in deep drilling reduces product quality. By analyzing the deep drilling process signals through time and frequency domains in tri-axial vibrations, the early conditions before tool failure can be detected. From the experimental data, vibration time domain signals were analyzed by short-time Fourier transform to detect the tool wear mechanism. Results showed that tool wear accelerated before failure as increasing feed rate and cutting speed were recognized in the *y*- and *z*-axes in time–frequency analysis.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz

Keywords: Deep hole drilling, Vibration, In-Process Measurement, Tool Condition Monitoring, Signal Processing Techniques

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1. Introduction

The world's manufacturing production increases yearly; with the growth of 16% from 2000 to 2010 [1]. This phenomenon has led to increased pressure on developing innovative ways to support manufacturing productivity and demand. In the machining sector, such as drilling application, deep drilling has been used to replace traditional drilling techniques to increase productivity and reduce production cost [2]. However, premature tool breakage can occur because of wear, chip clogging, and failure. By analyzing the deep drilling process signals through time and frequency domains in tri-axial vibrations, the early conditions before tool failure can be detected.

Signal is a time-varying quantity that carries information and needs further analysis and processing via a computer algorithm. Several signal processing techniques have been developed to monitor the machining processes of drilling, turning, and milling, such as fast Fourier transform (FFT), short-time Fourier transform (STFT), and wavelet transform (WT). FFT is the standard method for observing signals in the frequency domain, and it is widely used in tool condition monitoring [3–6]. The basic mechanism of FFT is to extract the fundamental frequency component of the fringe pattern in the 1D or 2D frequency domain and its inverse transform of the filtered frequency domain signal, which then provides the modulo 2p phase of the fringe pattern [7]. However, FFT cannot represent time and frequency signals at the same time and domain [4]. STFT is based on FFT as a time–frequency technique to deal with non-stationary signals that have a short data window centered on time [6, 8]. STFT is also widely used in monitoring tool wear for drilling applications [9–13].

Nomenclature

FFT	Fast Fourier Transform
STFT	Short time Fourier transforms
WT	Wavelet Transform
HHT	Hilbert-Huang Transform
a_x, a_y, a_z,	Acceleration in *x*, *y* and *z*-axes (m/s^2)

The WT and HHT concept are almost similar to STFT, which decomposes a single signal series in the time domain

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
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doi:10.1016/j.procir.2016.03.128

into a 2D function. Both method considers a series of band pass filters as different mixtures of independent source signals [12]. WT and HHT can also monitor tool conditions [10, 13–16], but both method require complex and long analysis to measure tool conditions compared with STFT [11].

STFT is rapid and appropriate for time–frequency analysis for tool condition monitoring [11, 17]. STFT is more popular in regular tool failures in uniaxial vibration analysis for normal drilling processes. To date, no research has examined the effect of tri-axial vibrations on tool failures. Minor studies have been conducted on deep twist drilling by Biermann and his co-authors, but they focused on heat analysis [17], thermal effect [18], and Heinemann focused on performance [19]. In the current study, the premature tool breakage problem was analyzed using STFT of the deep drilling process with *x*, *y*, and *z* as tri-axial vibration signals.

2. Experimental setup

The experiment was conducted on a Haas CNC three-axis vertical machining center VF6. The material used was a die material SKD 61 with HRC range of 50–55. The tool drill material was high speed steel with diameter of 8 mm and total length of 165 mm. The parameters involved in analyzing the tool failure mechanism of deep twist drilling were cutting speed, feed rate, and depth of cut. The ranges of cutting condition and tool manufacturer used in this experiment were based on [10, 18–23], as shown in Table 1. The cutting condition ranges were evaluated based on the Design of Experiment method. Three factors, five levels, and 25 different parameters were generated and applied for the drilling process experiment.

Table 1: Cutting parameters for deep drilling experiment

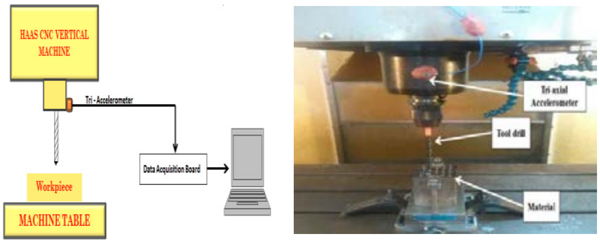
Cutting speed (m/min)	30 – 70
Feedrate (mm/rev)	0.10 - 0.30
Depth of cut (mm)	40 – 80

During the experiment, the tool wear mechanism was recorded based on vibration sensors from a PCB 356A32 miniature tri-axial accelerometer, as illustrated in Figure 1. The signal data were transferred to a computer using data acquisition signals (National Instrument, model 4431). Processed signals were analyzed using a signal processing technique in Matlab software. The experiment was repeated three times for each parameter to obtain accurate results. There are total 75 experiment were conduct in this study.

4. Results

Figure 2 shows the tool in good condition, with no difference in vibration level between the *x*- and *y*-axes within 1 m/s^2 and 0.5 m/s^2 for the *z*-axis. In STFT, the spectrogram at 5 s with frequency of 800 Hz and 0.08 FFT magnitudes indicated good tool conditions.

A small tool wear condition was indicated by a vibration level of 4.0 m/s^2 for the *y*- and *z*-axes and 1.0 m/s^2 for the *x*-axis, as shown in Figure 3. Both *x*- and *z*-axes increased, similar to the STFT spectrogram. This increase appeared at the end of the drilling process at 18 s with low frequency of 600 Hz and FFT magnitude of 0.1. The vibration level increased to 10 m/s^2 for the *y*- and *z*-axes but remained unchanged in the *x*-axis for a large tool wear condition, as shown in Figure 4. Vibration increased with two spikes at the end of cutting in both the *x*- and *z*-axes. Compared with small tool wear conditions, the vibration signals increased. However, in the STFT spectrogram, similar frequency and magnitude were observed.



a)Schematic diagram b)Experiment arrangement

Fig. 1. Deep drilling experimental settings

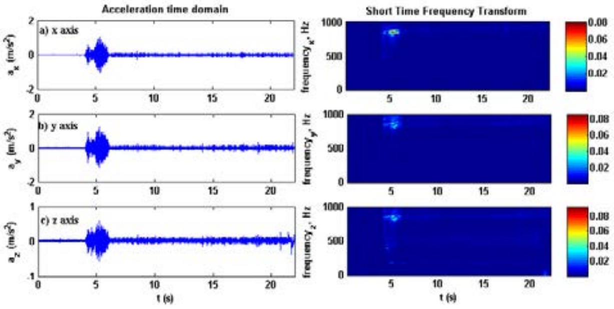


Fig. 2. Good tool conditions

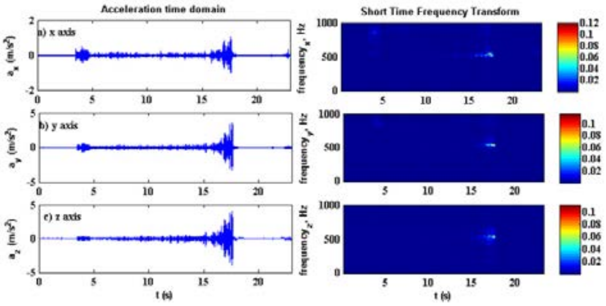


Fig. 3. Smaller tool wear conditions

As shown in Figure 5, a vibration level of 12.0 m/s^2 for the *y*- and *z*-axes and 2.0 m/s^2 for the *x*-axis indicated a blunt tool wear condition. Both the *y*- and *z*-axes increased compared with large tool wear conditions. However, the FFT magnitude increased to 0.2 at a similar frequency in the *y*- and *z*-axes for a large tool wear condition in the STFT spectrogram. This magnitude appeared 2 s before the end of drilling for the *y*- and *z*-axes. The vibration level was maintained (12 m/s^2) for the *y*- and *z*-axes but increased to 5 m/s^2 for the *x*-axis to indicate a fracture tool wear condition, as shown in Figure 6. Such tool failure was also represented by increasing vibration conditions at 6–11 s and about 5 s of cutting duration in all axes. Compared with blunt tool wear conditions, the vibration signal increased in the *x*-axis only but remained unchanged in the STFT spectrogram. In addition, two frequencies of 600 and 850 occurred in this axis because of a spike at the end of the drilling process.

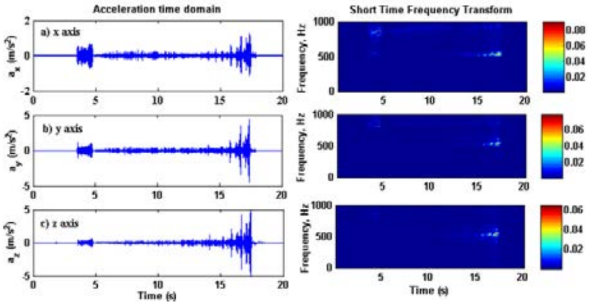


Fig. 4. Large corner tool wear conditions

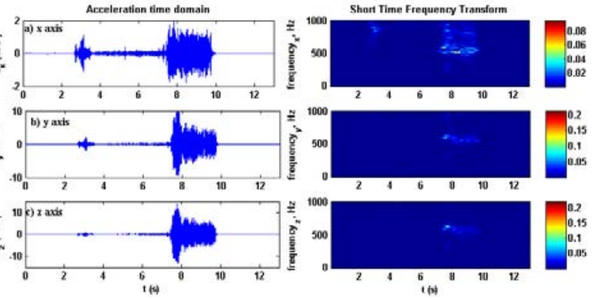


Fig. 5. Blunt tool conditions

5. Discussions

It been identified feedrate and cutting speed is the most influenced factor affected the tool condition from good to wear until failure. Meanwhile, other process parameter of depth of cut depends on other machining cutting parameters such as cutting speed and feedrate. For example, appropriate cutting speed and feedrate must suit with proposed depth of cut in deep drilling process. Good condition can be achieved within 30 to 50 m/min as cutting speed to achieve high deep drilling capability. Table 2 tabulates a good tool condition when accleration of a_x and a_y are balanced. Similar to feedrate, with range of 0.10 to 0.20 mm/min is still in good conditions. A low feedrate contributes to lower friction contact between tool and material, since there is no high friction magnitude occurred in good condition, as shown in Fig 2.

STFT only highlights initial contact for good tool condition due to low friction at frequency 800 Hz (Table 2). When cutting speed and feedrate are more than 50 m/min and 0.20 mm/rev respectively, it found that tool condition is changed to small and large tool wear conditions with 600 Hz frequency. The acceleration time domain in a_y and a_z increase about 4.0 to 4.5 m/s^2 significantly than a_x which maintains at 1.0-1.5 m/s^2. When the tool start to become blunt, a_x has small increase to 2.0 m/s^2 compared to a_y and a_z that suddenly increase to 10 m/s^2. High friction magntude highlighted by STFT that increased from small (0.08) to high (0.2) at 600 Hz in *y* and *z*- axes and 800 Hz for *x*-axis when feedrate is increased occured at the end of drilling process for about 2 s duration. Compared to fracture tool conditions, STFT magnitude happened with longer time of 4 s, loose contact in *x*-axis indicated by STFT as 0.02. While maintain other axes (*a* and *z*) for the STFT magnitude and acceleration, and also frequency as 600 Hz, a_x increase with a spike to 8 m/s^2 at the end of drilling process resulting 800 Hz.

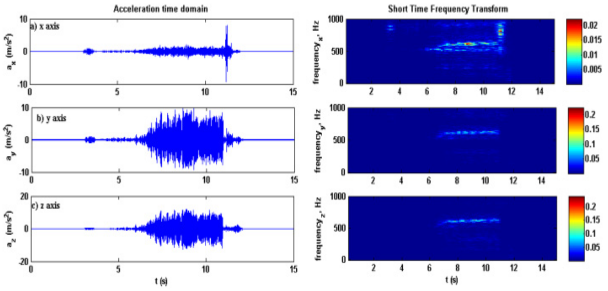


Fig. 6. Fracture tool conditions

Table 2: Summaries of time domain and STFT

Tool conditions	Acceleration time domain		Short Time Frequency Transform	
	a_x, a_y, a_z (m/s^2)	Critical time period (s)	Frequency (Hz)	Magnitude in *x*,*y*,*z* (STFT)
Good	1.0, 1.0,0.5	2.0 (initial)	800	0.08, 0.08, 0.08
Small wear	1.0,4.0,4.0	1.0 (end)	600	0.12, 0.1, 0.1
Larger wear	1.5,4.5,4.5	1.5 (end)	600	0.08, 0.06, 0.06
Blunt	2.0,10,10	2.0 (end)	600,500	0.08, 0.2, 0.2
Fracture	8.0,10,10	4.0 (end)	600,800	0.02, 0.2, 0.2

By manipulating the machine feed rate and time shown in the STFT spectrogram, the actual failure depth of tool drills can be known. For example, the first contact between the tool drill and material surface occurred within 5 s after operation, as shown in Figure 2. The machine parameters were feed rate of 159.2 mm/min, which was equal to 2.653 mm/s. The tool length offset used was 10 mm, and the center drill depth was 3 mm. The total cutting length was calculated as 13.27 mm from the actual first contact between the tool drill and material surface until tool wear or failure was detected.

The standard drill mechanism occurred when the rotation was balanced between the *x*- and *y*-axes (Figure 2), with a lower level of vibration caused by low friction between the tool and material surface [24]. Good tool conditions were noted when the feed rate was lower than 0.25 m/min and the cutting speed was less than 50 m/min. During initial contact between the tool and material surface in drilling, the tool started to lose its basic mechanism structure; for example, the tool started to bend and tool rotation became unbalanced under normal conditions (Figures 4 and 5) [5]. Meanwhile, the signal in the *z*-axis was more dominant than others, in which the highest axial friction was received by the tool. The forces supplied by machines to allow feeding resulted in the tool to lose support in the drilling process [10–12]. In the STFT spectrogram, higher vibrations occurred when the tool started to fail; this signal became more dominant than previous impact by the tool coming into initial contact with the material surface during early drilling, as indicated for blunt and fracture tool wear conditions.

In summary, tool pattern analysis showed that the first failure point was detected by controlling the level of vibrations. The *y*-axis could be used as a reference point to support the vibration levels generated by the *z*-axis. When the vibration level in the *y*-axis exceeded 2 m/s^2, tool damage had started. However, the *x*-axis was not influenced at the small failure region. The *x*-axis only started to increase when the tool was in blunt or fracture conditions, indicating small tool wear and large tool wear. The same phenomenon was observed in the *z*-axis; a vibration level of more than 4 m/s^2 indicated that the tool was starting to break. Referring only to time domain analysis is insufficient to clearly understand the tool failure condition. In STFT, detailed information of tool failure can be known. Figures 3 to 6 indicate that friction between the tool and material surface increased as the tool became damaged.

6. Conclusion

In conclusion, STFT is a simple, quick, and sufficient method for tool condition monitoring under the time and frequency domains. All failure occurred at 600 Hz when the tool became worn, blunt, and fractured. The failure tool length during drilling can be measured from the acceleration time domain, whereas STFT can predict the pattern of failure in blunt and fracture conditions indicated by frequency and magnitude values. By manipulating the machine feed rate and time shown in the STFT spectrogram, the actual failure depth of tool drills can be known. Tool wears accelerate before failure as increasing as feedrate and cutting speed are recognized in *y*- and *z*-axes. Data generated by tri-axial vibration sensors can sense the different tool conditions, particularly for the *y*- and *z*-axes. Tri-axial time–frequency analyses produce accurate, precise, and specific tool wear conditions of stable, small, and large wear and tool failure.

Acknowledgements

The authors would like to be obliged to Ministry of Science, Technology and Innovation (MOSTI) and Universiti Malaysia Pahang, Malaysia for providing laboratory facilities and financial assistance under e-science research fund project no. RDU140506.

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