Fault Detection of Face Milling Cutter through Spectrum, Cepstrum and Wavelet Analysis

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Abstract

Tool condition monitoring system provides a good quality product in terms of minimum surface roughness and desired dimension. The monitoring system helps to recognize/detect the faults during the process. This paper presents the fault detection of face milling tool using signal processing techniques. The vibration signals of milling tool under healthy and different faulty conditions are acquired. These vibration signals are analyzed by using time-domain plots, spectrum plots, cepstrum plots and continuous wavelet transform (CWT) plots. Experimental results show that, 54th multiple of tooth passing frequency (TPF) corresponding to 810 Hz is dominated among all the frequencies as illustrated using cepstrum and CWT techniques. From this results, CWT technique can be used to recognize the faults in face milling tool, as it provides frequency components with respect to time.

Keywords: Fault detection; Face milling; Spectrum analysis; Cepstrum analysis; Continuous wavelet transforms

1. Introduction

In machining process, two main factors such as dimension of the product and surface roughness play an important role in the quality of the product. The manufactured product is evaluated through precise dimension and low surface roughness value. Besides these factors, tool life also plays a vital role in the quality of the manufactured product (Orhan et al., 2007). As the tool wear increases consequently the quality of the machining product decreases. In order to maintain the quality of the product, a system is required for monitoring the cutting tool. Tool condition monitoring system

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works based on the acquired process parameters such as current signal, acoustic emission (AE) signal, cutting force, vibration signal, etc. to determine the condition of the cutting tool. Among these acquired signals, vibration gives better results about tool condition. One of the advantages of vibration signal measurement is that no modifications are required for experimental setup (Teti et al., 2010).

In signal processing techniques, no matter which process parameters are selected, signal processing techniques such as time domain, frequency domain and time-frequency domain analyses are very much useful to predict tool condition. Abouelatta and Madl (2001) correlated the surface profile of workpiece with the cutting parameters and cutting tool vibrations. Huang et al. (2012) investigated the stable and chatter machining processes through spectrum plots of cutting force and vibrational signals. Bisu et al. (2012) examined the dynamic behavior of the milling process to monitor the condition of the cutting tool through spectrum analysis using vibration signals. Sivasakthivel et al. (2011) developed a mathematical model with process parameters to analyze the vibration amplitude in high speed end milling of Al 6063 material using spectrum analysis. Antoniali et al. (2010) analyzed the variations in cutting force during milling of titanium alloy in time and frequency domain analyses.

From the past two decades, wavelet analysis has become one of the emerging and efficient tools for identifying the faults in signal processing and has its distinct merits. Some of the wavelet applications such as the time-frequency domain, denoising of weak signals and extraction of features related to faults, vibration signals compression, singularity detection for signals, etc. were used in machine condition monitoring and fault diagnostics (Peng and Chu, 2004). Mori et al. (1999) analyzed the transient responses in cutting force signals during drilling process using discrete wavelet transform (DWT) instead of using traditional spectrum analysis. Spectrum analysis has its own limitations (Zhu et al., 2009) as it can only be used for stationary signals. Li et al. (2005) revealed that the fast algorithm of wavelet transform is more reliable, sensitive and faster than spectrum analysis in prediction of tool wear condition during turning process. Li and Guan (2004) analyzed the feed motor current signals to predict cutting edge fracture through time-frequency plots in end milling process. Lee and Tarng (1999) determined milling tool breakage through discrete wavelet transform (DWT) using cutting force signals. Hsieh et al. (2012) studied the micro-milling tool condition monitoring using vibration signals and proposed a classifier to monitor the tool condition with the help of relevant features extracted from the vibration signals. Yao et al. (2010) applied wavelet transform for chatter detection and support vector machine (SVM) technique for pattern classification during boring process using vibration signals.

Limited literature is available regarding the usage of advanced signal processing techniques such as wavelet and cepstrum analysis in milling tool condition monitoring. This study aims to analyze the
spindle vibration signals of healthy and faulty conditions of face milling cutter using signal processing techniques for tool condition monitoring. The conventional vibration analyses such as time-domain, frequency domain, quefrency domain and advanced signal processing technique such as CWT method have been used to predict the tool conditions.

2. Signal Processing Technique

2.1 Time and Frequency Domain Analysis

Time domain plot helps to examine the amplitude and phase information of the vibration signal to determine the failure/defect of any rotating machinery system. Fault diagnosis using time series response is a difficult task. Fourier transform (FT) is the most widely used technique in vibration signal analysis. It converts given signal from time domain to frequency domain by integrating the given function over the entire time period. Fourier transform for the angular frequency $\omega = 2\pi f$ and time ‘t’ is given by,

$$X(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} \, dt$$  \hspace{1cm} (1)

Where $X(\omega)$ is the Fourier transform of the signal $x(t)$. FT technique earned much of its importance in processing stationary signal. Fast Fourier transform (FFT) is one of the extension of FT (Vernekar et al., 2014).

In milling process, one of the reasons for vibration of the cutting tool is due to variation in the cutting force. This cutting force signal is periodic and its variation frequency is tooth passing frequency (TPF), which depends on spindle rotating frequency ($f_s$) and number of teeth in the cutting tool. Spindle rotating frequency $f_s$ is defined as,

$$f_s = \frac{N}{60} = \frac{1000v}{60\pi D}$$  \hspace{1cm} (2)

where $D$ is the diameter of the mill, $N$ is the spindle speed (in revolutions per minute) and $v$ is linear speed (in meters per minute). TPF is defined as,

$$TPF = N_T \ast f_s = \frac{1000vN_T}{60\pi D}$$  \hspace{1cm} (3)

Where $N_T$ is the teeth numbers of the cutter, while the presence of peaks at additional frequencies represents the chatter. This TPF of milling dynamics is often used for detection of the
chatter (Huang et al., 2013).

2.2 Cepstrum Analysis

A cepstrum is considered as forward Fourier transformation of the logarithm of a spectrum. It is therefore defined as the spectrum of a spectrum. The cepstrum was originally referred as the power spectrum of the logarithmic power spectrum. Thus, the calculation of cepstrum involves the inverse Fourier transform of the natural logarithm of a spectrum (Randall, 1982). Given a real signal $x(n)$, cepstrum form can be expressed as follows. The real cepstrum of a signal $x(n)$ (Hasegawa, 2000):

$$c(n) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \log |X(e^{j\omega})| e^{j\omega n} d\omega$$

(4)

Where $n$ is cepstral ‘lag’, if $x(n)$ is real, then $\log|X(e^{j\omega})|$ is even. Cepstrum reveals the periodicity in frequency domain usually as results of modulation. Fig. 1 depicts relationship between spectrum and cepstrum.

![Fig. 1. The relationship between a spectrum and a cepstrum](image)

2.3 Wavelet Analysis

The Fourier transform is not suitable for analyzing non-stationary signals since it fails to reveal the frequency content of a signal at a particular time. In signal processing, the limitation of FT led to the introduction of new time-frequency analysis called wavelet transform (WT) (Vernekar et al., 2014).

Generally, conventional data processing is computed in time or frequency domain. Wavelet processing method combines both time and frequency informations. Wavelet analysis is one of the ‘time-frequency’ analysis. A wavelet is a basis function characterized by two aspects; first is its shape and amplitude, which is chosen by the user; second is its scale (frequency) and time (location) relative to the signal.
The continuous wavelet transform can be used to generate spectrograms which show the frequency content of signals as a function of time. A continuous-time wavelet transform of \( x(t) \) is defined as,

\[
\text{CWT} \ x_\psi(a,b) = \frac{1}{|a|} \int_{-\infty}^{\infty} x(t) \psi^* \left( \frac{t-b}{a} \right) \, dt, \quad \{a,b \in R, a \neq 0\} \tag{5}
\]

In the above equation (5), \( \psi(t) \) is a continuous wavelet function in time domain as well as the frequency domain called the mother wavelet and \( \psi^*(t) \) indicates complex conjugate of the analyzing wavelet \( \psi(t) \). The parameter ‘\( a \)’ is termed as scaling parameter and ‘\( b \)’ is the translation parameter. The transformed signal \( X_\psi(a,b) \) is a function of the translation parameter ‘\( b \)’ and the scale parameter ‘\( a \)’. In WT, signal energy is normalized by dividing the wavelet coefficients by \( \frac{1}{|a|} \) at each scale.

**Morlet Wavelet**

The Morlet wavelet transform belongs to CWT family. It is one of the most popular wavelet used in practice and its mother wavelet is given by,

\[
\psi(t) = \frac{1}{\sqrt{\pi}} \left( e^{jw_0t} - e^{-\frac{w_0^2}{2}} \right) e^{-\frac{t^2}{2}} \tag{6}
\]

In the above equation (6), \( w_0 \) refers to central frequency of the mother wavelet. The term \( e^{-\frac{w_0^2}{2}} \) involved in the equation is specifically used for correcting the non-zero mean of the complex sinusoid and in most cases, it can be negligible when \( w_0 > 5 \). Therefore, when the central frequency \( w_0 > 5 \), the mother wavelet can be redefined as follows (Vernekar et al., 2014);

\[
\psi(t) = \frac{1}{\sqrt{\pi}} e^{jw_0t} \, e^{-\frac{t^2}{2}} \tag{7}
\]

### 3. Experimental Setup

Experiments were carried out using universal milling machine with machining parameters recommended by Mitsubishi as mentioned in Table 1. Experimental setup consists of universal milling machine with data acquisition system as shown in Fig. 2. Face milling cutter with 3 carbide inserts (Mitsubishi make: SEMT13T3AGSN- VP15TF) of 80 mm diameter and work-piece material of AISI H13 steel were used in this work.
Fig. 2. Experimental setup

Table 1 Experimental condition of face milling process

<table>
<thead>
<tr>
<th>Experimental Condition</th>
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<tbody>
<tr>
<td>Work material</td>
</tr>
<tr>
<td>Insert material</td>
</tr>
<tr>
<td>Cutting speed</td>
</tr>
<tr>
<td>Feed rate</td>
</tr>
<tr>
<td>Depth of cut</td>
</tr>
<tr>
<td>Faulty conditions of the tool</td>
</tr>
<tr>
<td>Lubrication</td>
</tr>
</tbody>
</table>

Experiments were conducted with four different conditions of the tool (Fig. 3), out of which one is healthy and three fault conditions, namely;

a) Healthy tool [Fig. 3(a)]
b) Flank wear (one insert) [Fig. 3(b)]
c) Chipping on rake face (one insert) [Fig. 3(c)]
d) Tip breakage (one insert) [Fig. 3(d)]
In healthy condition (Fig. 3a) of the tool, all three inserts are new/unworn inserts, whereas in faulty condition of the tool, one out of three inserts is either flank wear or chipping or breakage (Fig. 3b or 3c or 3d) condition has been considered for analysis.

**Fig. 3.** Different conditions of face milling tool insert

**Fig. 4.** Schematic representation of condition monitoring of face milling cutter. Vibrational signals were acquired using tri-axial piezoelectric accelerometer (YMC145A100) which
was mounted on spindle housing. Data acquisition system (National Instruments DAQ 9234) was used to acquire the acceleration signals from the sensor with sampling frequency of 5 kHz and these signals were then processed by LabVIEW software and data was saved. Initially, rough machining was carried out with few passes to remove the oxidized layer and unevenness of the work-piece. The process was kept running for two or three minutes to stabilize the machine vibration before starting data acquisition. The procedure for fault detection of face milling tool using different signal processing techniques is as shown in Fig. 4.

4. Results and Discussion

4.1 Time-Domain Analysis

Fig. 5. Time-series plots of (a) healthy, (b) flank wear, (c) chipping and (d) breakage face milling tool conditions
The acceleration signals were acquired for healthy and different faulty conditions of the tool. Fig. 5 shows the time-series plots in feed direction for different conditions (healthy, flank wear, chipping and breakage) of the milling tool. In time domain analysis, slight variations in amplitude of vibration patterns is observed, but it is very difficult to recognize the different condition of the tool. It means time domain analysis does not give sufficient information about tool condition.

4.2 Spectrum Analysis

The experimental results of spectrum for different condition of the tool are shown in Fig. 6. From spectrum plot, under normal cutting condition in a milling process, the dominant frequency components in the spectrum graph are around the spindle rotating frequency (f_s), tooth passing frequency (TPF) and their harmonics (Orhan et al., 2007).
(b) Flank wear

\[ x: 810 \text{ Hz} \]
\[ y: 0.1 \text{ g} \]

(c) Chipping

\[ x: 810 \text{ Hz} \]
\[ y: 0.125 \text{ g} \]
Table 2 Characteristic vibration frequency of spindle speed running at 300 rpm.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle frequency ($f_s$)</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Tooth pass frequency (TPF)</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Total number of inserts in milling tool</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2 shows the characteristic vibration frequency of milling process with spindle speed running at 300 rpm. Tooth pass frequency for the given spindle speed and tool inserts is about 15 Hz. It can be noticed from spectrum plot that along with tooth pass frequency and its harmonics (1x, 2x, 3x,...etc), few peaks corresponding to chatter are also present. Figs. 6 (a) and (b) show the spectrum of healthy and flank wear conditions of the tool respectively, 54th multiple of tooth passing frequency (810 Hz) shows the dominancy among all other harmonics. The corresponding acceleration amplitude of 54th multiple of TPF is about 0.1 m/s$^2$. This signifies the presence of fault in the milling tool. The increase in the amplitude level of same frequency (54th multiple of TPF) with increase in severity of fault (chipping) can be visualized in spectrum as illustrated in Fig. 6(c).
magnitude of acceleration is increased from 0.1 to 0.125 m/s², which signifies the increase of fault level in the milling tool. Also for breakage condition, 54th TPF is the dominant frequency among all TPF harmonics. It might be evident that, 54th multiple of TPF coincides with the natural frequency (810 Hz) of tool-workpiece material structure. The cepstrum analysis has been carried out in order to recognize the tool conditions and also to validate the results of spectrum analysis.

4.3 Cepstrum Analysis

The cepstrum plots of face milling tool under different conditions (healthy, flank wear, chipping and breakage) are as shown in Fig. 7. As discussed in spectrum analysis, the dominant peak corresponding to 810 Hz (54th multiple of TPF) is the defect frequency. In cepstrum analysis, the defect frequency is called as defect quefrency of about 0.0012s (1/810Hz) which shows the variation in amplitude of acceleration for different conditions of the tool. Fig. 7(a) shows the cepstrum plot of a healthy tool where the acceleration of dominant peak at quefrency (0.0012s) is about 0.015 m/s² which is to be considered as a reference margin for fault detection. As the faults (flank wear, chipping and breakage) are introduced into the milling tool, the acceleration value at defect quefrency (0.0012s) is increased. In case of flank wear condition (Fig. 7(b)), 54th multiples of tooth passing quefrency (0.0012s) has the acceleration of about 0.031 m/s², which implies the presence of faults in the milling tool. For chipping condition (Fig. 7(c)), the acceleration value at quefrency (0.0012s) is about 0.04 m/s², which signifies the increase in the level of faults during milling process. In case of breakage tool condition, the acceleration at defect quefrency is about 0.035 m/s² as shown in Fig. 7(d).

From the above discussion of spectrum and cepstrum analyses of the face milling tool, it can be visualized that even with the presence of defect in the tool, it is quite difficult to identify the particular time at which the defect frequency/quefrency is being attained and it requires time-frequency domain analysis. Wavelet analysis demonstrates both time and frequency domains, meaning that it generates frequency content signals as a function of time.
Fig. 7. Cepstrum plots (a) healthy, (b) flank wear, (c) chipping and (d) breakage conditions.
4.4 Wavelet Analysis

Fig. 8 illustrates CWT plots of the milling machine spindle vibration with healthy and fault conditions of the face milling tool.
From Fig. 8, one can say that for the given time period (one second) there is some variation in intensity of high frequency band at 810 Hz, as the faults occur in the milling tool. The presence of high-frequency component at 810 Hz (54th multiple of TPF) which is one of the harmonics of TPF. Fig. 8 (a) depicts the CWT plot of healthy condition as a reference margin for fault detection. As the faults such as flank wear, chipping and breakage occur in milling tool, intensity of the high frequency (810 Hz) band has been increased as shown in Fig. 8(b), (c) and (d). This variations in intensity of high frequency band indicate the fault existence in milling tool.

5. Conclusion

In this paper, signal processing techniques such as spectrum analysis, cepstrum analysis and CWT were used to analyze the vibration signals under healthy and faulty conditions for identifying the faults in face milling tool. As seen from the plots of spectrum, cepstrum and CWT techniques, as the severity of fault increases, there is a dominant peak at 54th multiples of TPF and it nearly coincides with the natural frequency (about 810 Hz) of tool-workpiece material structure. This signifies the faults occurring in milling tool for the given workpiece material and process condition. Based on the experimental results, following conclusions are drawn.

- Time-series plots provide insufficient diagnostic information in vibration signals of different tool condition.
- Spectrum plots are used to detect faults in milling tool, it only gives information about frequency component of vibration signals as a dominant peak and does not provide time information about faults.
- In cepstrum plots, it is very much useful to assess defect quefrency of milling tool and it was observed that amplitude of this quefrency varies with the increase in fault level.
- CWT plots with vibration signals provide enough information about faults in milling tool in
both time and frequency domain. Based on the results obtained, it can be judged that cepstrum and CWT are recommended for practical applications in fault detection of the face milling tool.

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