Chatter Identification in End Milling Process Based on Cutting Force Signal Processing

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Abstract. During milling process, chatter is one of the major limitations of productivity, it has more negative effects on the surface finish, dimensional accuracy and tool life. It is thus necessary to detect and avoid chatter occurrence. In this study, a chatter detection approach based on cutting force signal is presented. The milling force signals were measured by cutting force sensor and then analyzed by using time-frequency analysis approaches such as short-time Fourier transform (STFT) and continuous wavelet transform (CWT) in order to identify chatter. The different sets of cutting conditions were utilized to recognize chatter presence. The spectrogram and scalogram results of the force signals represented a great difference in frequency content between stable and unstable cuttings. The analysis results were then validated by cutting force behavior in the time domain.

1. Introduction

Machine tool chatter is a self-excited vibration that causes machining instability, it results in reduced surface quality and increased tool wear during cutting process [1, 2]. Chatter detection is therefore very important to obtain stable cutting parameters such as feed rate, spindle speed, and depth of cut (DOC). A stability lobe diagram could be a useful way to predict chatter [3]. However, the stability lobe diagram would inevitably misinterpret the important features of nonlinear vibration because most cutting processes contain rich nonlinear characteristics, and the linear approximation [4]. It is therefore necessary to analyze the signal in time-frequency domain.

In order to distinguish chatter occurrence, some machining process signals have to be measured by using different techniques such as in-process real-time techniques based on force and displacement signals or off-line machined surface characterization [5]. The Fourier transform (FT) is widely used to transform time-domain signal into frequency domain signal and it is reportedly suitable for the stationary signal process, especially when the feature components of signals are obvious in magnitude [6]. For non-stationary signal, the wavelet transform as a flexible method is suitable for detection of a sudden frequency change in a signal [7]. Chatter is associated with amplitude modulation and an increase in the signal energy due to the high variation in the cutting force compared with chatter free conditions [8, 9]. There are a lot of studies using fast Fourier transform (FFT) to detect cutting chatter, this method is well known as a standard method for observing signals in the frequency domain [10]. Based on the Fourier transform analysis, the FFT is the main method that can produce an acceptable discrete spectrum analysis transferring from the time domain to the frequency domain. Schmitz et al., 2002 utilized FFT of the once per revolution sampled audio signal in milling to identify chatter [11].
Huang P et al., 2013 used the cutting force signal to detect chatter in milling operations. Based on Fourier transform, chatter can be ascertained and the chatter frequency can be obtained [12]. For nonstationary signal, the wavelet process gives better resolution capabilities in both time and frequency domain which is advantageous in the analysis of non-stationary time series arising in metal cutting [13]. To detect cutting chatter via force sensors based on wavelet transform, the cutting force signals are decomposed into a set of approximation coefficient and detail coefficients. The former is a low-frequency component, and the latter is high-frequency components of the signal that is called multilevel signal decomposition [14]. Khraisheh et al. reported that the WT can clearly define the boundary between the transient and the steady-state. By using the wavelet transform to determine the local dominant frequencies, system parameters can be accurately estimated [15]. The decomposition signals of cutting force can be obtained using the wavelet transform, and the abrupt changing amplitude of the decomposed signals can be seen as valid evidence to assess whether chatter occurred [7].

The present work focuses on the indirect approach to detect chatter in milling. For this approach, the tool conditions are not captured directly but estimated from the measurable signal feature. The milling force signals in the direction perpendicular to the machined surface were analyzed through time-frequency analysis. By conducting experiments with different cutting conditions, the effects of spindle speed, feed rates and depth of cut on milling stability were studied. The differentiation between various cutting states was made on the basis of qualitative features of fast Fourier transform, short-time Fourier transform, and CTW based on time-frequency plots. The cutting force behavior in the time-domain was utilized to validate the analysis result.

2. Signal analysis approaches

Figure 1 represents the flowchart of the utilized signal analysis approaches used to determine the presence of chatter. These methods used for evaluating the vibration signals involved in the transformation of the cutting force signals from time to frequency domain are Fast Fourier Transform (FFT), Short-Time Fourier Transform (STFT), and Continuous Wavelet Transform (CWT). Through these methods, it was possible to view properties or characteristic information of the cutting process hidden in the time domain [6]. Fast Fourier transform. The Fourier transform (FT) transforms the signal $x(t)$ from the time domain to the frequency domain $\hat{x}(\omega)$ described in Eq. (1).

$$\hat{x}(\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t} dt$$

Short-Time Fourier transform could overcome the limitation of FFT as mentioned previously, Gabor introduced a sliding window function to the FT and obtained a localized time-frequency [10] described in Eq. (2), where $g(t)$ is window function, $\phi_{\tau,\omega}$ is a complex function representing the phase and magnitude of the signal over time and frequency.

$$\left[ x(t) \phi_{\tau,\omega} \right] = \int_{-\infty}^{\infty} x(t) (t-\tau) e^{-j\omega t} dt$$

Wavelet is advantageous in the analysis of non-stationary time series arising in metal cutting due to its better resolution in both time and frequency domain, according to Burger et al. [13]. CWT of the signal $x(t)$ is defined by Eq. (3), in which $u$ is the position parameter of wavelet; $s$ is the function scale parameter of wavelet function, $s, u \in \mathbb{R}, s > 0$; $W_{\psi}$ is wavelet function, and $\omega(t)$ is scale function. The scale parameter could be converted to their frequency counterpart in the scalogram [16].

$$W_{\psi}x(s,u) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t) \psi \left( \frac{t-u}{s} \right) dt$$

Finally, the sampled once per revolution cutting force signal was used to verify the results of the chatter detection methods.
3. Experimental Setup
To investigate the proposed methodology for chatter identification, end-milling experiments were conducted using a 3-axis CNC milling. Al6061-T6 rectangular workpiece with dimensions 30mm x 30mm x 40mm was used to conduct the experiments. A carbide end mill cutter with a diameter of 12 mm, helix angle of 26 and two flutes was utilized. The cutting force signals were measured by a Kistler dynamometer (type 9129AA) mounted between the workpiece and workbench. The whole experimental setup is shown in Figure 2. A series of end milling experiments were conducted considering four different cutting conditions shown in Table 1. Then the cutting force signals in the feed direction were measured.

![Figure 2. Experimental setup](image-url)
Table 1. Cutting parameter for chatter tests.

| Cutting parameters | Case 1 | Case 2 | Case 3 | Case 4 |
|--------------------|--------|--------|--------|--------|
| Spindle speed (rpm)| 4500   | 4500   | 2500   | 2500   |
| Depth of cut (mm)  | 0.8    | 1.4    | 1.0    | 1.0    |
| Feed rate (mm/min)| 150    | 150    | 100    | 250    |

4. Results and discussions

Figure 3 shows the force spectrum plot after applying Fast Fourier Transform on the cutting force data. In the first case, Figure 3(a), shows the tooth passing frequency of 150 Hz and its harmonics. It should be noted that the tool passing and their harmonics are expected to be present in the force spectrum. There are no peaks beyond the frequency corresponding to the first or higher-order modes which are a typical chatter signature indicating that the process is stable. There are no (side lobes) disturbances near the natural frequencies of the tool i.e. 75 Hz, 150 Hz, and 225 Hz. Figure 3(b), however, shows the cutting force in the feed direction in the frequency-domain at 4500 rpm and 1.4 mm depth of cut (case 2). It is clearly noted that there are high peaks (between 4000 and 5000 Hz) beyond the tooth passing frequencies and their harmonics (natural frequencies) which signifies unstable condition thereby indicating the presences of chatter. The spectrum of the signal in case 3 is similar to case 1, in which it represents the tooth passing frequency of 83.3 Hz and its harmonics. The presence of chatter in Figure 3(d) can also be seen from the presences of disturbances near the natural frequencies.

However, it is not clear to define those frequencies whether they belong to chatter frequency. The Fourier-based methods are nonetheless based on the assumption that the analyzed signal is stationary in the time domain. The globally inclusive of information makes it difficult to provide any information about the individual frequency event of the signal. It is accordingly not suitable for many non-stationary systems when their transient responses are analyzed.

In this study, the Hanning window is used in the modeling of STFT, the spectrogram results are illustrated in Figure 4. Figure 4(a) shows that the process is chatter free since the frequency domain only shows the tooth passing frequencies at 175 Hz and their fundamental frequencies. The increase of the depth of cut from 0.8 mm to 1.4 mm resulted in the occurrence of chatter as shown in Figure 4(b). This effect of depth of cut can be explained by the high energy signal at approximately 4000 Hz. When different feed rate is used, the signal is scattered when feed is 250 mm/min as shown in Figure 4(d), this clearly supports the results found above by using the FFT. For the STFT approach, even though the Hanning window was applied with the appropriate length for getting better resolution, the
time resolution is still not really good in the time-domain. Furthermore, this analysis method takes a lot of time to simulate, and it is still difficult to detect unsteady changes quickly and accurately. Therefore, STFT analysis is unsuitable for real-time recognition of chatter vibrations. As mentioned, the limitation of the STFT approach can be solved by using the continuous wavelet to efficiently determine the signal frequency and exact time when chatter occurs.

Figure 4. STFT of force signals: (a) case 1, (b) case 2, (c) case 3 and (d) case 4.

Figure 5. CWT of force signals of (a) case 1, (b) case 2, (c) case 3 and (d) case 4.
The scalogram results of the continuous wavelet transform applied on force signals for four cases are illustrated in Figure 5. The tooth passing frequency, or fundamental frequency, is clearly shown at 175 Hz in the CWT 2-D contour shown in Figure 5(a). It is observed that there is no dominant frequency so far from those frequencies. On the other hand, as the depth of cut is increased, the wavelet contour in Figure 5(b) indicates an unstable cutting behavior, which has a set of high frequencies oscillating around 4000 Hz and a tooth passing frequency of 175 Hz. The high frequencies around 4000 Hz could be defined as chatter frequencies caused by the interaction between the cutting tool and the workpiece. These high chatter frequencies are generated by the regenerative effect; that is, multiple cutting behaviors happening within one single cut due to the surface waviness on the workpiece. Even though the depth of cut has a strong influence on the generation of chatter, the results show that the change in feed rate significantly affects the signal. Using identical depth of cut of 1 mm and different feed rate of 100 mm/min and 250 mm/min, as depicted in Figure 5(d) machining process instability is clearly shown by the presences of the scattered signals around the natural frequencies.

5. Verification of chatter detection method

The behavior of once per revolution sampled cutting force signal could be used to analyze the behavior of stable and unstable signals in time-domain. In this study, standard deviation values of once-per-revolution sampled cutting force data can be used to indicate a difference between stable and unstable cases. Figure 6(a) and (c) represent the once-per-revolution sampled cutting force data of case 1 and 3 respectively. Both of them show the repetitive behavior from one to the next revolution with small values of standard deviation illustrated in Table 2. Evidently, this behavior indicates maintained stable operation. On the other hand, sampled force data in Figure 6(b) and (d) show different behavior with the quasi-periodic, as a result of increasing the standard deviation values in both cases shown in Table 2. This demonstrates unstable behaviors in case 2 and 4. All the analyses in time domain using once-per-revolution sampled cutting force technique are also in good accord with the results obtained from the proposed time-frequency approach.

![Sampled force data in time domain: (a) case 1, (b) case 2, (c) case 3 and (d) case 4 ("+" once-per-revolution sampled cutting force).](image)

| Table 2. Standard deviation values. |
|-------------------------------|
| Case 1 | Case 2 | Case 3 | Case 4 |
| 0.7824 | 10.8110 | 0.9367 | 25.8462 |
6. Conclusions
In this study, the chatter vibration was detected in-process for the milling force signals. Different approaches were utilized for signal processing such as Fourier transform, short-time Fourier transform and continuous wavelet transform to detect the chatter. It can be concluded that the frequency content of the force signals on spectrogram and scalogram are much different between stable and unstable cuttings. The results from STFT and CWT analysis shows that chatter occurs at high frequency, beyond tooth passing frequency with high magnitudes. The feed rate was found to be the critical parameters which may drive the system into chaotic behavior. This was evidenced by exciting low and high frequencies well below and above the natural and harmonic frequencies. The frequency information contained in the wavelet transform describes the dynamic behavior of the system at the local time during the milling process. Thus, the CWT is recommended to use as a strategy not only for detecting the presence of chatter but also for an in-process control system.

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