Application of the Discrete Wavelet Transform to the Monitoring of Tool Failure in End Milling Using the Spindle Motor Current

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The paper presents an application of the discrete wavelet transform to the monitoring of tool failure in end milling operations using the spindle motor current. The discrete wavelet transform performs a multilevel signal decomposition to extract the tool failure feature from the spindle motor current. Experimental results have shown that tool failure in end milling operations can be clearly detected even under varying cutting conditions.

Keywords: Discrete wavelet transform; End milling; Spindle motor current; Tool failure

1. Introduction

Monitoring of tool failure in end milling operations is a necessary step toward the full automation of milling operations. To monitor tool failure successfully, the selection of an appropriate signal and signal processing algorithm is very important. In the literature, several signals in a milling operation have been considered to monitor tool failure, for example, cutting force [1,2], torque [3], vibration [4], acoustic emission [5], and spindle motor current [6,7]. In this paper, the use of spindle motor current as a sensing signal to monitor tool failure has been studied. This is because the spindle motor system is already built into machine tools and therefore the cost of sensor investment can be greatly reduced. In addition, the mounting of the sensor does not interfere with the operation of machine tools. On the other hand, the spindle motor current signal may not be as sensitive to the occurrence of tool failure, owing to the limited bandwidth of the spindle motor system. However, the response time for tool failure is still acceptable based on this study.

To extract the tool failure feature from the spindle motor current signal, a fast and reliable signal processing technique is required. In the past, various signal processing techniques in the time domain or in the frequency domain have been considered [2]. However, it is a great advantage to be able to develop a signal processing technique which can combine the tool failure feature in the time domain with the tool failure feature in the frequency domain. In this paper, the discrete wavelet transform, a relatively new tool for signal processing [8,9] has been considered to solve this task. The discrete wavelet transform can decompose a signal into the approximation and detail of the signal. The approximation is the low-frequency components of the signal and the detail is the high-frequency components of the signal. This decomposition process can be iterated so that one signal can be broken down into a hierarchical set of approximations and details, that can also be called a multilevel signal decomposition [10]. As a result, the tool failure feature in the time and frequency domains can be simultaneously obtained through multilevel signal decomposition. In this paper, a four-level wavelet decomposition of the spindle motor current signal is derived. The results of the level-four decomposition are used to monitor tool failure in the end milling operation. Experimental results have shown that tool failure in milling can be clearly detected by using this approach.

In what follows, the measurement of spindle motor current in end milling operations is discussed first. Then, the discrete wavelet transform is introduced to perform a multilevel signal decomposition of the spindle motor current. Experimental verification of the developed method for the monitoring of tool failure is shown. The paper concludes with a summary of this study.

2. Spindle Motor Current Measurement

The most often used type of spindle motor in the machine tool industry is an induction motor [11]. Basically, the induction motor consists of two components: a stationary stator and a rotating rotor. The rotor is separated from the stator by a small air gap. A three-phase set of voltages is applied to the stator causing a three-phase set of currents to flow. These currents produce a rotating magnetic field to drag the spindle
along in the direction of the rotating magnetic field. The torque developed by the induction motor is proportional to the square of the stator current of the induction motor \([12]\). It is known that the occurrence of tool failure will cause an excessive cutting force acting on the cutting edge. A large variation of the torque developed by the induction motor is then unavoidable owing to the excessive cutting force. Therefore, the stator current of the motor is considered as the sensing signal for the monitoring of tool failure in end milling in this paper.

In the experiments, a three-phase four-pole induction spindle motor (Fanuc 6S) was installed in the machining centre for the machining of an S45C steel workpiece using an end mill. For the induction motor, the stator current signal per phase is an a.c. signal at the supply frequency and has the same peak-to-peak amplitude but is displaced in time by the phase angle of \(120^\circ\). Therefore, only one of the stator current signals was measured by a current-to-voltage (C/V) sensor (LEM Module LA50-P) and recorded on a PC workstation through a data acquisition board (DT2828) with a sampling rate of 300 Hz. The frequency of the stator current \(f\) can be expressed as:

\[
f = \frac{Np}{120}
\]

where \(N\) is the synchronous speed (r.p.m.) which is almost equal to the spindle speed and \(p\) is the number of poles per phase.

To perform the sensitivity analysis for the frequency of the stator current, a dynamometer (Kistler 9265A2) was mounted under the workpiece. The dynamometer signal was transmitted through a charge amplifier (Kistler 5007) from which the cutting force signal was obtained and also recorded on the PC workstation. The transfer function between the square of the stator current and the cutting force is shown in Fig. 1. The transfer function indicates the frequency response of the square of the stator current of the induction motor \([12]\). It is known that a Fourier transform is a useful signal processing tool for transforming a signal from the time domain to the frequency domain. Based on the Fourier transform, a signal \(f(t)\) can be decomposed into a family of complex sinusoids \(e^{j\omega t}\) as basis functions and the coefficients \(F(j\omega)\) represent the amplitudes of complex sinusoids \(e^{j\omega t}\) in the signal \(f(t)\).

Therefore, the Fourier transform of the signal \(f(t)\) is defined as:

\[
F(j\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} \, dt
\]

However, the Fourier transform has an inherent drawback. Non-stationary transient information in the time domain cannot be clearly identified in the frequency domain after using the Fourier transform. As a result, it is very difficult to tell when a particular event (for example, tool failure) takes place from the frequency domain. To correct this deficiency, a windowing technique has been applied to the Fourier transform for a small section of the signal at a time, that is also called the short-time Fourier transform. However, the precision of the short-time Fourier transform is still limited and is greatly dependent on the size of the window. In recent years, a more flexible approach, called the wavelet transform, has been developed to decompose the signal \(f(t)\) into various components at different time windows and frequency bands using a family of wavelets as basis functions.

The wavelet transform of the signal \(f(t)\) is defined as the sum, over all time, of the signal \(f(t)\) multiplied by a scaled and shifted version of the wavelet function \(\psi(t)\). The coefficients \(C(a,b)\) of the wavelet transform of the signal \(f(t)\) can be expressed as:

\[
C(a,b) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \, dt
\]

where \(a\) and \(b\) are the scaling and shifting parameters in the wavelet transform.

Basically, a small scaling parameter corresponds to a compressed wavelet function. As a result, the rapidly changing features in the signal \(f(t)\), i.e. the high-frequency components, can be obtained from the wavelet transform by using a small scaling parameter. On the other hand, low-frequency features in the signal \(f(t)\) can be extracted by using a large scaling parameter with a stretched wavelet function. To summarise, a small scaling value is used for local analysis; a large scaling value is used for global analysis.

For a digital signal \(f(k), \ k = 0,1,2,\ldots\), the discrete wavelet transform can be used. The most commonly used discrete