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Early milling chatter identification by improved empirical mode decomposition and multi-indicator synthetic evaluation

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A B S T R A C T

Chatter is a kind of self-excited vibration which reflects changes of frequency and energy distribution in machining process and it always leads to poor surface quality of the materials. An effective early chatter identification method is necessary to avoid the damage caused by chatter. The key technique of chatter identification is to capture the feature signatures. In this paper, the characteristics of milling chatter signal is analyzed in details in the aspect of time-frequency domain and morphological feature. An intelligent early chatter identification method which based on the improved empirical mode decomposition (EMD) and multi-indicator synthetic evaluation is proposed in this paper. The acceleration signal is decomposed into a series of intrinsic mode functions (IMFs) by the improved EMD, and then the IMFs which contain the chatter information are selected to reconstruct a new signal, then a three-dimensional characteristic vector which based on the multi-indicators (i.e., the standard deviation, power spectral entropy and fractal dimension of the new signal) is constructed for chatter identification. A support vector machine chatter identification model is obtained based on the multi-indicators. The results of milling experiment show that the proposed chatter identification method can recognize early milling chatter effectively.

1. Introduction

Milling chatter is a major hindrance for high surface quality and it will reduce the tool and spindle life. If the early chatter stage is identified and controlled as soon as possible, the damage of workpiece can be avoided timely. In recent years, lots of methods have been proposed to avoid chatter. Quintana and Ciurana [1] pointed out that regenerative chatter is the most common phenomenon in milling process. Based on the regenerative chatter model, Altintas and Budak [2] proposed an

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analytical prediction method to obtain the stability lobes diagrams (SLD) in frequency domain, and the SLD was applied to select the chatter-free cutting parameters. Butcher et al. [3] presented a new technique for studying the stability properties of dynamic systems modeled by delay-differential equations (DDEs) with time-periodic parameters. Ding et al. [4] proposed a full-discretization method (FDM) which based on the direct integration scheme to predict the milling stability. Stepan [5] and his co-workers [6,7] did a tremendous work on chatter prediction by solving the periodic delay-differential equations. To avoid milling chatter, Wang [8] developed nonlinear tuned mass damper (TMD) to suppress machining chatter, the results show that the appropriately designed nonlinear TMD can improve the critical limiting cutting depth more effectively than the common linear TMD. In addition, the spindle speed variation technique [9] and other semi-active vibration control technique [10] are also applied to suppress the machining vibration. Thin-walled workpiece is easily suffered with distortion and chatter in the milling process due to the low rigidity of itself. It is very important to identify the early chatter of thin-walled parts. Liu et al. [11] proposed a chatter detection method for thin-walled parts by considering the geometry, tool path, and dynamics of the model. For Ti-6Al-4V titanium alloy thin-walled workpieces, Feng et al. [12] proposed a chatter detection method by analyzing the milling force signals in the direction perpendicular to the machined surface.

Recent years, some new methods for avoiding machine chatter of non-traditional machining process have also been proposed. Urbikain et al. [13] proposed a stability model for chatter in interrupted turning when the dominant vibration is orthogonal to the chip section plane, the experiment results show that the proposed model is effective in determining the stability boundary of interrupted turning. Later, Urbikain et al. [14] proposed the frequency analytical method and the Chebyshev Collocation Method (CCM) to determine the stability boundary in heavy-duty turning. The methods mentioned above are mainly passive or semi-active, while due to the time-varying properties of the cutting system, there are still challenges in the aspect of using passive or semi-active methods to prevent the machining chatter.

On-line chatter identification is necessary to suppress chatter for active methods. Some on-line chatter identification methods have been proposed by specialists and scholars. Liu et al. [15] proposed a method to identify the early chatter during gear grinding process, in Liu's method, the feature frequency band signal is selected by the wavelet packet transform. Fu et al. [16] proposed an energy aggregation characteristic-based Hilbert-Huang transform method for online chatter detection. Cao et al. [17] proposed a chatter identification method by combining wavelet packets and Hilbert-Huang transform (HHT). Recently, the method of combining empirical mode decomposition (EMD) and wavelet packets decomposition (WPD) [18], the energy entropy of variational mode decomposition (VMD) and wavelet packet decomposition (WPD) [19] were also proposed by Liu and Zhang, respectively. Ma et al. [20] proposed an active chatter suppression method for turning process by introducing an active sliding mode controller.

The first key technology to avoid chatter is chatter identification. Various signals can be applied to identify chatter, such as acceleration signal [21], sound [22], instantaneous angular speeds [23], torque signal [24], motor current [15,25] and cutting force [26]. Relation of cutting force with position can alter chatter behavior. To estimate the cutting force of sculptured surface machining, Lamikiz et al. [27,28] proposed a method for obtaining the shear and ploughing specific cutting coefficients for a ball-end milling cutting force model. To record the real cutting forces of complex parts, a diagnostic tool which generates spatial maps of the cutting forces for the machining of complex workpieces was proposed by Lopez de Lacalle et al. [29], and three application examples that involved the time reduction, detect problems in the machining of complex parts and thin walls milling were described in their paper.

Chatter is a complex self-excited vibration and the chatter signal is nonlinear and non-stationary. For purposes of dealing with nonlinear and non-stationary signal, Huang et al. [30] proposed a self-adaptive signal analysis method named empirical mode decomposition (EMD). EMD has big advantages over the traditional linear method in analyzing non-linear and non-stationary signals. However, the EMD method also has some limitations. One of the major drawbacks of EMD is mode mixing, not only it could cause serious aliasing in the time-frequency distribution but it could also make the individual IMF loses its physical meaning [31]. Wu and Huang [32] proposed ensemble empirical mode decomposition (EEMD) method to suppress mode mixing. EEMD can suppress mode mixing effectively, but it is time consuming, which is not suitable for real-time signal processing. The fundamental cause of mode mixing is that the process of EMD does not satisfy global orthogonality. In order to eliminate mode mixing, we should make sure that the IMFs are orthogonal to each other. Based on the theory above, Xiao et al. [33] embedded a decorrelation operator into EMD process to suppress mode mixing. Not only this method is effective, but it also consumes less computing time. So this improved EMD method is suitable for processing the signal timely.

When chatter occurs, the frequency and energy distribution in machining process will be changed [34]. For purpose of detecting chatter effectively, we should apply a good evaluation indicator to indicate the machining state. Yeh et al. [35] applied standard deviation to identify chatter, but standard deviation just can reflect the changes of energy distribution, it is difficult to reflect the changes of frequency. Cao et al. [36] identify chatter by power spectral entropy, which can reflect the changes of frequency, while this method cannot indicate the changes of energy. Fractal theory is proposed by Mandelbrot [37] and it can reflect the morphological characteristics of the signal. Fractals are virtual geometrical objects that appear identical regardless of the length scale, which can be characterized by a single parameter—fractal dimension (FD) [38]. Fractal dimension is an important indicator in the aspect of texture segmentation [39], shape classification [40], and graphic analysis [41]. There are four main categories to obtain fractal dimension: the box counting method [42], the variance methods, the spectral methods and the morphological covering method [43]. The morphological covering method is more robust when dealing with discrete signals, because it can yield results that are invariant with respect to shifting the signal's domain or affine scaling of its dynamic range.