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Chatter detection in milling process based on VMD and energy entropy

Changfu Liu, Lida Zhu *, Chenbing Ni

School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China

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ABSTRACT

This paper presents a novel approach to detect the milling chatter based on Variational Mode Decomposition (VMD) and energy entropy. VMD has already been employed in feature extraction from non-stationary signals. The parameters like number of modes (K) and the quadratic penalty (α) need to be selected empirically when raw signal is decomposed by VMD. Aimed at solving the problem how to select K and α, the automatic selection method of VMD's based on kurtosis is proposed in this paper. When chatter occurs in the milling process, energy will be absorbed to chatter frequency bands. To detect the chatter frequency bands automatically, the chatter detection method based on energy entropy is presented. The vibration signal containing chatter frequency is simulated and three groups of experiments which represent three cutting conditions are conducted. To verify the effectiveness of method presented by this paper, chatter feather extraction has been successfully employed on simulation signals and experimental signals. The simulation and experimental results show that the proposed method can effectively detect the chatter.

1. Introduction

To improve material removal rate and reduce cutting force, high speed milling has been widely employed in aerospace industry. But it is difficult to solve the chatter problem in high speed milling, which originates from a self-excited vibration. When chatter occurs, one of modes of cutter-workpiece system is excited by cutting force and so chatter frequency is close to natural frequency of the machine structure [1]. Chatter will reduce surface quality and production efficiency, and also result in tool wear [2,3]. Aimed at chatter problem of manufacturing system, many scholars have put forward many methods which involve chatter stability prediction [4], chatter detection [5], chatter suppression [6] and so on.

Due to intelligence, chatter detection methods become more and more important to achieve high efficiency and high precision machining. For machine operators, chatter stability methods are difficult to be carried out effectively in the actual machining processing. But chatter detection at an early stage allows the machine operator to interfere machining process so that chatter could be avoided in machining process. In recent years, researches using many signal processing methods on chatter detection have been widely done [7,8].

Feature extraction is a key technology in chatter detection. The feature extraction's first concern is how to select suitable signal for different situations. Various signals have been employed to monitor chatter, such as cutting force [9–11], acceleration signal [3,12,13], motor current [14,15], sound signal [16–18], torque signal [19], and vibration signal [20–23] and so on.

* Corresponding author at: School of Mechanical Engineering and Automation, Northeastern University, Shenyang, Liaoning 110819, China.
E-mail address: neulidazhu@163.com (L. Zhu).

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Axinte et al. [24] proposed that vibration signal was sensitive to detect the chatter marks compared to the cutting force and acoustic emission. Kuljanic et al. [25] designed a chatter detection system based on multiple sensors and verified that it was suitable for application in industrial conditions. Three sensors were applied in this research: two accelerometers mounted on the head of the milling machine in the X and Y direction and one accelerometers mounted an axial force sensor Fz. Sun et al. [26] proposed an on-line machining chatter forecast framework. The improved moving average algorithm was proposed in this paper, which was designed to improve the performance of local mean decomposition (LMD) method in dealing with non-stationary force signal and vibration signal.

No matter what kind of signal is employed to detect chatter, the frequency bands which include abundant chatter information all need to be identified accurately before chatter detection. The signal process methods play much more important role in searching the chatter frequency bands. Sanchez et al. [27] presented a state-of-the-art review of articles on signal processing techniques which were used in vibration-based structural health monitoring (SHM). At present, the signal processing methods, mainly including time domain, frequency domain, and time-frequency domain, have been employed to extract feature. Among them, the time-frequency domain method has been widely taken due to which can locate time and frequency [28,29], such as short Time Fourier Transform (STFT), Wavelet Transform (WT), Wavelet Packet Transform (WPT), Synchronous Compression wavelet (SSWT), Empirical Wavelet Transform (EWT) [30] et al. [31,32]. In 1998, Norden E. Huang (Huang E: China Taiwan oceanologist) et al. put forward Empirical Modes Decomposition (EMD) and Ensemble Empirical Mode Decomposition (EEMD) method which were a new time-frequency methods and have been widely introduced into the signal process [33,34]. LMD, which was based on EMD, was proposed by Smith in 2005. But all methods, which were based on EMD, need to strengthen their theoretical basis. This point limit their application due to EMD's unreliable theoretical basis. Although EMD can effectively decompose the non-stationary signal using sum of Amplitude-Modulated-Frequency-Modulated (AM-FM) signal, EMD cannot be analyzed from the theory and performance evaluation. So it is very difficult to define the EMD in algorithm aspect.

VMD was put forward by Dragomiretskiy in 2014 [35], which has solid theoretical basis. Indeed, this method is a generalization of the classic Wiener filter into multiple, adaptive bands. The proposed model is much more robust to sampling and noise. Ref. [36] showed VMD was a new developed technique for adaptive signal decomposition, which could non-recursively decompose a multi-component signal into a number of quasi-orthogonal IMFs. A comparison in this paper had also been conducted to evaluate the effectiveness of identifying the rubbing-caused signatures by using VMD, empirical wavelet transform (EWT), EEMD and EMD. The analysis results of the rubbing signals showed that the multiple features could be better extracted with the VMD. The extracted feature vectors, which have large dimension, were constructed using VMD in Ref. [37]. The results showed that the extracted features had the best detection accuracy. The classification of power quality disturbances, which was based on VMD and EWT, was considered by Aneesh [38]. Classification results combining SVM showed that VMD outperformed over EWT for feature extraction process and the classification accuracy. In summary, VMD has been widely used in feature extraction, but seldom used in chatter feature extraction. Although VMD has solid theoretical basis and its decomposition result is good, some parameters such as K and α which has a significant influence on VMD still rely on the experience at the moment. So a novel method to select automatically K and α based on kurtosis is proposed in this paper.

In the milling process, energy in each frequency band is different and changes with milling conditions [29]. So it is reasonable that energy entropy is used to represent cutting conditions in the milling. Similarly, EMD's energy entropy was proposed to identify roller bearing fault patterns by Yu et al. [21]. They verified that the diagnosis approach based on neural network by using EMD to extract the energy of different frequency bands as features could identify roller bearing fault patterns accurately and effectively and was superior to that based on wavelet packet decomposition and reconstruction. VMD is a strong tool to deal with non-stationary signals such as roller bearing signal and milling signal. Zhang et al. [39] presented a approach to detect the milling chatter based on energy entropy of VMD and WPT. The results showed that the energy entropy had an excellent performance for chatter premonition identification. However, the whole signal's energy entropy was extracted as the chatter indicator in this paper. To improve the sensitivity to the chatter, a novel chatter detection method of combining VMD and energy entropy is proposed in our paper, in which one IMF's energy entropy is extracted as the chatter indicator.

So the automatic selection method of VMD's parameters is firstly proposed to solve the selection of K and α. After IMFs are obtained by VMD, the chatter feature extraction method based on the largest energy entropy is proposed to find out the most suitable indicator for the chatter. The remaining section of this paper is organized as follows: Section 2 describes about the theoretical basis of VMD and energy entropy. In Section 3, the novel approach to detect the milling chatter based on VMD and energy entropy is described. In Section 4, the simulation signal is introduced to verify the effectiveness of method proposed in this paper. Section 5 presents the experimental component including setting up experimental platform and discussing the result. Some conclusions are obtained in Section 6.

2. Establishment of the theoretical model

2.1. Mathematical model of VMD

The goal of VMD is to decompose a real valued input signal into a discrete number of sub-signals (modes), r_k, that have specific sparsity properties while reproducing the input [35]. The sparsity prior of each mode is chosen to be its bandwidth in