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A novel approach to machining condition monitoring of deep hole boring

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ABSTRACT

In the optimization of deep hole boring processes, machining condition monitoring (MCM) plays an important role for efficient tool change policies, product quality control and lower tool costs. This paper proposes a novel approach to the MCM of deep hole boring on the basis of the pseudo non-dyadic second generation wavelet transform (PNSGWT). This approach is developed via constructing a valuable indicator, i.e., the wavelet energy ratio around the natural frequency of boring bar. Self-excited vibration occurs at the frequency of the most dominant mode of the machine tool structure. Via modeling dynamic cutting process and performing its simulation analysis during deep hole boring, it is found that the vibration amplitudes at the nature frequency of the machine tool rise with the tool wear. The PNSGWT that has relative adjustable dyadic time-frequency partition grids, good time-frequency localizability and exact shift-invariance is used to extract the wavelet energy in the specified frequency band. Accordingly, the MCM of deep hole boring can be implemented by means of normalizing the wavelet energy. Finally, a field experiment on deep hole boring machine tool is conducted, and the result shows that the proposed method is effective in the process of monitoring tool wear and surface finish quality for deep hole boring.

1. Introduction

Machining condition monitoring (MCM) plays an important role in machining process for efficient tool change policies, product quality control and lower tool costs [1]. For example, early replacement of a workable tool or late replacement of a worn tool may lead to time and/or production loss. The current progresses in MCM concentrate mainly on two fundamental approaches: direct methods and indirect methods [2]. The direct methods such as touch trigger probes, vision and optical approaches have the capacity of capturing actual geometric changes resulting from the tool wear and surface machining quality. However, it is also very difficult to make direct measurements because of the continuous contact between the cutting tool and the workpiece, and even it is almost impossible in the presence of cutting fluids [3]. Therefore, indirect methods are extensively used. The most common indirect approaches to MCM are analysis of vibration signals, dynamic forces signals, acoustic emission signals and ultrasonic signals [4–6]. Various modern signal processing methods, e.g. Fourier transforms and wavelet analysis [7], are widely employed for MCM, in order to identify the useful feature in relationship with the tool wear condition or the surface machining quality from these signals [8–10].

Deep hole boring is an extremely accurate machining process used to produce largely and bore precisely, which achieves close tolerances, excellent accuracy and good surface finishes. Deep hole boring applications can often be found in the petrochemical, hydraulic and aerospace industries as they often require precision tubes in sizes and specifications. MCM of deep hole boring is also more difficult than other machining methods, because boring tools must be inserted into the inner parts of workpieces which are filled with splashing cutting fluids and rolling iron scales.

Many researches [11–13] on boring machining monitoring are also conducted, and the corresponding research methods still focus on the indirect methods largely. The basic procedures are as follows: first, signal processing methods such as wavelet transforms are used to extract the features. Second, such as distance evaluation technique methods are utilized to select the salient features from the extracted features. Lastly, a MCM model based on these salient features is established. During the entire procedure, how to obtain "good" features plays a crucial role. For example, in [11], a sequential forward search algorithm was employed to select the best feature combination from fourteen features extracted by processing cutting force signals using virtual instrumentation. In [14], several meaningful signal features were automatically extracted from band pass signals using 22 different wavelets and used for tool condition monitoring. Among these feature extraction methods, the wavelet analysis is often employed due to its high computational efficiency and better spatial localizability.

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This paper studies the relation between the cutting tool wear and the self-excited vibration in the process of deep hole boring and proposes an alternative approach to implement MCM. Based on a single-degree-of-freedom dynamic cutting process model, the effects of cutting tool wear on the specific frequency band energy resulted from self-excited vibration are investigated systematically with simulations and experimental validations. The frequency band energy ratios (FBERs) are calculated by using the pseudo non-dyadic second generation wavelet transform (PNSGWT) in order to implement the MCM of deep hole boring. Lastly, the proposed method of MCM is verified through a field experiment.

2. Dynamic cutting model and simulation

It is well-known that the tool wear changes the cutting edge geometry and flank contact with the wavy surface finish. Accordingly, the vibration characteristics of the machine tool must change as well during the boring process.

2.1. Dynamic cutting modeling

Self-excited vibration caused by positive feedback mechanism leading to dynamic instability of cutting process. Self-excited vibration occurs at the frequency of the most dominant mode of the machine tool structure, i.e., vibration frequency is equal to natural frequency of tool oscillations. Excitation of this mode causes a relative motion between the machine tool and workpiece due to the tool cutting over a previously machined undulated or wavy surface as shown in Fig. 1.The equation of this motion can be given as

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=F_x$$
$$F_x=K_f a[x(t-T)-x(t)] \tag{1}$$

where $[x(t-\tau)-x(t)]$ are the dynamic cutting thickness due to tool vibration, K_f is the static cutting coefficient in the feed direction. a is the cutting width, and T is the time delay between current time and previous time.

There are a number of factors which influence the varying cutting forces, i.e., tool geometry, dynamic cutting depth and instantaneous direction of cutting. Tool wear phenomena occur during a cutting process and it changes the tool geometry resulting in a drastic change in the dynamics of the cutting process. The dynamic cutting model (1) considers only the effect of the dynamic cutting thickness due to tool vibration and does not consider flank contact due to tool wear. The influence of the flank-wave contact can be modeled by introducing both dynamic damping coefficient $K_d(t)$ and dynamic cutting coefficient$K_c(t)$[15–17].

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=F_x$$
$$F_x=aK_c(t)[h_0-x(t)+x(t-T)]+K_d(t)\dot{x}(t) \tag{2}$$

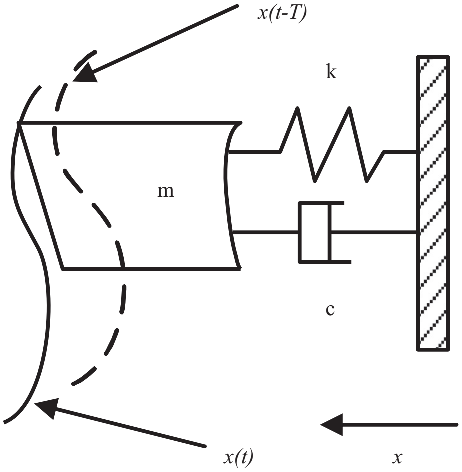

Fig. 1. Model scheme of the vibration system of dynamic cutting process in turning.

2.2. Simulation analysis of the model

For identifying the relationship between the tool wear and natural frequency of tool oscillations, the simulation are carried out by using SIMULINK mode of MATLAB as shown in Fig. 2. According to [15] and [17], it can be assumed that $K_c(t)\propto e^{\alpha V_B}$ and $K_d(t)\propto \beta V_B$, where α and β are constants, V_B is the tool wear.

With consideration of slight vibrations, it is reasonable to suppose that the outer vibrations are harmonic waves with white noises. Fig. 3 displays a quantitative analysis in which the vibration amplitudes in the nature frequency of the machine tool vary with tool wear. It can be observed that the vibration amplitude in the nature frequency of the machine tool have a growing trend with tool wear.

3. Evaluating procedure in practice

Generally, the system and the environment in which it runs are more complicated in practice, and thus it is very difficult to

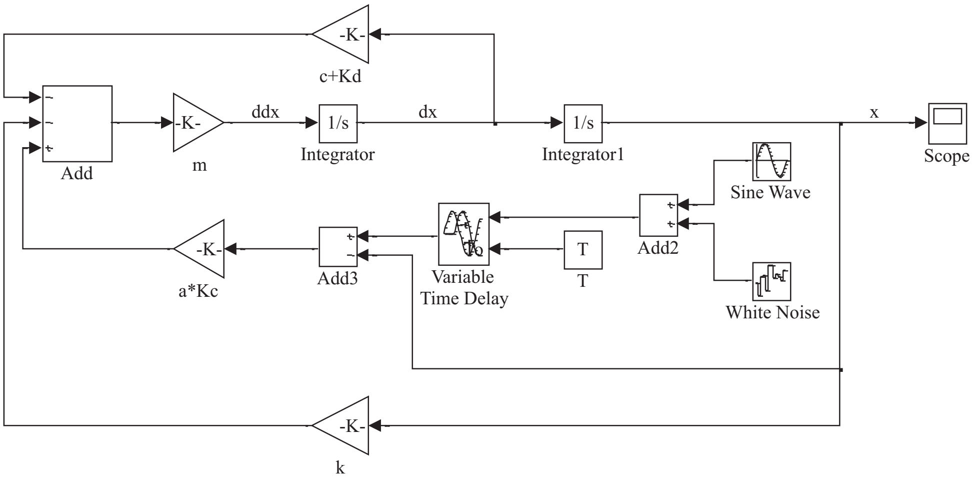

Fig. 2. Simulation of dynamic cutting process.