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Chaotic Characterization of Milling Vibration Information

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Abstract: In view of the strong nonlinearity of the signals in the gestation period of milling chatter, and the problem that the traditional time-frequency analysis methods cannot reveal the weak characteristics of the gestation period of chatter well, a chaotic characteristic analysis method of milling vibration information is proposed. The milling force signals of stable milling, chatter gestation and chatter outbreak states are collected through variable working condition milling force measurement experiments, and the chaotic phase space reconstruction method is used to obtain the attractor images of milling force signals in different vibration states. The experiments show that the attractor features in the chatter gestation period are more significant than the traditional time-frequency features, and the chaotic attractor images can better reveal the weak features in the chatter gestation period.

Keywords: Milling vibration information, Milling chatter, Chaotic phase space reconfiguration.

1. Introduction

Chatter, as a hazardous dynamic instability in the milling process, severely limits machining efficiency [1]. Milling chatter can be predicted by establishing a milling force model and analyzing the stability leaflet diagram [2], but the nonlinearity of the machining process and the time-varying nature of the machining conditions make it difficult for the prediction method based on the milling force model to completely avoid the occurrence of chatter. Therefore, accurate identification of the milling vibration state for timely adjustment of the machining process under different milling vibration states is beneficial to the realization of adaptive control of the milling process, while accurate identification of the chatter gestation period is beneficial to realize chatter early warning.

The general steps of milling vibration state identification are as follows: firstly, the milling force, vibration or noise signals are collected through milling processing experiments, and then the characteristic quantities characterizing the chattering breeding state are extracted with the help of signal analysis and processing methods. Chen et al. [3] implemented a recursive feature elimination method using wavelet transform and support vector machine for the identification of milling vibration states; Wang et al. [4] combined time-frequency features with features extracted from a self-encoder to accomplish the identification of milling vibration states; Tran et al. [5] used wavelet packet decomposition to analyze milling vibration signals and acoustic signals as a way to identify milling vibration states; Wang et al. [6] extracted the features of vibration data with the help of variational modal decomposition (VMD) and demonstrated experimentally that the method can effectively identify milling vibration states; Shrivastava et al. [7] constructed an artificial neural network with cutting parameters as input and chatter index and material removal rate as output, and the model predicted a stable domain for milling that was not only chatter-free but also had high productivity; Wang et al. [8] used the q-factor and the power spectrum value of the determined frequency band as the feature vector to identify the milling vibration state using support vector machine, and the identification accuracy was higher than the conventional index; Sener et al. [9] converted the milling vibration signal into a two-dimensional time-frequency image with the help of continuous wavelet transform, which was fed into a deep learning model to identify the milling vibration state; Unver et al. [10] processed milling vibration signals using ensemble empirical modal decomposition (EEMD) with Hilbert-Huang transform (HHT) and fed the resulting two-dimensional images into a deep learning model for the identification of milling vibration states.

The milling chatter phenomenon in the milling process is essentially a nonlinear process, and the collected signals have strong nonlinear and non-smooth characteristics [11]. The traditional time-frequency analysis method is a linear analysis method, which cannot better characterize the weak features of the chatter gestation period and is easily disturbed by noise, and is not conducive to the early identification of chatter. However, the non-linear, non-smooth milling chatter signals exhibit a strong randomness that coincides with the chaotic characteristics, so the chaotic characteristic analysis method, which is a non-linear analysis method, can better reveal the weak characteristics of the chatter gestation period.

To this end, a chaotic characteristic analysis method of milling vibration information based on chaotic phase space reconstruction is proposed. Firstly, the experimental platform is built to conduct multiple sets of milling machining experiments, and the milling force signals during the process from stable milling to chattering outburst are collected under variable depth of cut and width of cut conditions. Secondly, according to the chaotic characteristic analysis method, the chaotic phase space reconstruction technique is used to obtain the attractor images corresponding to the milling force signals under different working conditions. Finally, the attractor images are compared with the traditional time-frequency features to show the advantages of attractor images, and to lay the foundation for chaotic attractor images to forecast early chatter.

2. Chaotic Phase Space Reconfiguration

During the development of the milling vibration state from stable to chatter, the milling force signals can exhibit significant nonlinear, non-smooth and chaotic characteristics [11]. Chaotic phase space reconstruction is an important method to analyze chaotic time series, which can map the one-dimensional milling force signal to the three-dimensional chaotic phase space to get the corresponding attractor image. The attractor image contains the nonlinear characteristics of the milling force signal, and changes more obviously with the milling vibration state, which is beneficial to the identification of the chatter gestation period.

According to the theory proposed by Packard et al. [12], a one-dimensional time series can be reconstructed in a high-dimensional chaotic phase space by the coordinate delay reconstruction method. Suppose there is a set of time series $\{x_1, x_2, \cdots, x_n\}$, where n denotes the data length, and an m-dimensional phase space can be obtained by the coordinate delay reconstruction method:

$$\boldsymbol{X}_j = [x_j, x_{j+\tau}, \cdots, x_{j+(m-1)\tau}] \tag{1}$$

In the above equation, τ denotes the delay time; m denotes the embedding dimension; $j=1, 2, \cdots, N$; $N=n-(m-1)\tau$.

The phase space trajectory matrix obtained after reconstruction is as follows:

$$\boldsymbol{X} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} x_1 & x_{1+\tau} & \cdots & x_{1+(m-1)\tau} \\ x_2 & x_{2+\tau} & \cdots & x_{2+(m-1)\tau} \\ \vdots & \vdots & \ddots & \vdots \\ x_N & x_{N+\tau} & \cdots & x_{N+(m-1)\tau} \end{bmatrix} \tag{2}$$

In the above equation, the multidimensional phase space trajectory consists of N phase points, and the phase points consist of row vectors X_j.

According to Takens' theorem [13], for an ideal time series of infinite length and without noise, the delay time τ and the embedding dimension m can be chosen arbitrarily. However, the milling force signal collected during the actual milling process is of limited length and contains noise, so the appropriate parameters need to be selected by calculation. The C-C algorithm proposed by Kim H. S. et al. [14] can solve for both the delay time τ and the embedding dimension m. The method is not only easy to implement but also has good noise immunity [15]. Therefore, the C-C algorithm is used to determine the reconstruction parameters τ and m. The milling force signal samples are reconstructed in the chaotic phase space, and then the resulting chaotic phase space trajectories are projected in the two-dimensional plane to obtain two-dimensional attractor images, and finally, the axes are de-coordinated and grayed out in order to facilitate the observation of the attractor morphology. It should be noted that the three-dimensional chaotic phase space trajectory map can be projected in any two-dimensional plane to obtain the two-dimensional attractor image, but considering the simplicity of data processing, the projection in the (x(t), x(t+tau)) two-dimensional plane is chosen. The overall flow is shown in Figure 1.

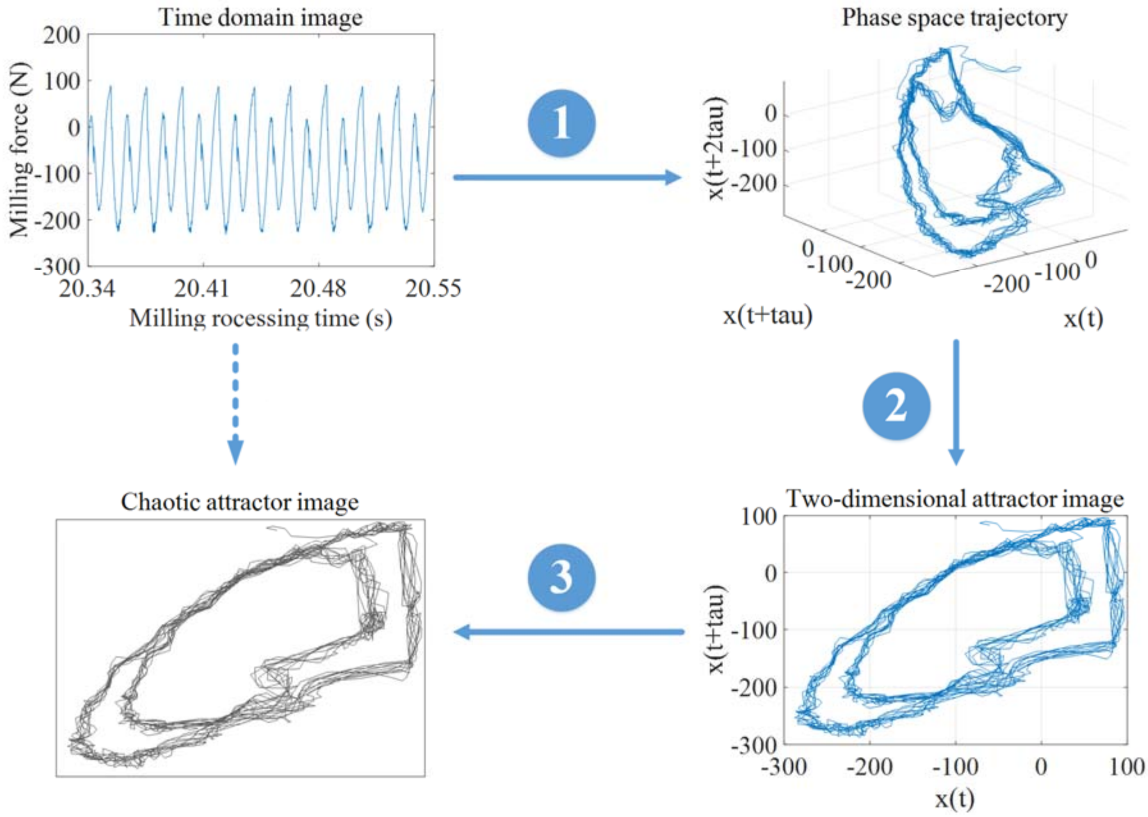


Figure 1. Chaotic phase space reconstruction of attractor image flow

3. Experiment and Analysis

3.1 Milling Force Signal Acquisition and Chaotic Phase Space Reconstruction

A vertical machining center was used to build the experimental platform for variable depth-of-cut and width-of-cut milling as shown in Figure 2, and to conduct the milling force measurement experiment. A 2-tooth carbide end mill with diameter φ=20 mm was selected for milling aluminum alloy specimen AL7075-T6 with axial depth of cut ranging from 0 to 8 mm and a constant machine feed rate of 200 mm/min. During the experiment, the X- and Y-directional milling force signals were collected using a Kistler 9265B force measurement stage with a sampling frequency of 9000 Hz during the experiment.

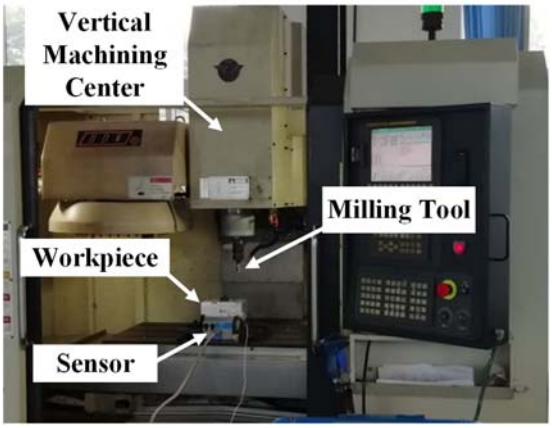


Figure 2. Milling experiment platform

A total of four sets of variable depth-of-cut and width-of-cut milling experiments with different machining parameters were designed, as shown in Table 1.

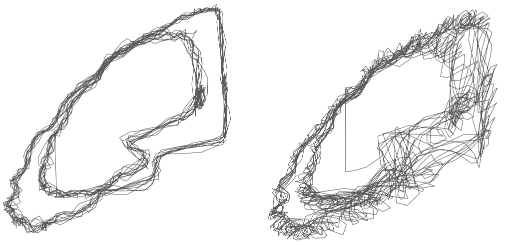
Table 1. Milling experiment parameters

Number	Spindle speed	Cutting depth	Cutting width
1	2600	0~8	20
2	3800	0~8	20
3	3050	6.5	10~20
4	2800	3~9	15~20

With 1024 data sampling points as one sample, 1328 time-domain milling force signal samples can be obtained by 4 sets of milling processing experiments. According to Fig. 1, the time domain signal samples are reconstructed in chaotic phase space to obtain the 3D chaotic phase space trajectory image, and the projection in the (x(t), x(t+tau)) 2D plane is selected to obtain the 2D attractor image of the samples.

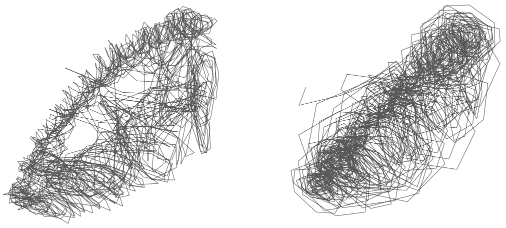
3.2 Analysis of Signals Chaos Characteristics

Based on the ratio of the amplitude of the chattering frequency to the tooth-pass frequency *K*, 1328 samples were divided, among which the numbers of stable milling, chattering breeding and milling chattering samples were 600, 128 and 600, respectively. The attractor images of the samples with different milling vibration states in the Y-direction of the experimental group No. 1 are shown in Figure 3.

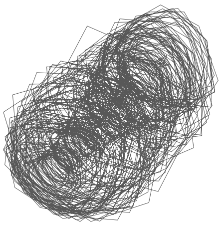


(a) Stable milling (K=0) (b) Chatter gestation (K=0.05)

(c) Chatter gestation (K=0.2)



(d) Chatter gestation (K=0.5) (e) Chatter gestation (K=0.8)



(f) Milling chatter (K≥1)

Figure 3. Attractor images of different milling vibration states

As can be seen from the figure, the shape of the attractor in the stable milling state has a self-similar structure, but there is no obvious nesting, such as (a) of Fig. 3, which indicates that the system has a certain chaotic order. The shape of the attractor in the chatter gestation state has a self-similar structure and starts to diverge outward, such as (b), (c), (d) and (e) of Fig. 3, which indicates that the system has certain chaotic properties. The attractor shape in the milling chatter state has a clear nested self-similar structure, such as (f) in Fig. 3, which indicates that the stability of the system decreases while the chaotic characteristics increase. From the above analysis, it can be obtained that the attractor shape has obvious differences during the process from stable milling to chatter outbreak, and the attractor image can be used as the basis for the identification of milling vibration state. In addition, the attractor shape in the chatter gestation period has obvious differences compared with the stable milling state, however, the time-frequency features in the chatter gestation period are weaker and not obvious enough, which indicates that the attractor image features in the chatter gestation period are more significant than the traditional time-frequency features, and the attractor image can better reveal the weak features in the chatter gestation period.

4. Summary

For the problem of weak characteristics of the gestation period of milling chatter, a chaotic characterization method of milling vibration information is proposed. Firstly, the milling experiments with variable depth of cut and width of cut were carried out on a high-speed vertical milling center, and four sets of milling force signal data were collected under different working conditions. Secondly, according to the chaotic characteristic analysis method of the signal, the chaotic phase space reconstruction method was used to map the milling force signal to the three-dimensional chaotic phase space, and the projection in the (x(t), x(t+tau)) two-dimensional plane was selected to form a two-dimensional chaotic attractor image. Finally, the differences between the chaotic attractor image and the time-frequency image are compared and analyzed, and it is demonstrated experimentally that the chaotic phase space reconstruction method is very suitable for the extraction of weak features, which provides a novel signal pre-processing method for the identification of milling vibration states. The comparison analysis shows that the features of the attractor image are more obvious in the chatter gestation period, which is difficult to distinguish in the time-frequency domains.

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