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Procedia CIRP 56 (2016) 422 – 427

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9th International Conference on Digital Enterprise Technology - DET 2016 – “Intelligent Manufacturing in the Knowledge Economy Era

Experimental study of thin wall milling chatter stability nonlinear criterion

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Abstract

The nonlinear dynamic behavior of milling process has been accompanied by the entire cutting process. In order to accurately determine and predict chatter stability of machining process, this article studied at both ends of the fixed thin part nonlinear criterion of milling chatter stability with experimental method. The experiment takes the vibration signal of thin part as the study object. And it analyses the vibration signal of different processing parameters based on the phase plane method, Poincare method and spectral analysis. Then, the relationship between the maximum Lyapunov exponent and the spindle speed and milling depth changes is discussed. Finally, taking the largest Lyapunov exponent as the criterion, the study determines the chatter stability domain of milling by using contour method. The comparative analysis is based on the milling chatter stability domain which obtained from the full discrete method. The experiments obtained the nonlinear stability criterion of aviation aluminium alloy 7075-T6 thin part.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: *Thin part; Milling chatter; Nonlinear criterion; Lyapunov exponent*

1. Introduction

The requirements of weight and intensity for the parts which used in modern aerospace are gradually increasing. Thin-walled structures are widely used in plane girder, wall plate, etc. The thickness of main load-carrying structure wall is always 1 mm only. Thin wall parts which have many advantages such as high strength and relatively light weight. But it has many problems during thin-walled parts processing. The vibration buckling (such as flutter) in the process of machining is severely restricts the thin-walled workpiece machining quality. A convenient and effective method for the flutter stability of the machining process for accuracy prediction and judgment which in order to ensure the stability of the milling process by milling parameter optimization is necessary. Spindle-cutting tool-workpiece, and the fixture system [1] is a complex nonlinear system during the machining process. In the traditional linear theory, the requirements of low speed processing can be met by using theory of linear approximation method in nonlinear system when cutting thickness is small.

But with the development of high speed milling, the traditional linear theory has not guarantee the accuracy of the model. It is difficult to predict the flutter critical value and the surface of the workpiece position errors and roughness, etc. So Gradisek et al. [2-3] analyze the influence of different cutting depth of the influence of nonlinear vibration. They put forward the chatter occurs in vibration signal with low dimensional chaotic vibration phenomenon which is based on the bifurcation model. David et al. [4] established type regenerative chatter model with second order delay which is based on the nonlinear dynamic cutting force. They analyzed the system vibration from the Hopf bifurcation to chaos vibration state and got Hopf bifurcation stability boundary conditions, the value of characterization. Szalai et al. [5] simplified the machining for the collision and established the nonlinear dynamic model of high speed milling. They think that chaos vibration exist during high speed milling process. On the other hand, they analyzed the subcritical bifurcation stability boundary. Stefanski et al. [6] pointed out that the

2212-8271
Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.10.075

Lyapunov index of dynamic system (Lyapunov Exponent, LE) is an effective approach for the analysis of chaotic motion. This method is mainly aimed at the nonlinear milling vibration. This is due to the nonsmooth features of dynamic cutting force make the phase space of the dynamic model multidimensional. While calculating the distance between the two trajectories and divergence between adjacent tracks is more difficult, the maximum Lyapunov index can be used to analyze the vibration signals of the milling system. Li Zhongqun et al. [8] solved nonlinear milling dynamics equation through numerical method and got the time-domain flutter stability domain according to the stability criterion. Kong fansen et al. [9] analyzed characteristics of the nonlinear behavior for cutting system from no flutter state to flutter. And this is based on Lyapunov index and Kolmogorov entropy. Wang Xibin et al. [10] found that nonlinear characteristic of the vibration signal processing is very clear in the study. It is hard to get the same processing effect under the condition of the same process parameters. At the same time, the study founded that the nonlinear characteristic of the vibration signal for thin-walled workpiece model is more obvious and complex than the vibration signal which is based on the theory [11] in the experiment of milling process. At present, the study about bifurcation and chaotic motions of several coupling vibration for the thin-walled workpiece has made some achievements. YEH and Wang ping et al.[12-14] studied the thermoelastic coupling vibration of rectangular plates of bifurcation and chaos.

Although the nonlinear dynamic model holds an enormous advantage in flutter prediction, how to judge the stability of the thin-walled cutting based on the nonlinear theory, to predict the flutter stability of the domain on the basis of experiment, to establish flutter stability criterion for specific artifacts milling process are still challenges.

The study takes 7075-T6 thin part which is fixed on both ends as the research object. And it takes the maximum Lyapunov index of workpiece vibration signal as the threshold. Then, the cutting chatter stability domain is determined through the milling experiment. On the other hand, the nonlinear criterion of flutter stability domain for thin part which is fixed both ends is determined. The study lays the nonlinear stability foundation for cutting vibration of thin part under thermal and mechanical coupling effect.

2. Flutter analysis method

The cutting vibration has obvious nonlinear characteristics due to the nonlinear characteristics of the milling system (dynamic milling force of smoothness, systems of nonlinear damping and stiffness, etc.). And Maximum Lyapunov Exponent index, Poincare ichnography, Poincare mapping and phase analysis methods are effective methods for the analysis of nonlinear dynamic behavior of milling chatter.

2.1Maximum Lyapunov exponent

According to the motion relationship between the motion axis and the motion joint of the five axes vertical machining center Mikron UCP 710, the model of the kinematic chain

Maximum Lyapunov exponent describes that two points closed infinitely separate with time evolution at the initial time. As the characteristic parameter of chaotic motion, maximum Lyapunov exponent means the maximum divergence degree of phase trajectory or the maximum sensitivity degree for the initial value [15].

Set the milling vibration signal of variable cutting depth as x_1, x_2, $\cdots$ x_N (univariate time series). In formula, N is the total number of time series. According to packed and others [16], the idea of time delay is proposed to reconstruct the phase space of the dynamics system observed. Based on this thought, time series is made the phase space reconstruction and get reconstructed trajectory X, and it can be expressed as

$$X = [X_1, X_2, \cdots, X_M]^T \tag{1}$$

In formula, M is the number of track points after reconstruction of the phase space, X_i is the state of milling vibration system in the discontinuous time point i, and it can be expressed as,

$$X_i = \left[x_i, x_{i+\tau}, \cdots, x_{i+(m-1)\cdot\tau}\right] \tag{2}$$

In formula, τ is the time delay. And m is embedded dimension. $M = N-(m-1)\cdot\tau$. Reconstructing phase space is divided into N sections: $[X_1, X_2, \cdots, X_T]$, $[X_{T+1}, X_{T+2}, \cdots X_{2T}]$, $\cdots$, $\left[X_{(n-1)T+1}, X_{(n-1)T+2}, \cdots, X_{nT}\right]$. Each section length $T = M/n$ is called evolutionary time.

Set initial point X_1, looking for the nearest neighbor points $X_{1'}$, the distance is $L_1 = \|X_1 - X_{1'}\|$. In formula, $\| \ \|$ stands for Euclidean norm. After the evolution time T, the distance changes into $L_1' = \|X_{1+T} - X_{1'+T}\|$. The nearest neighbor points of X_{1+T} is $X_{(1+T)'}$, getting the distance L_2. After the evolution time T, the distance changes into L_2' . By that analogy, maximum Yeli spectrum is

$$\lambda = \frac{1}{M\tau}\sum_{i=1}^{n}\log\frac{L_i'}{L_i} \tag{3}$$

In formula, Δt is a sample interval .

Under the different phase space dimension, vibration signal in milling thin part is analyzed and calculated in order to research milling chatter stability under different processing parameters.

2.2 Poincare mapping and phase plane portrait

Analytical method of Poincare mapping is that abscissa is displacement value of system response and ordinate is speed value of the system response. The calculation methods are conducting data extraction for each time interval. If the milling system is periodic vibration, it corresponds to an isolated point on the Poincare mapping. If the cycle of vibration signal is N, there are n independent points on the Poincare mapping, and the number of cycle is the same as the number of isolated points. If vibration signal changes drastically and flutter occurs, it is shown discrete points accumulated figure [16].

The trajectory of solution of vibration system in the phase space forms the motion curve. Phase plane portrait