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Chatter stability prediction for five-axis ball end milling with precise integration method

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ABSTRACT

The differential dynamic equation (DDE) considering regenerative chatter effect is derived from an ideal cutting model. At the same time, the ball end mill-workpiece engagement (BWE) in five-axis milling is efficiently extracted by the semi-analytical method, where the machining residual left on the finished surface is taken into account. The explicit precise integration method (PIM) is adopted to translate the DDE into a time series expression, ensuring stability prediction without any discretization error loss. With the relationship of cutter edge and BWE at different instants, the stability lobe diagram (SLD) is constructed by Floquet theory, which is subsequently testified in the five-axis NC machine tool. The experimental results keep good agreement with estimations, validating the proposed method. Compared with traditional method in dynamic cutting forces modeling, the proposed approach is more close to actual processing. In contrast to Runge-Kutta based complete discretization method, PIM shows higher superiority no matter in convergence rate or calculation accuracy. Lastly, the influences of different inclination angles on stability are revealed, which can give a reference to selection of suitable process parameters for higher productivity.

1. Introduction

In milling process, the cutting chatter caused by inappropriate machining parameters has a negative impact on processing efficiency, precision and quality. Prediction of stability is the effective way to avoid machining chatter. Five-axis milling with the advantages of high flexibility and high precision is widely used in aerospace, molds and automotive industries. Meanwhile, the ball-end mill, as an important point contact machining cutter, plays an increasingly role in machining of parts with sculptured surfaces. Therefore, it is of great significance to predict chatter stability for the five-axis ball-end milling.

The zero-order analytical (ZOA) method of constructing the stability lobe diagram (SLD) presented by Altintas and Budak [1] opened the beginning of the prediction of chatter stability, but its prediction accuracy is not desirable in low radial immersion [5]. On the basis of the ZOA method, Medrol et al. [2] proposed the multi-frequency method (MFM) by improving the transfer function with the harmonics of the tooth passing frequencies. With the development of computational mathematics, quite a few researchers focused on numerical solutions for prediction of chatter stability. Insperger et al. [3] presented a semi-discretization method (SDM), where the delay term of differential dynamic equation (DDE) is discretized. Later, first-order SDM for the prediction of stability is carried out in Ref. [4]. Ding et al. [5] proposed a full-discretization method (FDM), where the time delay and time periodic terms are discretized. In order to improve convergence speed, second-order FDM is put forward in Ref. [6]. Some comments about relation of SDMs and FDMs are given in Ref. [8], which states that similar as SDM, FDM also did not actualize complete discretization of iterative formula. Inspired by this goal, Li et al. [9] developed a complete discretization scheme with the Euler's method (CDSEM), where all parts of DDE, including delay term, time domain term, and parameter matrices are discretized. Later, based on complete discretization scheme, Li et al. [10] promoted a Runge-Kutta based complete discretization method (RKCDM).

Additional, Ding and co-authors [11] brought Newton–Cotes formula, Gaussian formula into the direct integration for faster calculation speed. Upon the foundation of classic Runge–Kutta method [12], an improved Runge–Kutta method is used in prediction of chatter stability by Niu et al [13]. Khasawneh et al. [15] proposed a spectral element approach with exponential convergence rates. Huang et al. [16] presented a semi-analytical method using linear acceleration approximation. Ding and co-authors [17] introduced

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the spectral technology to predict milling chatter stability. The stability of 1st and 2nd DDE is researched in Ref. [18] by the Chebyshev spectral approximation technology. Based on the Simpson's rule, Eksioglu et al. [19] proposed an integration solution to the DDE. Lambert W function is applied in prediction of chatter stability by Olgac N in Ref. [20]. Zhang et al. [22] utilized linear combination of multi-state function values to replace the 1st derivatives of state terms and proposed numerical differentiation method. By the summaries above, it can be seen numerous valuable methods of chatter stability prediction have been presented in succession, especially in recent year. However, no matter SDMs, FDMs or NIMs, they all focus on three-axis machining, which can not be suitable for five-axis milling because of the existing of lead angle and tilt angle.

Fo[23]. extended analytic method into chatter stability prediction of three-axis ball end milling, which has the same defect as ZOA [10]. Shamoto et al. [24] presented an analytical method to predict chatter stability in ball end milling, where tool inclination is taken into consideration. Budak et al. [25] employed single-frequency and multi-frequency analytical methods for prediction of chatter stability in five-axis ball end milling. Sun et al. [27] applied frequency domain method to achieve chatter free tool orientations of 5-axis ball-end milling. The analytical method is efficient, but it cannot take various nonlinear factors in milling process into account [6]. Besides, the extraction of ball-end mill-workpiece engagement (BWE) presented by Sun et al. [27] must rely on solid modeling, which is very complicated and time-consuming [28].

In this paper, based on classic precise integration method (PIM), an explicit PIM is introduced to solve DDE, which can achieve complete discretization of iterative formula in comparison with FDMs. Moreover, the ball end mill-workpiece engagement (BWE) in five-axis milling is extracted by a simple and efficient semi-analytical method. With the relationship of BWE and cutting edges at different instants, the stability lobe diagram (SLD) is constructed by Floquet theory at last. Henceforth, the rest of paper is organized as follows. Section 2 derives the delay dynamic equation from a simplified five-axis ball end milling model. Section 3 extracts ball-end mill-workpiece engagement (BWE) of five-axis milling using semi-analytical method. Section 4 gives the detailed algorithm of PIM. Section 5 carries out the experimental verification, comparison and discussion. Some conclusions are drawn in Section 6.

2. Dynamic modeling for five-axis ball-end milling

2.1. The dynamic equation for ball-end mill-workpiece system

As Fig. 1, the coordinate system O-X-Y-Z can be established, in which point O is the vertex of cutter; Z axis is the axis of the cutter. Just considering the vibration of cutter in x and y directions, the ball-end mill-workpiece system is simplified into two degrees of freedom system [26]. The dynamic equations can be expressed as Eq. (1).

$$\begin{bmatrix} m_{tx} & 0 \\ 0 & m_{ty} \end{bmatrix} \begin{bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \end{bmatrix} + \begin{bmatrix} 2m_{tx}\xi_x\omega_{nx} & 0 \\ 0 & 2m_{ty}\xi_y\omega_{ny} \end{bmatrix} \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{bmatrix} + \begin{bmatrix} m_{tx}\omega_{nx}^2 & 0 \\ 0 & m_{ty}\omega_{ny}^2 \end{bmatrix} \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} F_{tx}(t) \\ F_{ty}(t) \end{bmatrix} \quad (1)$$

where m_{tx}, m_{ty}, ξ_x, ξ_y, ω_{nx}, ω_{ny} are model mass, damping factor, natural frequency of cutter system in x, y directions, respectively; $F_{tx}(t)$ and $F_{ty}(t)$ are dynamic cutting forces of cutter tooth in x, y directions.

2.2. The dynamic cutting force

1) Geometric model for cutting edge of ball-end mill [32]

Since each element of cutting edge has a onE–To-one mapping with its corresponding axial angle, the coordinate of each point on cutting edge can be expressed as a function of the axial angle. The coordinate expression of ith cutting element on the jth tooth are given in Eq. (2).

$$\begin{cases} \psi_{ji}(k) = (R - R\cos k)\tan\mu/R \\ \phi_{10}(t) = 2\pi \cdot n \cdot t/60 \\ \phi_{ji}(t) = \phi_{10}(t) - (j-1)\cdot 2\pi/N_f - \psi_{ji}(k) \\ x_{ji}(t) = R\sin k \cdot \sin(\phi_{ji}(t)) \\ y_{ji}(t) = R\sin k \cdot \cos(\phi_{ji}(t)) \\ z_{ji}(t) = R - R\cos k \end{cases} \quad (2)$$

where R is the radius of ball-end mill; μ is the helix angle of cutting edge; t is the time in cutting process; k is axial immersion angle, varying in the range of [0,π/2] on one cutting edge; $\psi_{ji}(k)$ is radial lag angle; $\phi_{10}(t)$ is rotating angle at the tip of first cutting edge; n is spindle speed (r/ min); $\phi_{ji}(t)$ is radial immersion angle; N_f is the number of flutes; $x_ji(t)$, $y_ji(t)$ and $z_ji(t)$ are the coordinate values of ith cutting element on the jth tooth in established coordinate system.

2) Instantaneous dynamic cutting force modeling

Via the famous cutting force model proposed by Altintas et al. [33], the tangential force$dF_{t,ji}(\phi_{ji}(t), k)$, radial force $dF_{r,ji}(\phi_{ji}(t), k)$ and axial force $dF_{a,ji}(\phi_{ji}(t), k)$ acting on ith cutting element on the jth tooth are represented as:

$$\begin{cases} \mathrm{d}F_{t,ji}(\phi_{ji}(t), k) = K_{tc}h(\phi_{ji}(t), k)db \\ \mathrm{d}F_{r,ji}(\phi_{ji}(t), k) = K_{rc}h(\phi_{ji}(t), k)db \\ \mathrm{d}F_{a,ji}(\phi_{ji}(t), k) = K_{ac}h(\phi_{ji}(t), k)db \end{cases} \quad (3)$$

where the edge force components are ignored because they do not have relation of dynamic force components [23]; $h(\phi_{ji}(t), k)$ is the instantaneous chip thickness; K_{tc}, K_{rc}, $K_{ac}$are cutting force coefficients in tangential, radial, and axial directions, respectively; db is cutting width, equal to $db = R \cdot dk$[34].

$h(\phi_{ji}(t), k)$ consists of statistic chip thickness formed by the rigid body kinesiology, and regenerative dynamic chip thickness caused by the structural vibrations in x and y directions. It should be noted that statistic chip thickness excites only forced vibrations, and does not contribute to the regenerative mechanism, so it is neglected [23]. The instantaneous dynamic chip thickness $h_d(\phi_{ji}(t), k)$ can be expressed as [34]

$$h_d(\phi_{ji}(t), k) = \mathrm{V} \times [x(t) - x(t-T), y(t) - y(t-T), 0]^T \quad (4)$$

where $x(t) - x(t-T)$ and $y(t) - y(t-T)$ represent the dynamic vibration vectors in the x and y directions at the present t and prior tooth periods $(t-T)$, respectively; T is the tooth passing period, equal to $T = 60/\left(N_f n\right)$; N_f is total number of teeth, and n is spindle speed (r/ min); V is the normal vector, donated as $\left[\sin(k)\sin\phi_{ji}(t),\ \sin(k)\cos\phi_{ji}(t),\ -\cos(k)\right]$ [35].

Via the coordinate transformation, the dynamic cutting force of ith cutting element affecting on the jth in x and y directions are represented as:

$$\begin{bmatrix} \mathrm{d}F_{x,ji}(\phi_{ji}(t), k) \\ \mathrm{d}F_{y,ji}(\phi_{ji}(t), k) \end{bmatrix} = \mathrm{D} \times \begin{bmatrix} \mathrm{d}F_{t,ji}(\phi_{ji}(t), k) \\ \mathrm{d}F_{r,ji}(\phi_{ji}(t), k) \\ \mathrm{d}F_{a,ji}(\phi_{ji}(t), k) \end{bmatrix} \quad (5)$$