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Cutting force prediction in four-axis milling of curved surfaces with bull-nose end mill

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Abstract

This paper presents a mechanistic model for prediction cutting forces in bull-nose end milling of curved surfaces. Firstly, a mechanistic cutting force model for bull-nose end mill is established. Secondly, the machining process characteristics for four-axis milling of ring-shaped casings are discussed. A slice-based method is proposed for prediction the cutter-workpiece engagements. Then, the cutting forces with three different lead angles are predicted and compared with the corresponding experimental values. The results show the feasibility and effectiveness of the presented prediction approach.

Keywords: Cutting force; Four-axis milling; Curved surfaces; Bull-nose end mill; Tool-workpiece engagements

1. Introduction

In the milling process, the cutting forces play great effects on chatter stability analysis, machining error prediction, cutting power calculation, tool wear judgment and cutting parameters optimization. Therefore, it is necessary to establish a suitable model for accurately predicting the cutting forces. Many studies have been focused on this issue.

At present, the cutting force model mainly includes the following three types: the empirical model, the analytical model and the mechanistic model, among which the third one has the most extensive influence and application. Altintas[1] developed a typical mechanistic cutting force model. In this model, cutting forces are represented as the product of cutting force coefficients and chip load. The cutting force coefficients can be identified by the approach of linear regression. Gradisek[2] presented a semi-mechanistic identification method of the coefficients for a general helical end mill from milling tests at arbitrary radial immersion. Li[3] and Gao[4] applied and improved this method in the bull-nose end milling process. The chip loads can be determined according to the engagements between the tool and the workpiece. Kim[5] calculated the cutter contact area from the Z-map of the surface geometry and current cutter location. Yang[6] proposed a solid trimming method to determine tool-workpiece engagement maps. Based on the work of Altintas, Wan[7,8] proposed an instantaneous cutting force model, in which the cutting forces are separated into two parts: a nominal component independent of the runout and a perturbation component induced by the runout.

The casings are widely used to house and protect the whole aero-engine. They are typical thin-walled parts with ring-shaped and closed geometry structures. The outer surface of a casing is a curved surface and usually machined with bull-nose end mills. The machining accuracy and the surface quality will directly affect the safety and reliability of the aero-engine. And the accurate prediction of cutting force is a key factor to achieve effective control of the machining process. However, the chip load calculation during bull-nose end milling of aero-engine casings is difficult due to the complex geometries both of the tool and the workpiece. Additionally, the multi-axis milling manner makes the

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calculation of tool-workpiece engagement region more complicated.

In this paper, a mechanistic model for calculating cutting forces in bull-nose end milling of ring-type parts is presented. The cutting forces are predicted by considering the influences of lead angle. And several experimental tests are carried out to validate the feasibility and effectiveness of the proposed method.

2. Mechanistic cutting force model

Fig. 1 shows the envelope of a bull-nose end mill, which can be defined by four geometric parameters[1,2]: the tool diameter D, the corner radius R_c, the tool length L, and the flute length L_f. In order to clearly represent the related cutting parameters, a Cartesian tool coordinate system (TCS) is defined at the cutter tip. The z-axis is along the tool axis direction, and the x- and y-axes are on the transversal directions.

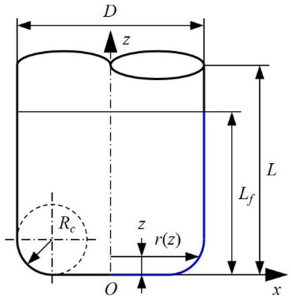

Fig. 1. Envelope of a bull-nose end mill.

The radius of the tool is variable along the z-axis, and will be calculated as:

$$r(z)=\begin{cases}\dfrac{D}{2}-R_c+\sqrt{R_c{}^2-(R_c-z)^2} & 0\le z\le R_c\\ \dfrac{D}{2} & R_c<z\le L_f\end{cases} \tag{1}$$

Fig. 2 shows a helical cutting edge, which is wrapped around the envelope of a bull-nose end mill. A vector ($\mathbf{r}_j$) drawn from the cutter tip (O) to any point (P) on the jth cutting edge can be expressed as:

$$\begin{aligned}\mathbf{r}_j&=x_j\mathbf{i}+y_j\mathbf{j}+z_j\mathbf{k}\\&=r(\varphi_j)(\sin\varphi_j\mathbf{i}+\cos\varphi_j\mathbf{j})+z(\varphi_j)\mathbf{k}\end{aligned} \tag{2}$$

with

$$\varphi_j(z)=\varphi+(j-1)\varphi_p-\psi(z) \tag{3}$$

$$\varphi_p=\frac{2\pi}{N} \tag{4}$$

$$\psi(z)=\frac{2z\tan i_0}{D} \tag{5}$$

where φ_j is the radial immersion angle of point P on the jth cutting edge, φ is the rotation angle of the first cutting edge at the elevation $z = 0$, φ_p is the pitch angle of the milling cutter, $\psi(z)$ is the radial lag angle caused by the local helix angle, N is the number of flutes on the tool, i_0 is the constant helix angle of the tool.

Based on the mechanistic cutting force model presented by Altintas[1], three orthogonal cutting force components of the jth flute can be expressed as:

$$\begin{cases}dF_{t,j}(\varphi,z)=K_{tc}h_j(\varphi,\kappa)db+K_{te}ds\\ dF_{r,j}(\varphi,z)=K_{rc}h_j(\varphi,\kappa)db+K_{re}ds\\ dF_{a,j}(\varphi,z)=K_{ac}h_j(\varphi,\kappa)db+K_{ae}ds\end{cases} \tag{6}$$

with

$$h_j(\varphi,\kappa)=f_t\sin\varphi_j\sin\kappa \tag{7}$$

$$db=\frac{1}{\sin\kappa}dz \tag{8}$$

$$\begin{aligned}ds&=|d\mathbf{r}|\\&=\sqrt{r^2(\varphi)+(r'(\varphi))^2+(z'(\varphi))^2}\,d\varphi\end{aligned} \tag{9}$$

$$\kappa(z)=\arccos\frac{R_c-z}{R_c} \tag{10}$$

where K_{tc}, K_{rc}, K_{ac} are the cutting force coefficients in tangential, radial and axial directions, respectively, K_{te}, K_{re}, K_{ae} are the edge force coefficients in tangential, radial and axial directions, respectively, $h_j(\varphi,\kappa)$ is the undeformed chip thickness, db is the projected length of the edge segment in the direction along the cutting velocity, ds is the length of the elemental edge, f_t is the feed per tooth, and $\kappa(z)$ is the axial immersion angle.

Once three force components are obtained from Eq. (6), they can be mapped into Cartesian tool coordinate system:

$$\begin{bmatrix}dF_{x,j}(\varphi,z)\\ dF_{y,j}(\varphi,z)\\ dF_{z,j}(\varphi,z)\end{bmatrix}=T_j(\varphi,\kappa)\begin{bmatrix}dF_{t,j}(\varphi,z)\\ dF_{r,j}(\varphi,z)\\ dF_{a,j}(\varphi,z)\end{bmatrix} \tag{11}$$

with

$$T_j(\varphi,\kappa)=\begin{bmatrix}-\cos\varphi_j & -\sin\varphi_j\sin\kappa & -\sin\varphi_j\cos\kappa\\ \sin\varphi_j & -\cos\varphi_j\sin\kappa & -\cos\varphi_j\cos\kappa\\ 0 & -\cos\kappa & -\sin\kappa\end{bmatrix} \tag{12}$$