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# Research on modeling of variable milling force coefficient for ruled surface in flank milling process

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**Abstract**

While considering the ruled surface geometry characteristics and its effect on milling force, the expression of variable start and exit radial immersion angles and axial cutter position are proposed through the analysis of contact area between cutter and workpiece in the flank milling process. The variable milling force coefficient model is established, and its result can be variable with the change of the curvature radius. The experimental analysis and solving results of the model are proposed. At last, the variable milling force coefficient model is verified by a flank milling force simulation result.



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*Keywords:* milling force coefficient; flank milling; ruled surface

## 1. Introduction

Milling force coefficient is one of the key parameters for milling force calculation process and stability analysis, and its accurate identification has an important significance for machining process state prediction and tool path optimization.

Wan et al. [1] defined the expression of various parameters in the milling force coefficient transformation formula, and the parameters are fitted as a function of the instantaneous uncut chip thickness. Li Hongjiang [2] proposed the definition of shear-specific coefficients for the three order polynomial function of the relative position of cutting elements. Cao Qingyuan et al. [3] proposed a method for calculating the curvature radius at the cutter contact point, and the analysis model of contact areas between cutter and workpiece was established. Gradisek et al. [4] presents a widely used method for the identification of milling force coefficients by slot milling experiment. Larue and Altintas [5] proposed a method to model and simulate the milling force in flank milling process for ruled surfaces.

## 2. Variable milling force coefficient model

In order to describe the different characteristics of milling force corresponding to the different cutting elements of cutter, a point P at an arbitrary position on cutting edge of ball-end mill is selected. The local edge coordinate system ($dF_t$, $dF_r$, $dF_a$) and the machine tool coordinate system (X, Y, Z) are shown in Fig. 1. In Fig. 1, $dF_t$, $dF_r$, $dF_a$ are the tangential, radial, and axial force components, $\beta$ denotes the helix angle of a point on the cutting edge, $dz$ and $\kappa(z)$ represent uniform differential height and axial immersion angle related to the axial disk element, respectively.

The edge length of cutting segment $dS$, can be obtained according to Fig. 1. It is varied with elevation z for $dS$, and it can be expressed as:

$$dS = \sqrt{1+(\sin\kappa)^2(\tan\beta)^2} \cdot dz \tag{1}$$

The axial immersion angle is defined as the angle between the cutter axis vector and normal vector of the cutting edge at point P, which can be derived from Eq. (2) as:


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$$\begin{cases} \kappa(z) = \arccos\left(\dfrac{R-z}{R}\right)(0 < z < R) \\ \kappa(z) = \pi / 2(z \geq R) \end{cases} \tag{2}$$

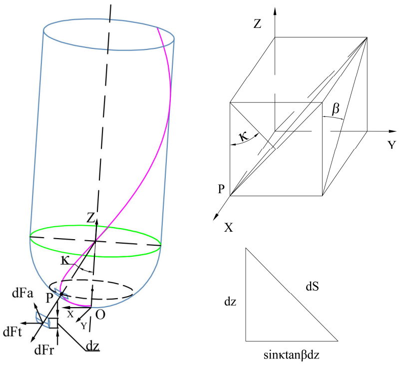



Fig. 1. Local coordinate system and differential element length calculation

The final linear equations to calculate the shear-specific and the edge-specific coefficients, $K_{uc}$ ($u$ represent $t$, $r$, $a$) and $K_{ue}$, could be obtained according to the method proposed by Gradisek et al. [4]:

$$K_{tc} = \frac{2\pi}{NA_1} \cdot \frac{C_3\bar{F}_{xc} - (C_2 - C_1)\bar{F}_{yc}}{C_3^2 + (C_2 - C_1)^2}$$

$$K_{rc} = \frac{2\pi}{N(A_2^2 + A_3^2)} \times \left[\frac{A_2\left((C_2 - C_1)\bar{F}_{xc} + C_3\bar{F}_{yc}\right)}{C_3^2 + (C_2 - C_1)^2} - \frac{A_3\bar{F}_{zc}}{C_5}\right]$$

$$K_{ac} = \frac{2\pi}{N(A_2^2 + A_3^2)} \times \left[\frac{A_3\left((C_2 - C_1)\bar{F}_{xc} + C_3\bar{F}_{yc}\right)}{C_3^2 + (C_2 - C_1)^2} + \frac{A_2\bar{F}_{zc}}{C_5}\right]$$

$$K_{te} = \frac{-2\pi}{NB_1} \cdot \frac{C_4\bar{F}_{xe} + C_5\bar{F}_{ye}}{C_4^2 + C_5^2}$$

$$K_{re} = \frac{2\pi}{N(B_2^2 + B_3^2)} \times \left[\frac{B_2\left(C_5\bar{F}_{xe} - C_4\bar{F}_{ye}\right)}{C_4^2 + C_5^2} + \frac{B_3\bar{F}_{ze}}{2C_1}\right]$$

$$K_{ae} = \frac{2\pi}{N(B_2^2 + B_3^2)} \times \left[\frac{B_3\left(C_5\bar{F}_{xe} - C_4\bar{F}_{ye}\right)}{C_4^2 + C_5^2} - \frac{B_2\bar{F}_{ze}}{2C_1}\right] \tag{3}$$

where

$$A_1 = \int_{z_1}^{z_2} dz,\ A_2 = \int_{z_1}^{z_2} \sin(k)\,dz,\ A_3 = \int_{z_1}^{z_2} \cos k(z)\,dz$$

$$B_1 = \int_{z_1}^{z_2} dS(z),\ B_2 = \int_{z_1}^{z_2} \sin k(z)\,dS(z),$$

$$B_3 = \int_{z_1}^{z_2} \cos k(z)\,dS(z)$$

$$C_1 = \frac{1}{2}\phi\Big|_{\phi_{st}}^{\phi_{ex}},\ C_2 = \frac{1}{4}\sin 2\phi\Big|_{\phi_{st}}^{\phi_{ex}},\ C_3 = \frac{1}{4}\cos 2\phi\Big|_{\phi_{st}}^{\phi_{ex}},$$

$$C_4 = \sin\phi\Big|_{\phi_{st}}^{\phi_{ex}},\ C_5 = \cos\phi\Big|_{\phi_{st}}^{\phi_{ex}} \tag{4}$$

Where $N$ is the Spindle speed, $f_z$ is the average feedrate per tooth, $z_1$, $z_2$ for integration boundaries denote cutter axial position, $\varphi_{st}$ and $\varphi_{ex}$ are the start and exit radial immersion angles, respectively.

The measured and analytical average cutting forces per tooth can be expressed as a linear function of average feedrate per tooth:

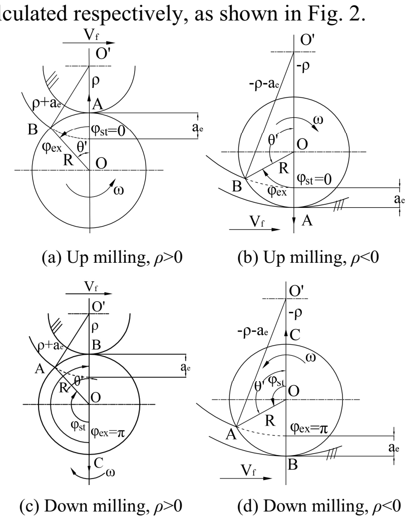
$$\bar{F}_q = \bar{F}_{qc} \cdot f_z + \bar{F}_{qe},\ q = x, y, z \tag{5}$$

By analyzing Eq. (3), it draws a conclusion that accurate calculation of cutter axial position and the start and exit radial immersion angles is one of key factors to integrate boundaries of calculating milling force coefficients. Therefore, it comprehensively analyzed the contact areas between cutter and workpiece in flank milling process for variable curvature surface in this paper.

## 3. Identification of boundary conditions

### 3.1. The start and exit radial immersion angles

Taking into account of the difference of the rotation direction of milling cutter and the feed direction, the start and exit radial immersion angles for up milling and down milling were calculated respectively, as shown in Fig. 2.




(a) Up milling, $\rho>0$ (b) Up milling, $\rho<0$

(c) Down milling, $\rho>0$ (d) Down milling, $\rho<0$

Fig. 2 Calculation of effective radial immersion angles considering different sculptured surfaces