New method for the calibration of cutter runout parameters in milling process

Pan Weiguang¹, Pan Wenjie¹*, Wu You¹, Guo Liang¹

¹Institute of Materials, China Academy of Engineering Physics, Jiangyou, Sichuan, 621907, P.R. China
*Corresponding author’s e-mail: panwenjie@caep.cn

Abstract. Cutter runout will induce irregular rotation radius of each flute and commonly exists in milling process. Due to the runout inducing great variation of milling forces, it is necessary to accurately identify the runout parameters. In this paper, a new model is proposed to calibrate the cutter runout parameters in flat end milling process. The relationship between the rotation radius of each flute cutting edge and the deviation of maximum uncut chip thickness utilizing the sampled data of cutting forces is made. Several flat milling experiments on a three-axis are made to verify the validity of proposed model and the result shows the predicted cutting forces using calibrated cutter runout parameters having a great agreement with the measured cutting forces in shape under different cutting conditions.

1. Introduction

Milling is an effective manufacture method for complex components in motor, aviation, mould fields. Due to the manufacture error and installing error, cutter runout exists in milling process which induces irregular rotation radius and affects instantaneous cutting force [1], machined surface accuracy, machining stability of cutting process [2]. With the requirement of modeling precision of cutting force, it is important to identify the values of the cutter runout parameters.

The methods of cutter runout parameters calibration are developed by many scholars. Armarego and Despande [3] proposed a best-fit iteration algorithm to estimate the cutter runout parameters based on the measured cutting force. Zhang et al. [4] proposed a measurement of radial cutter runout in revolving milling tool by using the laser sensor. Arizmendi et al. [5] used a dial gauge to measure cutter runout and analyze runout parameters by surface topography of the machined workpiece. Guo et al. [6] presented a new algorithm to compute the cutter runout parameters for flat-end mill utilizing the sampled data of cutting forces and derived process geometry parameters. Wan, et al. [7] presented a new algorithm to compute instantaneous cutting force coefficients and the cutter runout parameters for three-axis flat end milling process.

This paper proposed a new model to calibrate cutter runout parameters in milling process. Validation experiments are conducted on three-axis machining center to verified the proposed model and the results show a great agreement with the measured data.

2. Model Formulation

Duo to the cutter runout, the actual rotation radius differs from each flute, which will result to the difference of chip load and the amplitude of cutting forces. As shown in Fig. 1, cutter runout can be modeled by two parameters, \( \rho \) and \( \lambda \). \( \rho \) is the cutter axis offset, and \( \lambda \) is the locating angle for
the offset which is the angle between the direction of the offset and the nearest tooth.

\[ \rho = \lambda \]

\[ \rho = \rho \cos(\pi - \frac{2\pi(i-1)}{N} + \lambda) \]

(1)

where \( R_i \) is the actual cutting radius of the concerned cutting point of the \( i \)th flute, \( r \) is the nominal cutting radius of the cutter, \( N \) is the tooth number of the cutter. In this paper, \( N > 2 \).

Fig. 3 shows the general milling process of a flat end cutter. The tangential cutting force \( F_T \) which is going along the direction of the cutting speed is usually larger the cutting forces of radial and axial directions. For the reason that the tangential cutting force is chosen to calibrate the cutter runout parameters. The maximum tangential, radial and axial cutting forces of the \( i \)th flute can be expressed as:

\[ F_{T,i \text{max}} = K_T h_{i \text{max}}(\theta_i(\phi))z \]

\[ F_{R,i \text{max}} = K_R h_{i \text{max}}(\theta_i(\phi))z \]

\[ F_{A,i \text{max}} = K_A h_{i \text{max}}(\theta_i(\phi))z \]

(2)

Where \( K_T, K_R, K_A \) is the tangential, radial, axial cutting force coefficient, \( \phi \) is the cutter rotation.
angle, \( \theta_i(\phi) \) is the angular position related to the \( i \)th flute at \( \phi \), \( h_{\text{max}}(\theta_i(\phi)) \) is the maximum chip thickness, \( z \) is the axial cutting depth. In this paper, the axial cutting depth is a relatively small value, therefore the influence of helix angle is ignored.

\[
\theta_i(\phi), h_{\text{max}}(\theta_i(\phi)), z
\]

Figure 3. General milling process of a three-fluted end flat mill

Ideally, the value of maximum cutting force of each flute is the same without the influence of cutter runout. The nominal maximum cutting force \( F_{\text{in max}} \) of each flute is the mean value of each flute maximum cutting force in one rotation period.

\[
F_{\text{in max}} = \frac{\sum_{i=1}^{N_f} F_{T,i\text{max}}}{N}
\]

The deviation of chip thickness of the \( i \)th flute differ from the nominal chip thickness can be expressed as:

\[
\Delta h_{\text{max}} = \frac{F_{T,i\text{max}} - F_{\text{in max}}}{K_f z}
\]

As seen in Fig.2, the radius of the concerned cutting point of the \( i \)th flute at the axial coordinate \( z \) is differ from the \((i+1)\) th flute which results in the deviation of chip thickness \( \Delta h_{\text{max}} \). The relationship of chip thickness deviation \( \Delta h_{\text{max}} \) and cutting radius of the corresponding cutting point can be expressed as the following:

\[
\begin{bmatrix}
R_1 - R_N \\
R_2 - R_1 \\
\vdots \\
R_N - R_{N-1}
\end{bmatrix}
= 
\begin{bmatrix}
\Delta h_{1\text{max}} \\
\Delta h_{2\text{max}} \\
\vdots \\
\Delta h_{N\text{max}}
\end{bmatrix}
\]

Now, the values of \( \rho \) and \( \lambda \) can be calibrated using the linear least-square method.

3. Model Verification

One milling test of one cutter is carried out on a three-axis CNC vertical machining center to calibrate the cutter runout parameters \( \rho \) and \( \lambda \), with a three-fluted flat end mill of diameter of 16mm and a helix angle of \( \beta = 30^\circ \). The workpiece material is aluminum alloy 7050 and the cutting parameters are listed in Table 1. A three-component Kistler dynamometer is used to measure the instantaneous cutting forces which are amplified by a Kistler charge amplifier and recorded in a computer. To ignore the
influence of cutter wear on cutting process, a new three-fluted flat end mill is used in the milling process which will be terminated once stable cutting force signals are sampled.

| Test | Milling type | Cutter radius(mm) | Number of flute | Radial depth of cut(mm) | Axial depth of cut(mm) | Feed per tooth(mm/tooth) |
|------|--------------|-------------------|-----------------|-------------------------|------------------------|--------------------------|
| 1    | Down         | 6                 | 3               | 2                       | 1                      | 0.05                     |
| 2    | Down         | 8                 | 4               | 4                       | 1                      | 0.1                      |

The instantaneous cutting forces are obtained in Cartesian coordinate and will be transformed into a local system on the normal plane. The tangential, radial and axial cutting forces related to the $i$th flute can be obtained as the following expression:

$$
\begin{bmatrix}
F_{X,i}(\phi) \\
F_{Y,i}(\phi) \\
F_{Z,i}(\phi)
\end{bmatrix} =
\begin{bmatrix}
-\cos \theta_i(\phi) & -\sin \theta_i(\phi) & 0 \\
\sin \theta_i(\phi) & -\cos \theta_i(\phi) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
F_{Ti}(\phi) \\
F_{Ri}(\phi) \\
F_{Ai}(\phi)
\end{bmatrix}
$$

The cutter runout parameters are calibrated based on Eq. (5), and the result are shown in Table 2.

| Test | $\rho$ (mm) | $\lambda$ (°) |
|------|-------------|---------------|
| 1    | 0.0063      | -30.4         |
| 2    | 0.0215      | 7.5           |

In order to verify the accuracy of the model proposed in this paper, several milling experiments using the two cutter are executed. Comparisons between the measured cutting forces and the predicted cutting force using the calibrated runout parameters are shown in Fig. 4. Note that only X- and Y-forces are selected for illustration since they mainly influence the machining errors and stabilities. The predicted cutting forces fit very well the measured cutting forces in shape under different cutting conditions.

4. Conclusions

In this paper, a new model is proposed to calibrate the cutter runout parameters in flat end milling process.
Mathematical derivations for the rotation radius of each flute obtained runout offset and its orientation is described in details. By one milling test the two cutter runout parameters can be calibrated without complex experiment. The validity of the model proposed in this paper is verified through three-axis milling experiments. The predicted cutting forces have a great agreement with the measured cutting forces in shape under different cutting conditions.

Acknowledgements
This work was supported by Science Challenge Project, No. TZ2018006-0205-04.

References
[1] Kline, W., DeVor, R., (1983) The effect of runout on cutting geometry and forces in end milling. International Journal of Machine Tool Design & Research, 23: 123–140.
[2] Zhang, X.J., Xiong, C.H., Ding, Y., Xiong, Y.L., (2011) Variable-step integration method for milling chatter stability prediction with multiple delays. Science China Technological Sciences, 54: 3137–3154.
[3] ARMAREGO E. J. A., DESPANDE N. P., (1991) Computerized end milling force prediction with cutting models allowing for eccentricity and cutter deflections. Annals of the CIRP, 40: 25-29.
[4] Zhang, X.J., Xiong, C.H., Ding, Y., Dynamic cutter runout measurement with laser sensor. In: International Conference on Intelligent Robotics and Applications. Montreal. pp. 264-272.
[5] Arizmendi, M., Fernandez, J., Gil, A., Veiga, F., (2010) Identification of tool parallel axis offset through the analysis of the topography of surfaces machined by peripheral milling. International Journal of Machine Tools and Manufacture, 50: 1097-1114.
[6] Guo, Q., Sun, Y.W., Guo, D.M., Zhang, C.T., (2012) New mathematical method for the determination of cutter runout parameters in flat-end milling. Chinese Journal Of Mechanical Engineering, 25: 947-952.
[7] Wan M., Zhang W. H., Tan G., et al. (2006) New algorithm for calibration of instantaneous cutting-force coefficients and radial run-out parameters in flat end milling. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 221: 1007–1019.