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Prediction of Milling Force Based on Actual Radial Cutting Depth in Peripheral Milling of Complex Curved Surface

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Abstract. In order to predict the milling forces in the process of peripheral milling of complex curved surface with high efficiency and precision, this paper make a description on the workpiece contour and tool path through parametric curved surface. New methods are proposed to calculate actual feed per tooth and actual radial cutting depth, and calculation equations are derived. And then, a model for instantaneous milling force is established. Through simulation, this paper prove that curvature has little or even no effect on feed per tooth. Curvature mainly influences actual radial cutting depth. Also, when tool diameter is greater, curvature has more significant influences on actual radial cutting depth. Then, a method to predict milling force based on actual radial cutting depth is proposed. Moreover, this paper make a prediction on the milling force in peripheral milling of complex curved surface and conducted tests for validation. The predicted and experimental results have a good consistency both in variation tendency and amplitude, and time cost of simulation is significantly reduced, which show that the presented method has high precision and calculation efficiency.

1. Introduction
Milling force as one of the most important physical parameters in the milling process, directly influences the deformation of tools and workpieces, milling stability, tool wear, and etc., and thus further influences processing precision, processing efficiency and energy consumption. Therefore, there is great significance in establishing precise milling force model and realizing its prediction. At present, the studies on milling force are mainly focused on straight line milling which has zero curvature and circular-arc milling which has constant curvature. Under the two kinds of circumstances, because of the invariance of geometric conditions, the instantaneous milling force takes on periodical changes. In the fields of aviation, molding, automobile and electronics, the curvature of most complex curved surfaces are constantly changing. Influenced by curvature, the processing parameters such as actual radial cutting depth and actual feed per tooth deviated from nominal values, and got time-varying characteristics, thus it is difficult to predict instantaneous milling force with precision through traditional methods. Therefore, some scholars studied the prediction method of milling force in variable curvature surfaces.

Taking peripheral milling as study object, Rao systematically studied the process geometric and established the process geometric model and proposed the calculation method of actual feed per tooth and entry/exit angles. By considering the situation of tool bending and deformation, Rao established
the analytical model of milling force and analyzed the influence of curved tool path on milling force and surface errors [1-2]. On this basis, Desai took Bezier curve as an example and studied the influence of parameterized direction of curved surfaces and tool diameter on milling force and surface errors, and further improved the milling force model of variable curvature milling [3]. By utilizing the actual feed per tooth proposed by Rao, Qi established a milling force model for low-rigidity cycloid gear profile [4]. The references from [1] to [4] all took the distance between two neighboring teeth and their intersection point with the surface to be processed as equivalent feed per tooth, and calculated the instantaneous undeformed chip thickness on this basis. This method simplified the calculation of instantaneous undeformed chips, but it may affect the prediction precision of milling force.

On the basis of preliminary studies, Desai further analyzed the influence of cutter runout on milling parameters and proposed the implicit algorithm of instantaneous undeformed chip thickness. However the method requires calculation on a great deal of system of nonlinear equations, so the calculation efficiency of this method is very low [5]. By finding out the cutter location point through NC code, Wei proposed the calculation method of instantaneous chip thickness and entry/exit angles, and established a milling force model in peripheral milling of curved surface with variable curvature, and the sudden changes in tool feeding direction brought about sudden changes in milling force prediction [6]. Yang proposed a new method of finding out the cutter location point based on NC codes, and densified the cutter location points. This method overcame the defect of sudden changes in milling force prediction and offered an explicit formula of instantaneous undeformed chip thickness by simplifying the micro-line curve into circular arcs, and improved calculation efficiency [7-8]. Through coordinate transformation, Hao proposed a calculation formula of simplifying instantaneous undeformed chip thickness including tool runout [9]. By taking into account the tool path, tool runout and actual movement of the tool, Zhang put forward an iterative algorithm of instantaneous undeformed chip thickness [10]. Ji offered a kind of new calculation method for instantaneous undeformed chip thickness and actual radial cutting depth, and applied them to corner milling force of any molds [11], and on this basis, Liu proposed load-based optimization of feed speed [12]. Cao [13] and Zeroudi [14] analyzed the calculation equation of undeformed chip thickness and entry/exit angles in 3D curved surface processing. The calculation methods proposed in references [5-14] could improve the milling force prediction precision, but may affect calculation efficiency.

This paper proposed a new calculation method of actual feed per tooth and actual radial cutting depth and established the instantaneous milling force model in peripheral milling of complex curved surface. In addition, it analyzed the influence of curvature on actual feed per tooth and actual radial cutting depth, and on this basis, it simplified the milling force model and verified the precision of milling force prediction through milling test. The method has the advantage of avoiding solution of a great deal of formulas and can significantly improve the prediction efficiency.

2. Geometric description of peripheral milling of complex curved surface

The peripheral milling of complex curved surface is shown in Figure 1. With constant changes in curvature of target contour, since the tool has different feed directions and different engaging status at different locations, for convenience of milling force calculation, the fixed coordinate system \(\alpha xy\) and follow-up coordinate \(o, x, y_s\) were established. \((x(u), y(u), z(u))\), \((x_s(u), y_s(u))\) and \((x(u), y(u))\) represent tool path, contour before processing and target contour respectively. \(R\) is tool radius, \(a_e\) is nominal radial cutting depth, and \(A\) and \(B\) are the center points of the tool.

Regarding the parametric geometry of desired surface as reference, the tool path and workpiece contour can be expressed by
\[
\begin{align*}
    x_w(u) &= x(u) - \frac{a_x y'(u)}{\sqrt{x'(u)^2 + y'(u)^2}} \\
    y_w(u) &= y(u) + \frac{a_y x'(u)}{\sqrt{x'(u)^2 + y'(u)^2}} \\
    x_i(u) &= x(u) - \frac{R y'(u)}{\sqrt{x'(u)^2 + y'(u)^2}} \\
    y_i(u) &= y(u) + \frac{R x'(u)}{\sqrt{x'(u)^2 + y'(u)^2}}
\end{align*}
\]

(1)

Where, \(x'(u)\) and \(y'(u)\) represent the differential of the parametric curve.

The positive and negative values of the curvature of plane curve show the bending direction of the curve, if the curvature of concave curve is set as negative, the curvature of convex curve is set as positive, then the curvature calculation equation of the curved surface is

\[
C(u) = \frac{x''(u)y'(u) - x'(u)y''(u)}{(x'(u))^2 + (y'(u))^2}^{3/2}
\]

(2)

Where, \(C(u)\) is the curvature of corresponding point of parameter \(u\).

\(o_s x_s\) is the instantaneous tool feed direction, the angle between \(o_s x_s\) and \(o_x\) represent the feed direction angle. If we stipulate the outward rotation of \(o_s x_s\) relative to \(o_x\) as positive, and inward rotation as negative, then the feed direction angle is

\[
\theta(u) = \arcsin \frac{y'(u)}{\sqrt{(x'(u))^2 + (y'(u))^2}}
\]

(3)

Where, \(\theta(u)\) is the feed direction angle when the tool is at the location of parameter \(u\).

Figure 1. Representation of peripheral milling of complex curved surface

3. Calculation of actual milling parameters

3.1. Actual feed per tooth

Feed per tooth is the displacement of cutter at feed direction relative to workpiece when the tool rotates over a tooth spacing angle. In milling of complex curved surface, because of the constant changes in workpiece contour curve and tool feed direction, the actual feed per tooth would deviate
from the nominal feed per tooth. In Figure 2, $o_s x_s$ is the tool feed direction when the tool center is at point $B$, and point $C$ is the intersection point of the previous tooth trajectory and contour before process, $D$ is the intersection point of current tooth trajectory and contour before process, and draw a parallel line of $o_s x_s$ at $D$, which intersects the previous tooth trajectory at $E$. The definition of feed per tooth indicates that, DE is the instantaneous actual feed per tooth of the tool.

By applying the geometric relation between tooth milling trajectory and contour curve before process, the corresponding parameter $u_d$ of $D$ can be obtained by

$$[x_t(u_b)-x_u(u_d)]^2+[y_t(u_b)-y_u(u_d)]^2 = R^2$$ (4)

According to the curve parameter $u_b$ of point $B$, parameter $u_a$ of point $A$ can be calculated by

$$[x_t(u_a)-x_t(u_b)]^2+[y_t(u_a)-y_t(u_b)]^2 = f_z^2$$ (5)

Based on parallel relation between $DE$ and tool feed direction, the coordinate of point $E$ $(x_e, y_e)$ can be obtained by

$$\begin{align*}
\frac{y_u(u_d)-y_e}{x_u(u_d)-x_e} &= \tan(\theta(u_b)) \\
(x_e-x_t(u_d))^2+(y_e-y_t(u_d))^2 &= R^2
\end{align*}$$ (6)

Then, actual feed per tooth of tool center point at point $B$ is

$$f_{zc}(u_b) = \sqrt{(x_e-x_u(u_d))^2+(y_e-y_u(u_d))^2}$$ (7)

Where, $f_{zc}(u_b)$ is instantaneous actual feed per tooth.

3.2. Actual radial cutting depth

In the peripheral milling of complex curved surface, because of constant changes in curvature of workpiece contour, actual radial cutting depth deviates from nominal radial cutting depth. Moreover, with changes of tool positions, the actual radial cutting depth may also change constantly, and there might be changes of cutting engaging area and time-varying characteristics of entry/exit angles, which may have important influences on the precise prediction of milling force and judgment of milling stability. In Figure 2, $FH$ is parallel to feed direction of tool $o_s x_s$, and $DH$ is perpendicular to $FH$. $DH$ is the actual radial cutting depth when tool is at point $B$. Apparently, in processing concave surface, the actual radial cutting depth is larger than nominal radial cutting depth and in processing convex curved surface, the actual radial cutting depth is lower than nominal radial cutting depth. Geometric relation shows that, the calculation equation of actual radial cutting depth when the tool is at point $B$ can be described as

$$a_{zc}(u_b) = \left| x_u(u_d)-x(u_b) \right| \sin \theta(u_b) - \left| y_u(u_d)-y(u_b) \right| \cos \theta(u_b)$$ (8)

Where, $a_{zc}(u_b)$ is the actual radial cutting depth of tool at point $B$. 
4. Milling force modeling in peripheral milling of complex curved surface

In the tool axis direction, the milling-cutter edge is separated into several small cutting edges, then there is oblique cutting for each micro-element, and the cutting force on the $j$th micro-element at $i$th tooth can be expressed as

$$
\begin{align*}
\{ dF_{x,i}(u) &= K_i(h_{j,i}(u))h_{j,i}(u)dz \\
\{ dF_{r,i}(u) &= K_i(h_{j,i}(u))h_{j,i}(u)z \\
\end{align*} 
$$

(9)

Where, $dF_{x,i}(u)$ and $dF_{r,i}(u)$ are the tangential and radial cutting force of the micro-element $(i,j)$. $h_{j,i}(u)$ is the instantaneous undeformed chip thickness of micro-element $(i,j)$. $dz$ is the axial length of micro-element. $N_f$ is the number of teeth. $M$ is equivalent fractions of each tooth. $K_i(h_{j,i}(u))$ and $K_r(h_{j,i}(u))$ are tangential and radial cutting force coefficients, whose relationship with undeformed chip thickness in reference[15] is defined as

$$
\begin{align*}
\{ K_i(h_{j,i}(u)) &= T_0 h_{j,i}(u) T_1 \\
K_r(h_{j,i}(u)) &= R_0 h_{j,i}(u) R_1 \\
\end{align*} 
$$

(10)

Where, $T_0$, $T_1$, $R_0$ and $R_1$ are constants, which are determined by elements such as workpiece materials, tools and spindle speed, and not influenced by feed per tooth, axial cutting depth and radial cutting depth.

When the center position of tool is at parameter $u$, the undeformed chip thickness of micro-element $(i,j)$ based on actual feed per tooth can be calculated by

$$
\begin{align*}
\{ h_{j,i}(u) &= f_{ui}(u) \sin(\varphi_{ui}(u)) & \varphi_{ui}(u) \leq \varphi_{ui}(u) \leq \varphi_{xi}(u) \\
\{ h_{j,i}(u) &= 0 & \text{else} \\
\end{align*} 
$$

(11)

$$
\varphi_{ui}(u) = \varphi_x(u) - \frac{2\pi(i-1)}{N_f} - \frac{(j-0.5)\tan \beta dz}{R} 
$$

(12)
Where, $\phi_{st,j}(u)$ is the position angle of micro-element $(i,j)$ in the follow-up coordinate $o_xo_yo_z$, $\phi_s(u)$ is the position angle of tool at follow-up coordinate $o_xo_yo_z$. $\phi_{st}(u)$ and $\phi_{su}(u)$ are instantaneous entry and exit angles. $\beta$ is tool helical angle.

Separating tool trajectory curve into several tiny curves by equivalent parameter intervals and imitate tool trajectory, then the instantaneous position angle of tool in follow-up coordinate can be determined with

$$
\begin{align}
\phi_s(u) &= 2\pi n_s t(u) + \theta(u) \\
t(u) &= \frac{60}{f_s N_s n_s} \sum_{k=1}^{u/\Delta u} L((k-1)\Delta u, k\Delta u)
\end{align}
$$

(13)

Where, $n_s$ is the spindle speed. $L((k-1)\Delta u, k\Delta u)$ is the distance between two neighboring parameter points at tool path. $\Delta u$ is parameter spaces.

Based on actual radial cutting depth, the entry and exit angles can be calculated by

$$
\begin{align}
\phi_{st}(u) &= \pi - \arccos \left(1 - \frac{a_{st}(u)}{R}\right), \quad \phi_{su}(u) = \pi \quad \text{down milling} \\
\phi_{st}(u) &= 0, \quad \phi_{su}(u) = \arccos \left(1 - \frac{a_{st}(u)}{R}\right) \quad \text{up milling}
\end{align}
$$

(14)

Then, transforming cutting force of micro-element into the direction component of $x_s$ and $y_s$ in follow-up coordinate $o_xo_yo_z$, and summatting the cutting forces of micro-elements, instantaneous milling forces in feed direction and normal direction can be expressed by

$$
\begin{align}
F_{xs}(u) &= \sum_{i=1}^{N_x} \sum_{j=1}^{M} \left[ \cos \phi_{st,i}(u) dF_{i,j}(u) - \sin \phi_{st,i}(u) dF_{ri,j}(u) \right] \\
F_{ys}(u) &= \sum_{i=1}^{N_x} \sum_{j=1}^{M} \left[ \sin \phi_{st,i}(u) dF_{i,j}(u) - \cos \phi_{st,i}(u) dF_{ri,j}(u) \right]
\end{align}
$$

(15)

Where, $F_{xs}(u)$ and $F_{ys}(u)$ are milling force in instantaneous feed direction and normal direction respectively.

Since the feed direction and normal direction are change constantly, the milling forces in feed direction and normal direction are difficult to be measured in process. So, the milling forces are transformed into the fixed coordinate system $oxy$ and can be expressed as

$$
\begin{align}
F_x(u) &= F_{xs}(u) \cos \theta(u) - F_{ys}(u) \sin \theta(u) \\
F_y(u) &= F_{xs}(u) \sin \theta(u) + F_{ys}(u) \cos \theta(u)
\end{align}
$$

(16)

Where, $F_x(u)$ and $F_y(u)$ are milling forces at directions of $x$ and $y$.

5. Simulation analysis and test verification of peripheral milling

In order to analyze the influence of curvature on peripheral milling, the workpiece contour is designed in Figure 3, and the workpiece contour includes concave curve segments, convex curve segments and linear segments. The parametric equation of target contour is described with a Bezier curve as follows
Figure 3. Workpiece contour

Calculating curvature with Equation 2, the distribution of curvature on tool trajectory is shown in Figure 4.

![Curvature variation along tooth path](image)

Figure 4. Curvature variation along tooth path

The processing parameters are determined as follows: spindle speed is 3000 r/min, radial cutting depth is 5 mm, nominal cutting depth is 3 mm and nominal feed per tooth is 0.02 mm/r.

The machine tool is DMG High-speed Processing Center DMC 70V hi-dyn. Milling forces are measured by a force meter Kistler 9257B. The tool is Sandvick 1P240-1000-XA1630, with 10 mm in diameter, four cutting edges and flute helix angle of 35°. The workpiece material is Al6061-T6, and processing methods are dry cutting and down milling.

5.1. Influence of curvature on actual feed per tooth

Simulation of actual feed per tooth is done on tool with diameter of 10 mm by three methods, as is shown in Figure 5. The actual feed per tooth is calculated by solving the undeformed chip thickness \( h_c \) (\( CJ \) in Figure 2) and is divided by the sine value of position angle \( \theta_c \), namely, \( f_{z_e} = \frac{h_c}{\sin \theta_c} \).
Figure 5 shows that actual feed per tooth obtained by the calculation method in this paper is almost the same with the reverse calculation, and there is great discrepancy between the actual feed per tooth obtained by the method proposed in [1] and that by reverse calculation. This demonstrates that, the method presented in this paper has higher precision. Moreover, there is little influence of curvature on actual feed per tooth, which is approximately the nominal feed per tooth.

![Figure 5. Actual feed per tooth](image)

5.2 Influence of curvature on actual radial cutting depth

Based on Equation 8, a simulation of actual radial cutting depth in milling of tool with three different diameters, and the simulation results are shown in Figure 6. Figure 6 shows that, there is significant influence of curvature on actual radial cutting depth, when the entry point of tool reaches curve segments, the actual radial cutting depth starts to change. In concave curve milling, the actual radial cutting depth is greater than nominal radial cutting depth, and in convex curve milling, the actual radial cutting depth is less than nominal radial cutting depth, and decreases with the increase of curvature. The maximum and minimum values of actual radial cutting depth are related to tool diameters, the greater the tool diameter is, the more significant influence on the actual radial cutting depth would be.

![Figure 6. Actual radial cutting depth](image)
5.3. Simulation and experimental validation of milling force

The simulation result of actual feed per tooth and actual radial cutting depth show that, in peripheral milling of complex curved surface, curvature mainly influences actual radial cutting depth and has little influence on actual feed per tooth, then equation 7 can be simplified as

\[ f_{xe} = f_z \] (18)

In this case, only by substituting nominal radial cutting depth with actual radial cutting depth, the instantaneous milling force in peripheral milling of complex curved surface can be calculated by the calculation method of milling force in straight line milling.

Then, the line milling is tested to find out the cutting force coefficient. Spindle speed is 3000 r/min. Axial cutting depth is 2 mm. Nominal cutting depth is 2 mm, and feed per tooth is 0.03 mm/r. According to the method in reference [16], the cutting force coefficient can be obtained as

\[
\begin{align*}
K_r(h) &= 409.21h_0^{-0.3809} \\
K_t(h) &= 200.71h_0^{-0.4425}
\end{align*}
\] (19)

The parameter interval \( \Delta u \) is set as 0.00002. Then predict milling force by adopting the method proposed in this paper and the identified cutting force coefficient and make a verification test. The instantaneous position of the tool is shown in Figure 6, and the prediction result of milling force and test results in y direction are shown in Figure 7. Obviously, the predicted milling forces are in good agreement with measured forces both in variation tendency and amplitude in y-direction. The little differences in terms of amplitude is mainly caused by not considering the actual tool runout in simulation. The same conclusion is drawn by comparing predicted milling forces and measured milling forces at x direction. This shows high precision of the milling force model.

Under similar simulation parameters, time cost of simulation with the method proposed in reference [2] is 52s, while time cost with the presented method is 3.3s, which show that the method presented in this paper can improve simulation efficiency greatly. The main cause is that actual radial cutting depth is introduced into the milling force model, and calculation of instantaneous undeformed chip thickness and entry/exit angles are simplified to avoid solution of a great deal of equations.

![Figure 7. Instantaneous position of tool](image-url)
6. Conclusion
A new approach is proposed to predict the milling force for peripheral milling of complex curved surface. Firstly, this paper describes the workpiece contour through parametric curved surface and derived the calculation equation for actual feed per tooth and actual radial cutting depth. Then, an instantaneous milling force model is established. The influence of curvature on actual feed per tooth and actual radial cutting depth are analyzed with simulation. Results show that curvature has little influence on actual feed per tooth, and actual feed per tooth can approximate nominal feed per tooth. Curvature has significant influence of curvature on actual radial cutting depth. The higher the tool diameter is, the influence may be more significant. On this basis, milling force model is further simplified. The identification of cutting force coefficients are completed by straight line milling. Based on the identified milling force coefficients, simulation and test on peripheral milling of complex curved surface are done, and there is good consistency between simulation results and test results, which validates the precision of the milling force model. In the meantime, this method can avoid a great deal of complicated calculation, significantly improve simulation efficiency. Therefore, the presented method can be applied to predict stability for milling of complex curved surface and optimize milling parameters.

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