Title:
Ramp Approach Parameter Correction Method for 3-axis Web Machining

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Introduction:
In computer numerical control (CNC) pocket milling, the web features on the bottom surface of a pocket are usually machined by a 3-axis pocketing operation using axis motion and the ramp motion. If the ramp parameters of the approach macro are inappropriate, interference occurs when machining the pocket with a NC machining program. However, the process file corresponding to the NC machining program is often missing; thus, it is impossible to intuitively detect the approach interference of the main surface by the current commercial CAM system. Therefore, it is necessary to detect and correct the ramp approach parameters to avoid interference.

A lot of research has been made on interference in NC machining. In the review paper by Tang [4], collisions are classified as either local or global. In the study by Li et al. [3], cutter interference is classified into two types, gouging and collision. Both of these led low tool life, surface quality, and even severe equipment damage [1,2]. Zhang et al. [7] model the interference between a tool and a workpiece as the approaching extent evaluation of the tool swept envelope surface and the vibrating workpiece surface in the milling process. Wang and Sun [5] use the interference-free spiral milling NC machining tool path to predict and compensate for deformation errors. The tool entry/exit angle is considered in the cutter/workpiece engagement model of the 5-axis ball-end milling in the study by Zhang et al. [6]. In Yu et al.'s paper [8], a novel tool orientation optimization method for 3 + 2-axis machining based on the sample points selection method is introduced. However, most of these existing studies focused on interference-free tool path generation for 5-axis NC machining. Interference avoidance strategies for tool plunging into materials for 3-axis machining has received little attention. This paper focuses on ramp approach parameter correction for 3-axis web machining to avoid interference.

Correction principles of ramp approach parameters:
As we know, to avoid cutter damage, ramp, pre-drill and helix are three common approach methods when the cutter entry the stock material. As shown in Fig.1, the ramp tool-path includes three parameters: the rising/falling height h, the ramp angle α, and the ramp length *l*.

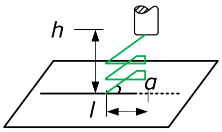


Fig. 1: Schematic diagram of the ramp approach.

Principle for the ramp length

As shown in Fig. 2, the solid line represents the tool state at the start position of the ramp, *abc* is the area to be machined by the inner edge of the insert milling cutter, and the dotted line represents the tool state at the end position of the ramp. If the ramp length l in the horizontal direction is small, then region *abc* is not completely removed by the inner edge of the tool. Area *cde* (the red region in Fig. 2) represents the residual region. As can be seen from Fig. 2, when d and c coincide, there is no residual area. Thus, the minimum ramp length l_{min} should satisfy $l_{min} = D - 2r$. Thus, the principle for ramp length is:

$$l \geq l_{min.} \tag{1}$$

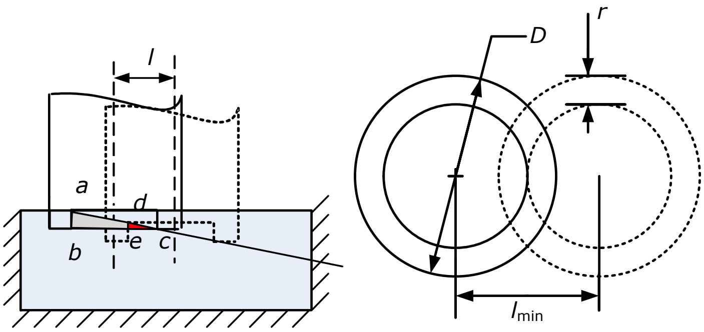


Fig. 2: Selection of ramp length in horizontal direction.

Principle for the ramp angle

As shown in Fig. 3, the critical ramp angle α_{lim} should satisfy $\alpha_{lim} = \arctan(h_{ic} / l_{nc})$, where h_{ic} is the cutting height in the tool; and l_{nc} is the length of the non-cutting section at the bottom of the tool. Here, $l_{nc} = D - 2r$, where D and r are the diameter and the bottom circle radius of the insert milling cutter, respectively.

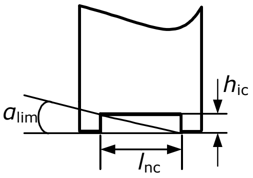


Fig. 3: Critical ramp angle.

As shown in Fig. 4, A_1 is a material body that can be cut by a tool, and A_2 is a material body that needs to be removed in the entire cavity. To ensure that the non-cutting edge of the insert tool does not participate during the cutting, the ramp angle α should satisfy the inequation $\alpha \leq \alpha_{lim}$. That is,

$$\alpha \leq \arctan(h_{ic} / l_{nc}) \tag{2}$$

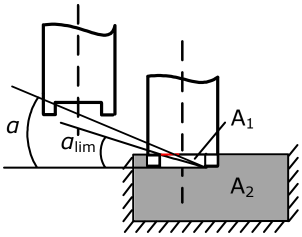
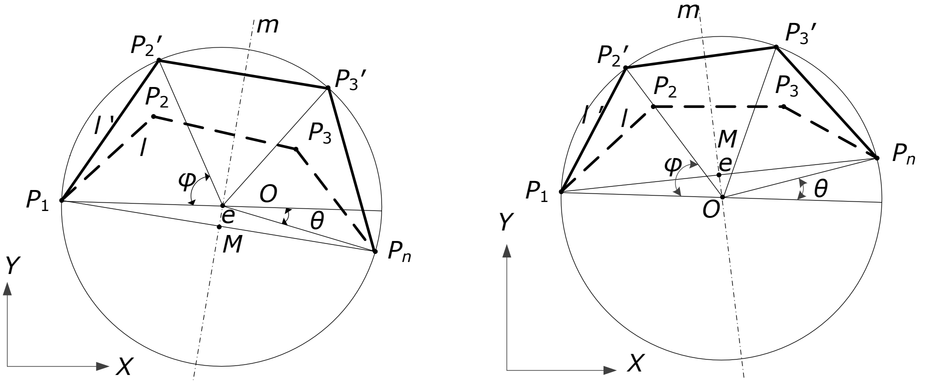


Fig. 4: Non-cutting edge participating cutting.

<u>Correction of ramp approach parameters:</u>

Ramp length correction

To correct the ramp length, a circumscribed circle method is proposed. As shown in Fig. 5, the projection of the ramp approach section on the *XOY* plane in the machine coordinate system is $P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow \ldots \rightarrow P_n$, i.e., a total of $n-1$ line segments. The length of the line segment between the adjacent two points is called the ramp length l.



a. O and the endpoints are on the same side   b. O and the endpoints are on different sides

Fig. 5: Semantic diagram of ramp length correction.

Make a mid-perpendicular line m pass through the midpoint M of line segment P_1P_n. Take a point O on the mid-perpendicular line m and ensure that O and the points P_2, P_3, …, $P_{n\text{-}1}$ are on the same side of the line segment P_1P_n. Make an auxiliary circle with O as the center and OP_1 as the radius. Next, divide the superior arc P_1P_n into $n-1$ equal parts to obtain the corrected projection $P_1 \rightarrow P_2' \rightarrow P_3' \rightarrow \ldots \rightarrow P_n$ of the polyline. Let the optimized ramp length be l', where l' satisfies $l' \geq l_{\min}$; the polyline corresponding to the projection with $P_1 \rightarrow P_2' \rightarrow P_3' \rightarrow \ldots \rightarrow P_n$ as end points is the approach section that satisfies Eq. (1). The calculation formula is

$$180^\circ + \theta = (n-1)\,\varphi$$

where $\tan\frac{\theta}{2} = \frac{e}{0.5s}\left(-\frac{\pi}{2} \leq \frac{\theta}{2} \leq \frac{\pi}{2}\right)$; $\sin\frac{\varphi}{2} = \frac{0.5l'}{R}\left(-\frac{\pi}{2} \leq \frac{\varphi}{2} \leq \frac{\pi}{2}\right)$; $R = \sqrt{\frac{1}{4}s^2 + e^2}$; e is the distance between O and M; s is the length of the line segment P_1P_n; φ is the arc angle corresponding to each arc after the superior arc P_1P_n is equally divided; and θ is the angle between the extension line of P_1O and OP_n. The relation between l' and e can be obtained as

$$\theta = 2\arctan\frac{2e}{s}$$

$$\varphi = 2\arcsin\frac{l'}{\sqrt{s^2 + 4e^2}}$$

$$90^\circ + \arctan\frac{2e}{s} = (n-1)\arcsin\frac{l'}{\sqrt{s^2 + 4e^2}}$$

By selecting the appropriate e, l' can satisfy $l' \geq l_{\min}$.

When point O, which is on the vertical line m, is on the other side of the line segment P_1P_n, that is, O and the points P_2, P_3, …, $P_{n\text{-}1}$ are not on the same side, as shown in Fig. 6b, corresponding formulations can be easily obtained by the above method.

After obtaining the projection of the corrected ramp tool-path, the optimization result of ramp length can be obtained according to the X and Y coordinates of endpoints P_2', P_3', …, $P_{n\text{-}1}'$.

Equal-ratio compression method for ramp angle correction

To make the new ramp angle $\alpha'<\alpha$, the height of the ramp inflection point of the approach section is reduced by compression, while the rest of the data is unchanged. This method is called the equal-ratio compression method. Taking the main surface of the web as the reference surface, the ratio of the new position height to the original position height, denoted by v, is called the compression ratio.

As shown in Fig. 6, P_2 is the start ramp point, and P_5 is the end ramp point, $h_1 = z_2 - z_5$, $h_2 = z_3 - z_5$, $h_3 = z_4 - z_5$. Taking the main surface of the web as the reference surface, the optimized position height $h_1' = A_P$+2~3 mm and the compression ratio $v = h_1'/h_1$, where A_p is the maximum depth of cut for the pocket machining; and 2~3 mm is an experience value. Lower the start ramp point P_2 to the height position of h_1' obtaining $P_2'(x_2', y_2', z_2')$, where $z_2' = z_2 + h_1'$. The remaining endpoints are sequentially compressed at compression rate v except the end point. During the compression process, for the new ramp angle α' to satisfy $\tan\alpha' = v\tan\alpha$ and to further obtain the optimized ramp tool-path, only the z-coordinate is multiplied by the compression ratio, while the x- and y-coordinates are unchanged. After the equal-ratio compression, if the optimized α' does not satisfy inequation (2), the layer-adding method is adopted to solve the ramp angle parameter correction problem.

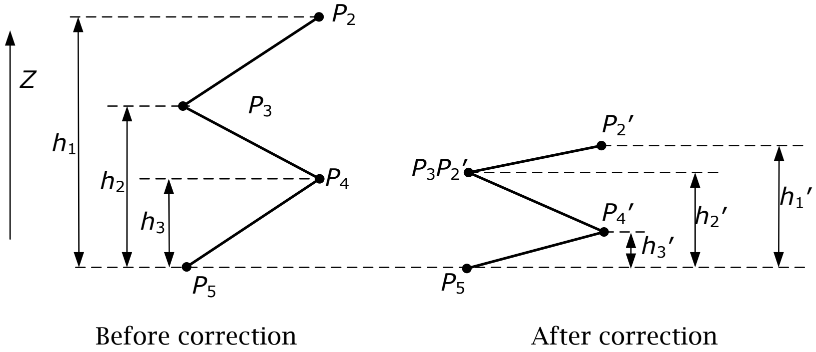


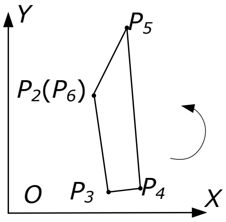
Fig. 6: Schematic diagram of equal-ratio compression method.

Layer-adding method for ramp angle correction

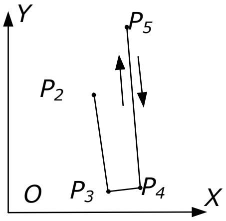
To make the new ramp angle $\alpha' < \alpha$, the method of increasing the number of ramp layers and performing equal-ratio compression is called the layer-adding method. The ratio of the number of corrected ramp layers to the number of the original ramp layers is called the layer-adding rate, which is represented by w. As can be seen from the definition of the layer-adding method, the layer-adding method includes the principle of equal-ratio compression. Using the layer-adding method, an appropriate ramp angle α' ($\alpha' \leq \alpha_{\text{lim}}$) is first calculated. Next, the layer-adding rate is derived inversely according to the compression ratio v ($v = \dfrac{\tan\alpha'}{\tan\alpha}$). Finally, the machine position coordinates corresponding to the new ramp tool-path are calculated.

Firstly, the ramp tool-path is projected onto the XOY horizontal plane. According to whether the projection trajectory is closed, the layer-adding type is divided into unidirectional layering and bidirectional layering. As shown in Fig. 7a, if the projection trajectory is closed, that is, when the x and y coordinates of the start point and the end point of the ramp tool-path are the same, unidirectional layering is adopted. If the projection trajectory is open, that is, when the projections of the start point and the end point do not coincide, the bidirectional layering method is applied, as shown in Figure 7b, where the direction of the arrow is the direction of the layer-adding.

Set the original ramp height to h; then $h' = v^*h$ is the height compressed by the compression ratio v. If the unidirectional layering method is adopted, the layer-adding ratio is $\omega = \lceil \Delta h/h' \rceil = \lceil (1-v)/v \rceil$. If the bidirectional layering method is applied, the layer-adding ratio is $\omega = \lceil \Delta h / h' \rceil = \lceil (1-v)/(2v) \rceil$, where the symbol '$\lceil\ \rceil$' means to round up to the nearest integer.



a. Unidirectional layering



b. Bidirectional layering

Fig. 7: Layer-adding method.

Conclusions:

In this study, principles of the interference-free of the ramp approach by the insert milling cutter is proposed, and the algorithm for checking and correcting the parameters of the ramp approach is established and developed. The algorithm is also verified by several test parts and the experiment result shows that there's no interference in the 3-axis web machining by the addressed techniques. And the algorithm is effective.

In the ramp angle correction, there is no way to predict whether the equal-ratio compression method is appropriate, but the trial and error method is adopted. This is a limitation of the study. Our further research will focus on to solve the problem as much as possible.

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References:

[1] Lee Y. S.: Admissible tool orientation control of gouging avoidance for 5-axis complex surface machining, Comp.-Aided Des. 29(7), 1997, 507-521. https://doi:10.1016/S0010-4485(97)00002-X

[2] Lee Y. S., and T. C. Chang.: 2-phase approach to global tool interference avoidance in 5-axis machining, Comp.-Aided Des. 27(10), 1995, 715-729. https://doi:10.1016/0010-4485(94)00021-5

[3] Li, X. Y., C. H. Lee, P. C. Hu, Y. Zhang, and F. Z. Yang.: Cutter partition-based tool orientation optimization for gouge avoidance in five-axis machining, The International Journal of Advanced Manufacturing Technology, 95(5-8), 2018, 2041-2057. https://doi: 10.1007/s00170-017-1263-4

[4] Tang T. D.: Algorithms for collision detection and avoidance for five-axis NC machining: a state-of-the-art review, Comp.-Aided Des., 51, 2014, 1-17. https://doi: 10.1016/j.cad.2014.02.001

[5] Wang M. H., and Y. Sun.: Error prediction and compensation based on interference-free tool paths in blade milling, The International Journal of Advanced Manufacturing Technology, 71(5-8), 2014, 1309-1318. https://doi:10.1007/s00170-013-5535-3

[6] Zhang X, J. Zhang, X. Zheng, B. Pang, and W. Zhao.: Tool orientation optimization of 5-axis ball-end milling based on an accurate cutter/workpiece engagement mode, CIRP Journal of Manufacturing Science and Technology 19, 2014, 106-116. https://doi:10.1016/j.cirpj.2017.06.003

[7] Zhang X. M., D. Zhang, L. Cao, T. Huang, J. Leopold, and H. Ding.: Minimax Optimization Strategy for Process Parameters Planning: Toward Interference-Free Between Tool and Flexible Workpiece in Milling Process, Journal of Manufacturing Science and Engineering 139(5), 2017, 051010. https://doi: 10.1115/1.4035184

[8] Zhu Y., Z. T. Chen, Ning T, and R. F. Xu.: Tool orientation optimization for 3+ 2-axis CNC machining of sculptured surface, Computer-Aided Design 77, 2016, 60-72. https://doi:10.1016/j.cad.2016.02.007