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A High-Speed Machining Algorithm For Continuous Corners

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Abstract: *In order to meet the requirements of high-speed machining of continuous small line segments, the mid-point constraint algorithm is proposed based on the kinematic smoothing algorithm based on jounce constrained acceleration for the overlap of corner transition contours caused by the short distance between adjacent corners. By limiting the length of the corner transition section to avoid the occurrence of contour overlap, the optimal corner transfer speed is solved under the premise of fully utilizing the performance of the driver, and the corner smooth transition is realized. By comparing and analyzing the traditional point-to-point interpolation algorithm, the processing time of the proposed algorithm is reduced by 6.8%, the processing efficiency is obviously improved, and the acceleration curve satisfies G1 continuous.*

Keyword: *High-speed machining ; Jounce ; corner smooth*

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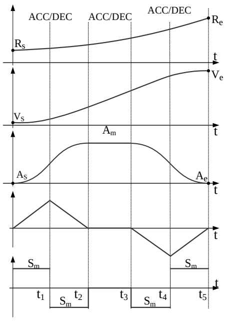
I. Introduction

In high-speed machining of complex surfaces, CAD/CAM is often used to discretize complex surfaces into a series of consecutive tiny segments based on constraints such as tolerances and machine dynamics. However, in this process, the smooth transition between small and continuous line segments is not fully considered, resulting in frequent start and stop of the system, which has a great impact on the machine tool, and it is difficult to ensure the processing quality and processing efficiency [1]. In recent years, some research scholars have made improvements to early linear interpolation and circular interpolation [2][3][4]. Also well developed are various spline interpolation methods that use high-order spline interpolation to smooth sharp corners in the machining path, allowing the machine to achieve continuous uninterrupted feed motion at the corners of the machining path. Common splines include: PH, Bezier and NURBS curves [5-7].In addition, some scholars have explored the global corner smoothing from the perspective of kinematics. The literature [8] and [9] proposed a corner smoothing method for high-speed machining based on the jump constraint. The literature [10] further proposes a jump-based approach. Degree constrained kinematic smoothing algorithm. Although the traditional point-to-point direct interpolation method can avoid this phenomenon, the feed motion must be decelerated to stop at the corner of the path. Otherwise, the acceleration value or the jump value of the drive may exceed the system limit, resulting in smooth surface of the machined part. Reference [9] uses the parameter constraint method to limit the feed rate, but the acceleration curve also has serious abrupt and non-guide points. The midpoint acceleration value of the corner profile will cause abrupt vibration to cause the inertial vibration of the feed motion, resulting in decline in quality.

In this paper, the kinematics smoothing algorithm proposed in [10] is used to realize the corner transition, and the midpoint constraint method is proposed. On the basis of the overlap of the corner contours, the midpoint of the straight line segment between the two corners is set as the constraint point. , limit the length of the transition section to avoid overlapping corner profiles. At the same time, the speed and acceleration of the feed motion at adjacent corners are smoothly transferred. Finally, the proposed algorithm is analyzed experimentally, and the effectiveness of the proposed algorithm is verified by comparing the traditional point-to-point interpolation algorithm.



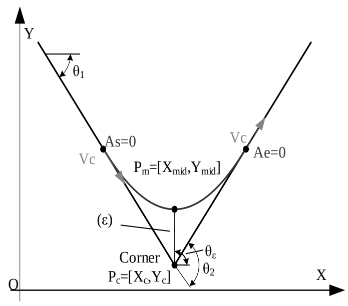


Fig1. Acceleration constrained by Jounce**Fig2.**Corner transition path

I. Adjacent corner midpoint constraint algorithm

2.1kinematics smoothing algorithm based on Jounce

The principle of jounce constrained acceleration is shown in Fig.1. The jounce-limited acceleration curve produces a smooth velocity and acceleration transition profile that limits the feed axis from a smooth transition from initial velocity and acceleration to final velocity and acceleration, When the displacement Rs, the velocity Vs and the acceleration As, the jounce-limit Sm, and the acceleration-limit Am are known, the jerk j(t), the acceleration a(t), and the velocity can be obtained by integrating the hopping curve s(t). For the formula for calculating the v(t) and displacement r(t) curves, according t equation (2-1).

$$\begin{cases} j(t)=\int_0^t s(\tau)d\tau \\ a(t)=A_s+\int_0^t j(\tau)d\tau \\ v(t)=V_s+\int_0^t a(\tau)d\tau \\ r(t)=R_s+\int_0^t v(\tau)d\tau \end{cases} \quad (2\text{-}1)$$

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$$R_C=\left|\frac{2V_sT_1+2A_sT_1^2+\frac{7}{12}S\,T_1^4}{\cos(\theta_1)+\cos(\theta_1+\theta_2)}\right| \quad (2\text{-}2)$$

Assuming the X axis is the limit axis, then the acceleration, velocity, and maximum contour error constraints of the limit axis can be calculated:

$$\begin{cases} A_C\cos(\theta_1+\theta_2)=-A_C\cos(\theta_1)+S_xT_1^2 \\ V_C\cos(\theta_1+\theta_2)=V_C\cos(\theta_1)-2A_C\cos(\theta_1)T_1+S_xT_1^3 \\ \varepsilon\cos(\frac{\pi}{2}+\theta_1+\frac{\theta_2}{2}) \\ =\frac{V_C\cos(\theta_1)T_1(\cos(\theta_1+\theta_2)-\cos(\theta_1))-A_C\cos(\theta_1)T_1^2(\frac{1}{2}\cos(\theta_1+\theta_2)-\frac{3}{2}\cos(\theta_1))+S_xT_1^4(\frac{1}{24}\cos(\theta_1+\theta_2)-\frac{13}{24}\cos(\theta_1))}{\cos(\theta_1)+\cos(\theta_1+\theta_2)} \end{cases} \quad (2\text{-}3)$$

2.2Midpoint constraint algorithm

Although the kinematic smoothing algorithm enables smooth transitions in feed axis speed and acceleration during continuous short-segment tool path machining. However, the relationship between the length of the line segment between adjacent corners and the length of the corner transition section cannot be considered. There may be a phenomenon that the corner transition contour overlaps during the machining process, as shown in Fig. 3. The distance between the short segments of the two corner contours is:

$$R=\left\|P_c^k-P_c^{k+1}\right\|-(R_c^k+R_c^{k+1}) \quad (2\text{-}4)$$

The following parameters were set for easy calculation：

$$\left\| P_c^k - P_c^{k+1} \right\| = d, \quad R_c^k = l_1, \quad R_c^{k+1} = l_2 \quad (2\text{-}5)$$

Where d is the length of the straight segment between the two corners, is the length of the transition of the previous corner, is the length of the transition of the latter corner.

If R>0, it means that there is no overlap between the kth and (k+1)th corner contours, and the front and rear corners of the short line segment are independent corners, which do not affect each other. If R<0, it means that the kth and (k+1)th corner profiles overlap each other, indicating that the front and rear corners of the short line segment interact with each other. Once this happens, the feed motion must lower the transfer speed at the corner, otherwise The feed motion of the overlap will exceed the limits of the drive system, causing the machine feed to tremble. At the same time, the acceleration profile may also have a beating or non-leading point, which affects the processing quality.

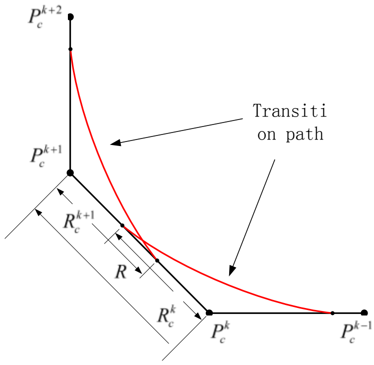


Fig3. Overlapping corner transition path

If $\min\{l_1,l_2\}>0.5d$ means that the two corner transition linear segments are more than half of the line segment between the inflection points, so set $l_1=l_2=0.5d$ then the new transfer speed at the two corners is: $V_c=V_{c1}=V_{c2}$

If $\min\{l_1,l_2\}<0.5d$ means that one side exceeds the midpoint and the other side does not exceed the midpoint, then set $l_1= 0.5d$ The new transfer speed of the former corner and the second corner can both be calculated.

$$\begin{cases} V_{c1}{}' = V_c{}' \\ V_{c2}{}' = V_{c2} \end{cases} \quad (2\text{-}6)$$

Midpoint constraint algorithm is to select the segment midpoint as the constraint point of the transition segment, limit the segment length of the transition segment, and use it as a known parameter to re-solve the corner transit speed.

$$\begin{cases} V_{sx} = V_c\cos(\theta_1) \\ A_{sx} = -A_c\cos(\theta_1) \\ A_c\cos(\theta_1+\theta_2) = -A_c\cos(\theta_1) + S_xT_1^2 \\ V_c\cos(\theta_1+\theta_2) = V_c\cos(\theta_1) - 2A_c\cos(\theta_1)T_1 + S_xT_1^3 \\ R_c = \left| \dfrac{2V_{sx}T_1 + 2A_{sx}T_1^2 + \frac{7}{12}S_xT_1^4}{\cos(\theta_1)+\cos(\theta_1+\theta_2)} \right| \end{cases} \quad (2\text{-}7)$$

Assuming that the limit axis is fed at the maximum hop limit of the drive, the optimum transfer speed is determined according to Eq.(2-7) and Eq. (2-8):

$$\begin{cases} T_1 = \sqrt[4]{\dfrac{12(\cos(\theta_1)+\cos(\theta_1+\theta_2))R_c}{7S_x}} \\ A_c = \dfrac{S_x\sqrt[2]{\dfrac{12(\cos(\theta_1)+\cos(\theta_1+\theta_2))R_c}{7S_x}}}{\cos(\theta_1)+\cos(\theta_1+\theta_2)} \\ V_{CS\max} = \dfrac{S_x(\sqrt[4]{\dfrac{12(\cos(\theta_1)+\cos(\theta_1+\theta_2))R_c}{7S_x}})^3}{\cos(\theta_1)+\cos(\theta_1+\theta_2)} \end{cases} \qquad (2\text{-}8)$$

Assuming that A=Amax , then the optimum transfer speed can be calculated.

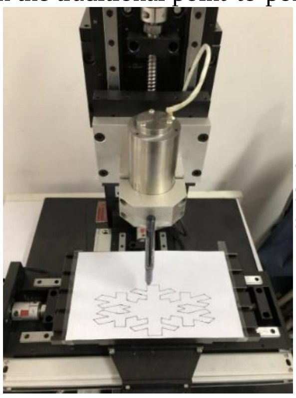
$$\begin{cases} T_1 = \sqrt{\dfrac{12R_c}{7A_c}} \\ S_x = \dfrac{7A_c^2(\cos(\theta_1+\theta_2)+\cos(\theta_1))}{12R_c} \\ V_{CA\max} = \sqrt{\dfrac{12A_cR_c}{7}} \end{cases} \qquad (2\text{-}9)$$

In summary, the new transfer speed can be calculated.

$$V_C^{'} = \min\{V_{CS\max}, V_{CA\max}\} \quad (2\text{-}10)$$

II. Simulation and experiment

In order to verify the effectiveness of the proposed algorithm, the continuous short-segment processing path is compared with the traditional point-to-point direct interpolation algorithm.



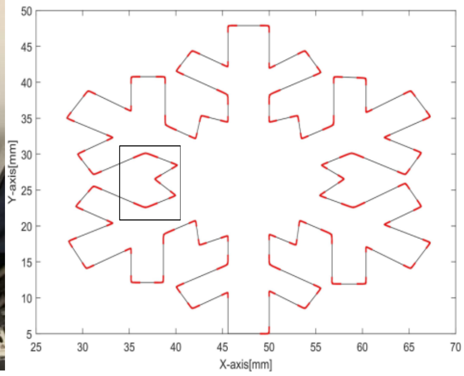


Fig4. Experimental path**Fig5.**Simulation path

The experimental equipment is shown in Fig 4. The planar XY motion is driven by two linear motors to ensure good position synchronization and path tracking. The linear encoder feedback resolution is 0.8um. The closed-loop sampling time of the servo system is 0.1ms, and the position feedback bandwidth of the X and Y axes is w_n=25Hz. The experimental processing path is a 'snowflake' path as shown in Fig 5, with a total length of 296.25 cm and 77 corners.

In order to show that the method can play the performance of the driver, it is compared with the traditional point-to-point direct difference compensation algorithm. The point-to-point interpolation algorithm requires the tool to start decelerating before each corner point until the corner stops completely, and then the steering feed is fully synchronized with the path specified by the G01 code; the experimentally set maximum allowable contour error is 0.1 mm. Real-time sampling and commanding of different algorithms using a servo controller. Set the maximum feed speed of each axis of the drive to 100mm/s, the maximum acceleration is 1000cm/s2, the maximum jump is 1×10^5mm/s4, and the maximum jump is 2×10^7mm/s4.

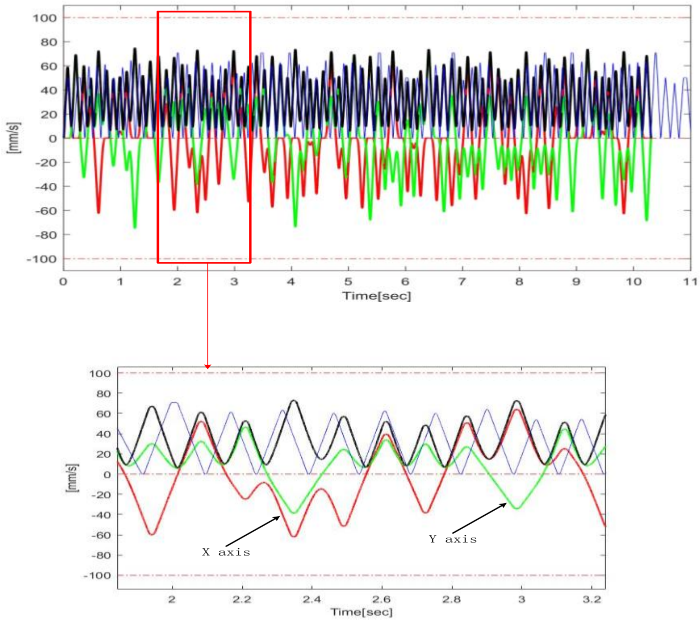


Fig6. Comparison of speed curves of two algorithms

Fig 6 shows the velocity profile of the two algorithms moving on the machining path. It can be seen that the velocity curve of the point-to-point interpolation algorithm has large fluctuations, and the algorithm needs to stop completely at each corner, the acceleration jumps, and the drive The load is large. It can also be seen from the figure that the midpoint constraint algorithm takes 10.28s, the point-to-point algorithm costs 11.08s, and the processing efficiency increases by 6.8%. At the same time, the acceleration curve of the proposed algorithm reaches G1 continuously as shown in Fig 7.

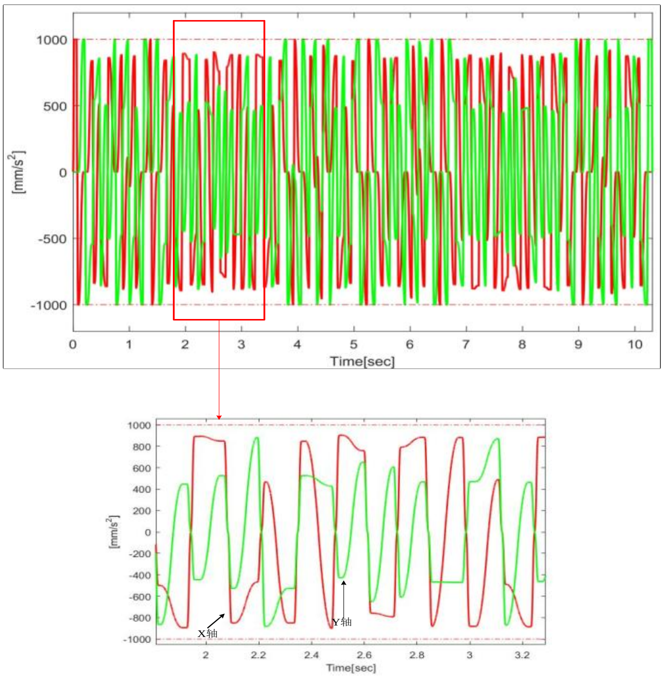


Fig7. Acceleration curve based on midpoint constraint algorithm

III. Conclusions

In this paper, we use the method of hopping to constrain the acceleration curve, and propose a midpoint constraint method for the special case in the processing path, that is, the overlapping of adjacent corner contours, limit the length of the transition segment to prevent the corner transition contour from overlapping, and achieve smooth speed and acceleration. Transfer, the acceleration curve reaches G1 continuously. Finally, the algorithm is compared with the traditional point-to-point direct interpolation algorithm. It is found that the processing time of the midpoint constraint algorithm is reduced by 6.8% compared with the point-to-point interpolation algorithm, and the processing efficiency is improved.

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