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A Mixed Bi-directional S-curve Acceleration/Deceleration Control Algorithm for Continuous Segments

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Abstract: *During the continuous segments interpolation for high-speed machining, the 7-period S-curve Acceleration/Deceleration(ACC/DEC) algorithm is complicated to implementbecause of complexclassification and huge computation. Though 5-period S-curve is a simplified model, it spends more time in accelerating and decelerating because acceleration changes constantly. Therefore a mixed bi-directional S-curveACC/DECinterpolation algorithm is presented to control the velocity from the positive and reverseof each segment, and obtain the information of feedrate and displacement.It can significantly reduce the time of velocity planning, improve the machining efficiency, and effectively avoid the mechanical vibration caused by the saltation of velocity and acceleration. Finally, the proposed algorithm is analyzed and validated by using a simulation example.*

Keywords - *High-speed machining, S-curve algorithm, acceleration/deceleration control, interpolation,*

I. INTRODUCTION

High-speed and high-precision numerical control (NC) machining is mainly applied to machining a series of continuous linesegments thatarediscretely formed by complex curves and surfaces [1].When NC interpolates the continuous linesegments, the ACC/DEC algorithm is widely used as follows: linear ACC/DEC algorithm[2], exponential ACC/DEC method[3], S-curve ACC/DEC algorithm[4]. Due to the easy formulation and less computation, linear ACC/DEC algorithm and exponential ACC/DEC methodare generally used ineconomical computer numerical control (CNC) systems.However the acceleration mutation in two ACC/DEC algorithmcauses machine tool vibration and affects the machining quality. S-curve ACC/DEC algorithm has good flexibility and high machining quality, and can realize the continuous smooth changes of velocity and acceleration, which becomes one of most important research in ACC/DEC algorithm and is widely used in high-grade CNC system[5].

S-curve ACC/DEC algorithm can be divided into 7-period S-curve and 5-period S-curve, and5-period S-curve is obtained from the 7-period S-curve which simplify the uniform acceleration and the uniform deceleration. Mecklet al. [6] proposed a method to minimize the residual vibration by optimizing the parameters of asymmetric S-curve federateprofile.Erkorkmazet al. [7] presenteda S-curve algorithmby generating a quintic spline trajectory to produce continuousposition, velocity, and acceleration profiles.Chen et al. [8] developed an S-curve ACC/DEC algorithmtogenerate federateprofiles with limited values offederate, feed acceleration, and feed jerk by using a quinticfeedrate function. Yau et al.[9] proposed a method to make the single block achieve C^1 continuity and jerk-limited capability by using the S-shaped federate profile for ACC/DEC planning. Zhang et al.[10] used the equivalent trapezoidal velocity profile to analyze the speed of S-curve velocity profileand work out the accurate interpolation method of S-curve velocity profile. Zheng et al. [11] proposed the 5-period S-curveto implement S-curve acceleration and deceleration based on the control of anticipation time. The

7-period S-curvealgorithmis complicated to implementbecause ofcomplicatedclassification and huge computation.Compared to 7-period S-curve, the 5-period S-curve is a simplified model, but its acceleration changes constantly and cannot maintain a higher value so that the velocity changes slower and spends more time in accelerating and decelerating.

In this paper a 7-period and 5-period mixed bi-directional S-curveACC/DEC algorithm is proposed to control the velocityfrom the positive and reverse of each segmentand obtain the information of velocity and displacement.Due to the symmetry between the acceleration period and the deceleration period in S-curve, the deceleration period can be regarded as the reverse acceleration period. Thus only the acceleration period is considered in S-curve algorithm so as to simplify the operation. So the proposed algorithm can significantly reduce the time of velocity planning, improve the machining efficiency, and achieve the continuous smooth of velocity and acceleration.

The rest of this paper is organized as follows: the mixed bi-directional S-curve ACC/DEC algorithm is presented in Section 2, which including the basic principle of the algorithm, the determination of velocity parameters of the accelerationregion, and the determination of the mixed S-curve type and parameters. Then Section 3 presents the simulation and experimental results obtained with the proposedalgorithm, and the conclusions are summarized in Section 4.

II. Amixedbi-directional S-curve ACC/DEC algorithm

2.1The basic principle of the algorithm

Fig. 1 presents a mixedbi-directional ACC/DEC algorithm with 7-period S-curve and 5-period S-curve. The basic idea is that if the CNC accelerates from the initial velocity (transition velocity) v_i and end velocity v_{i+1} to the maximum velocity $v_{\max}$ along the positive and reverseof the (i+1)thtool path respectively, then the type of the S-curve ACC/DEC algorithm can be obtained by comparing the relations between displacement S_a of the positive acceleration period, the displacement S_b of the reverse accelerationperiod and the (i+1)th displacement S. In practical applications, it is difficult for the CNC system to predefine whether the machining velocity v can reach the programmingvelocity v_f so that the calculation formula of S-curve cannot be determined. So by assuming the machining velocity can reach the programmingvelocity, and then the type of the S-curve ACC/DEC algorithm and the corresponding calculation equations are decided by the comparison of displacement and velocity.

The type of S-curve ACC/DEC algorithm can be judged in Fig. 2. Where ① shows that the velocity can reach the programmingvelocity v_f along the positive and reverse tool path respectively, and the S-curve has the uniform period. ②represents that if $S_a + S_b > S$, then the velocity cannot reach the programmingvelocity v_f, and the velocity parameters can be recalculated by setting $S_a + S_b = S$, and the S-curve has the accelerationperiod and decelerationperiod. The S-curve only has the uniformperiod in ③. ④shows that if $S_a < S$, then the type of S-curve is accelerationperiod and uniformperiod. If $S_a = S$, then the S-curve only has the accelerationperiod. If $S_a > S$, then setting $S_a = S$ and the S-curve only has the accelerationperiod, therefore velocitycan be calculated. ⑤represents that if $S_b < S$, then the type of S-curve is uniformperiod and decelerationperiod. If $S_b = S$, then the S-curve only has the decelerationperiod. If $S_b > S$, then setting $S_a = S$, sovelocity parameters can be worked out because the S-curve only has the reverse acceleration period. ⑥shows that the velocitycan just accelerate to v_f along the positive and reverse tool path respectively, so that the S-curve only has the accelerationperiod and decelerationperiod.

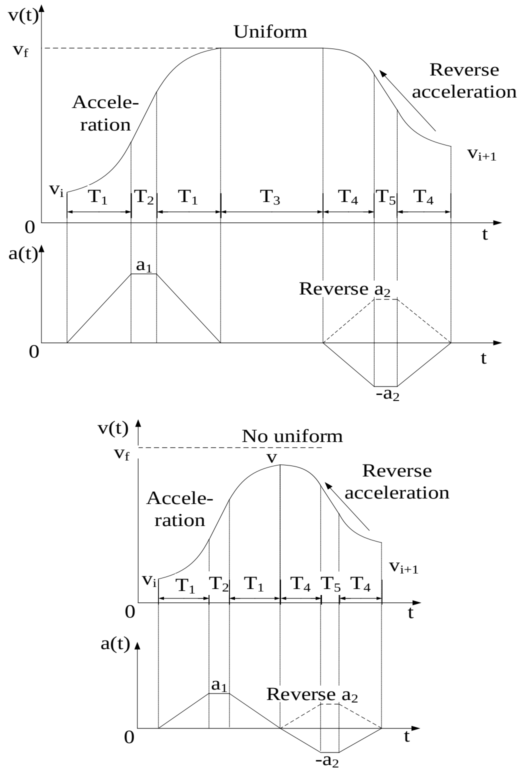

Fig. 1. S-curve ACC/DEC

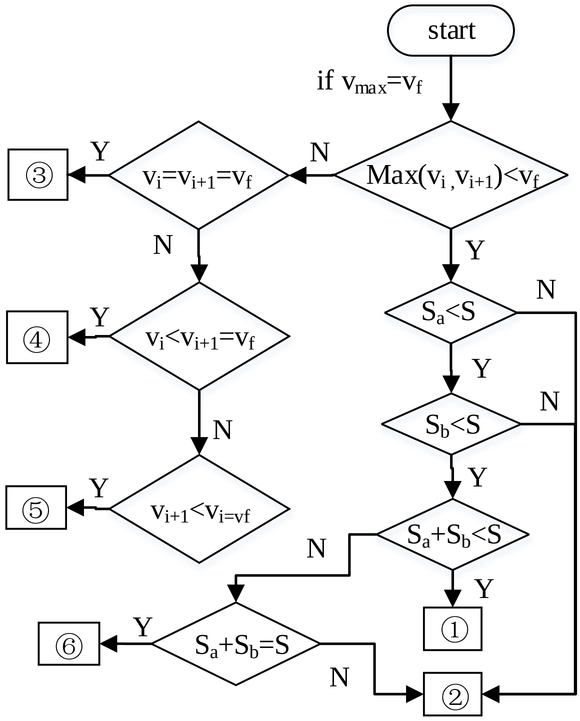

Fig. 2.The flow chart for determining the type of S-curve ACC/DEC algorithm

2.2 The determination of velocity parameters of the accelerationperiod

Taking the positive ACC-period as example, and J is the jerk, and the variation of the velocity Δv is computed as $\Delta v = v - v_i$ (Δv reaches to the maximum value when v is equal to v_f).Due to the different formulae of displacement between 7-period ACC/DEC and 5-period ACC/DEC, the critical of the mixed ACC/DEC algorithm is to determine displacement formula. By considering the ACC/DEC formula of S-curve algorithm,it is concluded that the variation of the velocity for 5-period ACC/DEC is obtained by $\Delta v = a^2 / J$, while the velocity changes in 7-period ACC/DEC can be expressed as $\Delta v > a^2 / J$. By comparing Δv and a^2 / J , the calculation formula of displacement can be determined as:

$$S_a = \begin{cases} (v+v_i)\sqrt{\Delta v / J} & \Delta v \le a_{max}^2 / J \\ \dfrac{(v+v_i)(J\Delta v + a_{max}^2)}{2Ja_{\max}} & \Delta v > a_{max}^2 / J \end{cases} \tag{1}$$

The concrete algorithm is as follows:

Step 1.After calculating Δv and a_{max}^2 / J , the corresponding displacementformula can be computed by using Eq. (1).

Step 2.If $\Delta v \le a_{max}^2 / J$, and the displacement S_a of acceleration periodcan be obtained. In order to guarantee the acceleration and jerk not to exceed the kinematical limits of machine tool, the acceleration a is adjusted to $a = \sqrt{J\Delta v}$ and the time of acceleration and deceleration can be computed as $T_1 = a / J$.

Step 3.If $\Delta v > a_{max}^2 / J$, after acquiring the acceleration displacement S_a , then the parameters can be solved according to the formula of 7-period S-curve, and the time of acceleration period and deceleration period is calculated by $T_1 = a_{max} / J$, and the acceleration time T_2 is expressed as $T_2 = \frac{\Delta v}{a_{max}} - \frac{a_{max}}{J} = \frac{\Delta v}{a_{max}} - T_1$.

2.4The determination of the mixed S-curve type and parameters

One reason why S-curve algorithm computes complexly is that different lengthsof machining paths lead to different calculation formulaeof S-curve.If the path length is long enough, the machining velocity can reach the programming velocity,sothat there is uniform period in the S-curve. If the path length is short, the machining velocityis less than the programming velocity, thus the S-curve do not have uniform period. Hence the determination of the mixed S-curve type and parameters must be divided into two cases.

(1) The machining velocity can reach the programming velocity

In this case, the velocity increases from v_i to v_f , and keeps uniform v_f , then decreases to v_{i+1} . Where S is the machining path length, S_a is the length of acceleration period, S_b is the length of reverse acceleration period. When the machining velocity reaches the programming velocity v_f , the displacement must satisfy that $S_a + S_b \le S$ (when $S_a + S_b = S$, the machining velocity can reach the programming velocity v_f , while there is no uniform period). So we can obtain $\Delta v = v_f - v_i$, $\Delta v = v_f - v_{i+1}$ and a_{max}^2 / J , then the time, displacement, etc. and the type of S-curve can be determined by using the algorithm in section 2.2. When $S_a + S_b < S$, there is uniform period in the S-curve, so the length of uniform period and the uniform time can be formulated as $S_c = S - S_a - S_b$ and $T_3 = (S - S_a - S_b) / v_f$, respectively.

(2) The machining velocity cannot reach the programming velocity

There is $S_a + S_b > S$ when the machining velocity can reach the programming velocity. So only the maximum machining velocity is smaller than v_f , we can conclude that $S_a + S_b = S$. Thus the S-curve has no uniform period, and for $S_a + S_b = S$, the velocity parameters must be recalculated. Because the unknown of the maximum velocity leads to the uncertain relationship between the Δv and a^2 / J , there are several possible calculation formulasof displacement. In order to simplify calculation anddefinite displacement formulas, supposingthe relation between Δv and a^2 / J is just satisfy with the 5-period S-curve, then the variety of velocity in acceleration and deceleration can be expressed as:

$$\begin{cases} v - v_i = a_{max}^2 / J_1 \\ v - v_{i+1} = a_{max}^2 / J_2 \end{cases} \tag{2}$$

The displacements are calculated as follows:

$$\begin{cases} S_a = (v + v_i) a_{max} / J_1 \\ S_b = (v + v_{i+1}) a_{max} / J_2 \\ S_a + S_b = S \end{cases} \tag{3}$$

The maximum machining velocity is solved as $v = \sqrt{(S a_{max} + v_i^2 + v_{i+1}^2)/2}$ from Eq. (2) and Eq. (3), then the jerks J_1, J_2, and time T_1, T_4 can be obtained. Thus, we know all the parameters of the mixedbi-directional S-curve ACC/DEC algorithm, then the formulas of the displacement, velocity, acceleration can be written.

III. Simulation and experiment results

In this section, the proposed algorithm is proved to be correct and efficient by the experimental segments showed in Fig. 3 based on MATLAB. NC machining parameters areused the following settings: the programming velocity v_f is constrained to 60 mm/s, the maximum acceleration a_{max} is 3000 mm/s^2, the jerk is limited to 200 m/s^3. And the interpolation period T, the startingvelocity, and the endingvelocity are set to 4 ms, 0 and 0, respectively.

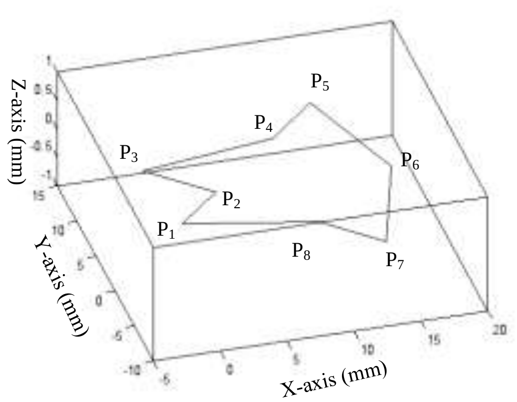

Fig. 3 Experimental segments

Tab. 1The summarized motion results.

Path segments	1	2	3	4	5	6	7	8
v_i (mm/s)	8.5	6.3	19.4	7	19.4	7	27.8	0
S_i (mm)	5	6	10.4	5.5	10.4	10.4	5.5	9.86
S_a (mm)	1.1	1.1	1.1	1.13	1.09	1.13	1.09	1.13
S_b (mm)	1.1	1.1	1.13	1.1	1.13	1.09	1.13	1.1
S_c (mm)	2.8	3.8	8.17	3.27	8.18	8.18	3.28	7.63

Tab.2 Computational time

Computational time (s)	Look-ahead pre-interpolation	Interpolation
The proposed algorithm	0.022	1.25
5-period S-curve	0.038	1.293

Tab. 1.lists the summarized algorithm results and this paper takes the third segment as an example to illustrate the effectiveness of the proposed algorithm

Firstly, the transition velocity v_3 and path length S_3 of the third segment can be obtained with $v_3 = 19.4\ mm/s$ and $S_3 = 10.4\ mm$. Secondly, according to Eq. (8), forpositive acceleration period, we can calculate that $\Delta v = 53.7 > a_{max}^2 / J = 45$, and compute the acceleration displacement S_a with 1.1 *mm*. For reverse acceleration period, there is $\Delta v = 40.6 < a_{max}^2 / J = 45$, and we can obtain the reverse acceleration displacement S_b with 1.13 *mm*. So we can conclude $S_a + S_b < S_3$, thus the type of the third segment can be determined as type ① which the velocity can reach the maximum velocity v_f along the positive and reverse respectively, and the S-curve has the uniform period. Similarly we can verify the other paths, this paper will not be discussed in detail.

After the implement of MALAB programming, the velocity profile and acceleration profile which can be obtained by comparing the proposed algorithm and 5 S-curve algorithm which are shown in Fig. 4 and Fig. 5.

As can be seen in Fig. 4 and Fig. 5, the proposed algorithm and 5-period S-curve algorithm can both realize the velocity and acceleration transitioncontinuouslyand smoothly, and improve the flexibility of controlling system.Thus can effectively avoid the tool vibration and overcut caused by acceleration and velocity mutation, and greatly improve the machining quality of parts.The two algorithm are computed with Intel i5-4210m CPU and 8G RAM. As shown in Table 2, the machining time of proposed algorithm is 1.254s, compared with the operation time 1.293s of 5-period S-curve, the working time is shortened by 0.039s.Specially, the proposed algorithm is very useful for the look-ahead interpolation period. It is faster nearly twice time than the 5-period S-curve algorithm. Furthermore, with the increase of machining paths, the working efficiency will be improvement more obvious.Therefore, the proposed algorithm has faster response time, better real-time performance, and more efficiency.

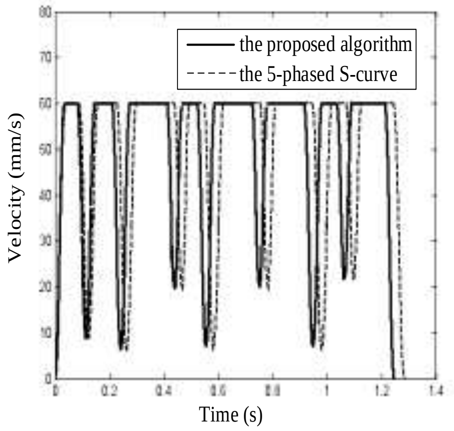

Fig. 4 Comparison of velocity

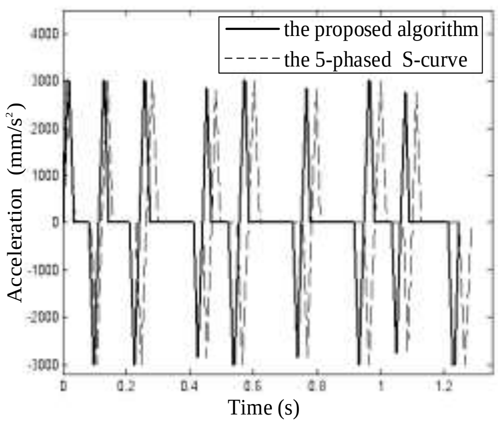

Fig. 5 Comparison of acceleration

IV. Conclusions

One focal and difficult point forhigh-speed machining of continuous segments is on basis of simplicity and rapidity trying to guarantee high-speed and achieve the velocity and acceleration transitioncontinuouslyand smoothly. Hence, based on the 7-period S-curve and 5-period S-curve, this paper proposes a 7-period and 5-periodmixed bi-directional S-curveACC/DEC Algorithm to plan the velocity from positive and reverse of each path, and obtain the information of speed and displacement. The proposed algorithm can guarantee the simplicity of calculations, significantly reduce the time of velocity planning, improve the machining efficiency, and realize the continuous smooth changes of velocity and acceleration.

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