DOI: 10.3901/CJME.2011.**.***, available online at www.cjmenet.com; www.cjmenet.com.cn

Algorithm for Smooth S-curve Feedrate Profiling Generation

CHEN Youdong, WEI Hongxing, SUN Kai, LIU Miao, and WANG Tianmiao

School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China

Received September 16, 2009; revised December 8, 2010; accepted January, 2011; published electronically January, 2011

Abstract: The works for feedrate profile generation, such as linear and S-curve profiles, have been proposed all over the world, and these algorithms can greatly improve the smoothness of motion. However, most of the algorithms lead to the discontinuous acceleration/deceleration and jerk, or high jerk levels, which is very harmful to machine tool or robot in most occasions. This paper presents a smooth S-curve feedrate profiling generation algorithm that produces continuous feedrate, acceleration, and jerk profiles. Smooth jerk is obtained by imposing limits on the first and second time derivatives of acceleration, resulting in trapezoidal jerk profiles along the tool path. The discretization of smooth S-curve feedrate is realized with a novel approach that improves the efficiency without calculating the deceleration point in each sampled time. To ensure that the interpolation time is a multiple of the value of sampled time, the feedrate, acceleration, jerk, and jerk derivative are recalculated. Meantime, to improve the efficiency, the interpolation steps of all regions are computed before interpolation. According to the distance of trajectory, the smooth S-curve acceleration and decelerations are divided into three blocks: normal block, short block type-I, and short block type-II. Finally feedrate discretization of short block type-I and type-II is obtained with considering the efficiency. The proposed generation algorithm is tested in machining a part on a five axis milling machine, which is controlled with the CNC system for newly developed high-speed machine tools. The test result shows that the smooth S-curve approach has the smoother feedrate, acceleration, deceleration, and jerk profiles than S-curve. The proposed algorithm ensures the automated machinery motion smoothness, and improves the quality and efficiency of the automated machinery motion planning.

Key words: S-curve acceleration/deceleration, feedrate control, computer numerical control(CNC)

1 Introduction

Feedrate profile generation is one of the important issues in automated industrial applications including manufacturing machinery and robotics. Manufacturing machinery, such as computer numerical control machinery, requires high speed, high accuracy, and smooth motion for better product quality and less production time. Therefore, it is very important to plan the profile of the motion of automated machinery. One of the easiest ways to generate the smooth profile of motion is to use trapezoidal feedrate profile, which has been widely used in machinery controllers. However, the acceleration of trapezoidal profile is discontinuous. Therefore, machinery may easily suffer mechanical shock because of the discontinuous acceleration[1]. Another way is to use polynomial functions to generate feedrate profiles[2–3]. However, higher degree polynomial profiles demand high computational efforts. The computational complexity increases almost exponentially along with the order of polynomial. Although the digital convolution is much more efficient than polynomial function method, it can only generate symmetric feedrate profiles[4]. Trigonometric function has consecutive velocity, acceleration, jerk, and displacement for smooth motion[5]. In addition, the computational cost is so high that the data need to be computed off-line to meet the real-time requirements. S-curve profile has been widely investigated and adopted for motion control in theory as well in practice[6–11]. Although the values of discontinuity are not as infinite as the trapezoidal profile, the acceleration of the S-curve profile is discontinuous. Therefore, the required smooth dynamic in machinery is not available.

This paper presents an algorithm for smooth S-curve acceleration and deceleration, which can be used in industrial robots and computer numerical control(CNC) machine tools. The algorithm can generate a continuous acceleration continuity, which provides sufficiently smooth acceleration and feedrate profiles to reduce jerk levels, minimize discontinuities and reduce mechanical shock. The interpolation computation time also meets the controller requirements. In the algorithm, the number of interpolation steps for constant speed zone is obtained; then the jerk derivation, jerk, acceleration, and feedrate are recomputed; finally the feedrate during each sampling time is calculated.

* Corresponding author. E-mail: chenyd@buaa.edu.cn

This project is supported by Major National S&T Program of China (Grant No. 2009ZX04009-014-02), and National Hi-tech Research and Development Program of China (863 Program, Grant No. 2009AA043901)

The feedrate fluctuation is so small that it can be neglected.

The rest of this paper is organized as follows. The smooth S-curve acceleration and deceleration are explained in section 2, followed by the normal block feedrate profile generation in section 3. Then the short block feedrate profiles are given in section 4. Simulation and experiment results are presented in section 5. Finally the conclusions are drawn in section 6.

2 Smooth S-curve Acceleration and Deceleration

S-curve acceleration/deceleration(acc/dec) is achieved by making constant changes to acceleration in the specified acceleration change time. Smooth S-curve acc/dec performs control in the way that the acceleration changes in an S-curve form by specifying the jerk change time for S-curve acc/dec. Therefore, acc/dec for smooth S-curve tends to be smoother, which helps to reduce vibration and shocks to the machine in acc/dec regions. Thus, by altering the jerk change time, jerk constant time and jerk zero time, the acc/dec can be easily modified on the fly.

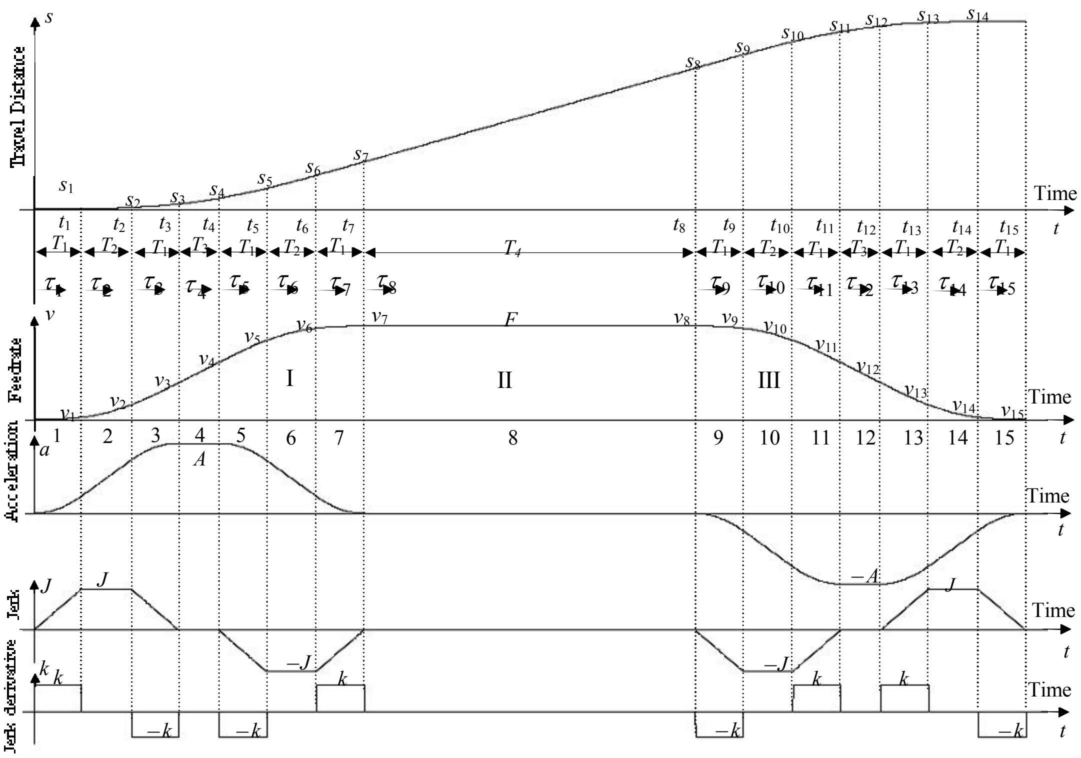


Fig. 1. Kinematic profiles for smooth S-curve acceleration based feedrate generation

The kinematic profiles used in feedrate generation are illustrated in Fig. 1. The profiles can be divided into zones I, II and III, i.e., acceleration zone, constant zone, and deceleration zone. For the motion along the tool path, jerks have trapezoidal profiles with pre-specified slopes (the jerk derivative values). Acceleration profiles are S-curve profiles. Jerk profiles are linear. Acceleration profiles are parabolic. Feedrate profiles are cubic and displacement profiles are quartic in regions 1, 3, 5, 7, 9, 11, 13, 15, where jerk derivatives are constant. Jerk values are constant. Jerk derivatives and jerks are zero in regions 2, 6, 10, 14, where acceleration profiles are linear, velocity profiles are parabolic, and displacement profiles are cubic. Acceleration values are constant. Jerks and jerk derivative are zero in regions 4, 12, where velocity profiles are linear and displacement profiles are parabolic. In region 8, jerk derivative, jerk, and acceleration values are zero; feedrate is constant and displacement is linear.

2.1 Formulation

As shown in Fig. 2, the initial feedrate is zero, the desired feedrate is F, the initial jerk and acceleration are zero, J is the desired jerk, a_d is the desired acceleration, the jerk change time is the same T_1, the jerk constant time is the same T_2, the jerk zero time is T_3.

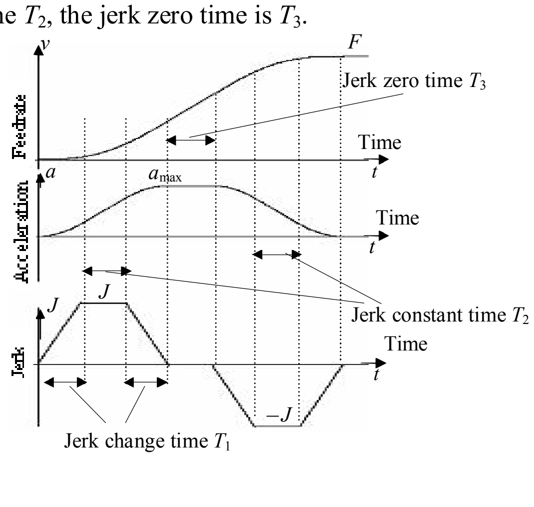


Fig. 2. Smooth S-curve acceleration

If the initial conditions of jerk derivative, jerk, acceleration, feedrate and displacement at time t_k (k=1, 2,⋯, 15) are known, jerk $J(t)$, acceleration $a(t)$, feedrate $v(t)$, and displacement $s(t)$ profiles can be obtained by integrating the jerk derivative profile $k(t)$ as follows:

$$J(t)=J(t_i)+\int_{t_i}^{t}k(\tau_i)\mathrm{d}\tau_i,\ a(t)=a(t_i)+\int_{t_i}^{t}J(\tau_i)\mathrm{d}\tau_i,$$
$$v(t)=v(t_i)+\int_{t_i}^{t}a(\tau_i)\mathrm{d}\tau_i,\ s(t)=s(t_i)+\int_{t_i}^{t}v(\tau_i)\mathrm{d}\tau_i.$$

The jerk derivative k profile in Fig. 1 can be obtained by

$$k(\tau)=\begin{cases} k, & 0\le t<t_1, \\ 0, & t_1\le t<t_2, \\ -k, & t_2\le t<t_3, \\ 0, & t_3\le t<t_4, \\ -k, & t_4\le t<t_5, \\ 0, & t_5\le t<t_6, \\ k, & t_6\le t<t_7, \\ 0, & t_7\le t<t_8, \\ -k, & t_8\le t<t_{10}, \\ 0, & t_9\le t<t_{10}, \\ k, & t_{10}\le t<t_{11}, \\ 0, & t_{11}\le t<t_{12}, \\ k, & t_{12}\le t<t_{13}, \\ 0, & t_{13}\le t<t_{14}, \\ -k, & t_{14}\le t<t_{15}, \end{cases} \tag{1}$$

where k is the jerk derivative, t denotes absolute time, t_k (k=1, 2,⋯, 15) denotes the time boundaries of each region. By integrating Eq. (1) with respect to time, the jerk profile is then expressed as follows:

$$J(\tau)=\begin{cases} k\tau_1, & 0\le t<t_1, \\ kT_1, & t_1\le t<t_2, \\ kT_1-k\tau_3, & t_2\le t<t_3, \\ 0, & t_3\le t<t_4, \\ -k\tau_5, & t_4\le t<t_5, \\ -kT_1, & t_5\le t<t_6, \\ -kT_1+k\tau_7, & t_6\le t<t_7, \\ 0, & t_7\le t<t_8, \\ -k\tau_9, & t_8\le t<t_{10}, \\ -kT_1, & t_9\le t<t_{10}, \\ -kT_1+k\tau_{11}, & t_{10}\le t<t_{11}, \\ 0, & t_{11}\le t<t_{12}, \\ k\tau_{13}, & t_{12}\le t<t_{13}, \\ kT_1, & t_{13}\le t<t_{14}, \\ kT_1-k\tau_{15}, & t_{14}\le t<t_{15}, \end{cases} \tag{2}$$

where τ_k ($\tau_k=t-t_{k-1}$ (k=1, 2,⋯, 15)) is the relative time parameter that starts at the beginning of the kth region as shown in Fig. 1. By integrating Eq. (2) with respect to time, the acceleration profile is obtained as follows:

$$a(\tau)=\begin{cases} p\tau_1^2, \quad 0\le t<t_1, \\ a_1+p_1\tau_2, \quad t_1\le t<t_2,\ a_1=pT_1^2, \\ a_2+p_1\tau_3-p\tau_3^2, \quad t_2\le t<t_3,\ a_2=a_1+p_1T_2, \\ a_3,\ t_3\le t<t_4,\ a_3=a_2+pT_1^2=p_1(T_1+T_2)=a_{\mathrm{d}}, \\ a_4-p\tau_5^2, \quad t_4\le t<t_5,\ a_4=a_3, \\ a_5-p_1\tau_6, \quad t_5\le t<t_6,\ a_5=a_4-pT_1^2, \\ a_6-p_1\tau_7+p\tau_7^2, \quad t_6\le t<t_7,\ a_6=a_5-p_1T_2, \\ 0, \quad t_7\le t\le t_8, \\ -p\tau_9^2, \quad t_8\le t<t_9, \\ a_9-p_1\tau_{10}, \quad t_9\le t<t_{10},\ a_9=-pT_1^2, \\ a_{10}-p_1\tau_{11}+p\tau_{11}^2,\ t_{10}\le t<t_{11},\ a_{10}=a_9-p_1T_2, \\ a_{11}, \quad t_{11}\le t<t_{12},\ a_{11}=a_{10}-pT_1^2, \\ a_{12}+p\tau_{13}^2, \quad t_{12}\le t<t_{13},\ a_{12}=a_{11}-pT_1^2, \\ a_{13}+p_1\tau_{14}, \quad t_{13}\le t<t_{14},\ a_{13}=a_{12}+pT_1^2, \\ a_{14}+p_1\tau_{15}-p\tau_{15}^2,\ t_{14}\le t<t_{15},\ a_{14}=a_{13}+p_1T_2, \end{cases} \tag{3}$$

where a_k (k=1, 2,⋯, 15) is the acceleration reached at the end of the corresponding region, p=0.5k, p_1=2pT_1.

By integrating Eq. (3) with respect to time, the feedrate profile is expressed as follows:

$$v(\tau)=\begin{cases} p_2\tau_1^3, & 0\le t<t_1, \\ v_1+3p_2T_1\tau_2(T_1+\tau_2), & t_1\le t<t_2, \\ v_2+p_2\tau_3(p_3+3T_1\tau_3-\tau_3^2), & t_2\le t<t_3, \\ v_3+6p_2T_1(T_1+T_2)\tau_4, & t_3\le t<t_4, \\ v_4+p_2\tau_5(6T_1^2+6T_1T_2-\tau_5^2), & t_4\le t<t_5, \\ v_5+3p_2T_1\tau_6(T_1+2T_2-\tau_6), & t_5\le t<t_6, \\ v_6+p_2\tau_7(3T_1^2-3T_1\tau_7+\tau_7^2), & t_6\le t<t_7, \\ v_8, & t_7\le t<t_8, \\ v_8-p_2\tau_9^3, & t_8\le t<t_9, \\ v_9-3p_2T_1\tau_{10}(T_1+\tau_{10}), & t_9\le t<t_{10}, \\ v_{10}-p_2\tau_{11}(p_3+3T_1\tau_{11}-\tau_{11}^2), & t_{10}\le t<t_{11}, \\ v_{11}-60T_1(T_1+T_2)\tau_{12}, & t_{11}\le t<t_{12}, \\ v_{12}-p_2\tau_{13}(6T_1^2+6T_1T_2-\tau_{13}^2), & t_{12}\le t<t_{13}, \\ v_{13}-3p_2T_1\tau_{14}(T_1+2T_2-\tau_{14}), & t_{13}\le t<t_{14}, \\ v_{14}-p_2\tau_{15}(3T_1^2-3T_1\tau_{15}+\tau_{15}^2), & t_{14}\le t<t_{15}, \end{cases} \tag{4}$$

where v_k (k=1, 2,⋯, 15) is the feedrate reached at the end of the corresponding region, and

$$p_2=\frac{1}{6}k,$$
$$p_3=3T_1^2+6T_1T_2,$$

$$
\begin{aligned}
&v_1 = p_2 T_1^3,\\
&v_2 = v_1 + 3p_2 T_1 T_2 (T_1 + T_2),\\
&v_3 = v_2 + p_2 T_1 (6T_1^2 + 6T_1 T_2 - T_2^2),\\
&v_4 = v_3 + 6p_2 T_1 T_3 (T_1 + T_2),\\
&v_5 = v_4 + p_2 T_1^2 (5T_1 + 6T_2),\\
&v_6 = v_5 + p_2 T_1 T_2 (T_1 + T_2),\\
&v_7 = v_6 + p_2 T_1^3 = 6p_2 T_1 (T_1 + T_2)(2T_1 + T_2 + T_3) = F,\\
&v_8 = v_7,\\
&v_9 = v_7 - p_2 T_1^3,\\
&v_{10} = v_9 - 3p_2 T_1 T_2 (T_1 + T_2),\\
&v_{11} = v_{10} - p_2 T_1^2 (5T_1 + 6T_2),\\
&v_{12} = v_{11} - 6p_2 T_1 T_3 (T_1 + T_2),\\
&v_{13} = v_{12} - p_2 T_1^2 (5T_1 + 6T_2),\\
&v_{14} = v_{13} - p_2 T_1 T_2 (T_1 + T_2).
\end{aligned}
$$

Where F is the desired feedrate which needs to be achieved at the end of the seventh region. By integrating Eq. (4) with respect to time, the displacement profile is yielded:

$$
s(\tau) = \begin{cases}
p_3 \tau_1^4, & 0 \le t < t_1,\\
s_{11} + p_4 \tau_2 (2T_1^2 + 3T_1 \tau_2 + 2\tau_2^2), & t_1 \le t < t_2,\\
s_{21} + p_3 \tau_3 (s_{22} + s_{23} \tau_3 + 4T_1 \tau_3^2 - \tau_3^3), & t_2 \le t < t_3,\\
s_{31} + 6p_4 \tau_4 (T_1 + T_2)(2T_1 + T_2 + \tau_4), & t_3 \le t < t_4,\\
s_{41} + p_3 \tau_5 (s_{42} + 2s_{23} \tau_5 - \tau_5^3), & t_4 \le t < t_5,\\
s_{51} + p_4 \tau_6 [s_{52} + 3(T_1 + 2T_2)\tau_6 - 2\tau_6^2], & t_5 \le t < t_6,\\
s_{61} + p_3 \tau_7 (s_{62} + 6T_1^2 \tau_7 - 4T_1 \tau_7^2 + \tau_7^3), & t_6 \le t < t_7,\\
s_{71} + kT_1 (T_1 + T_2)(2T_1 + T_2 + T_3)\tau_8, & t_7 \le t < t_8,\\
s_{81} + p_3 \tau_9 (s_{82} - \tau_9^3), & t_8 \le t < t_9,\\
s_{91} + p_4 \tau_{10} (s_{92} - 3T_1 \tau_{10} - 2\tau_{10}^2), & t_9 \le t < t_{10},\\
s_{101} + p_3 \tau_{11} (s_{102} - 4T_1 \tau_{11}^2 + \tau_{11} \tau_{11}^3), & t_{10} \le t < t_{11},\\
s_{111} + 6p_4 \tau_{12} (T_1 + T_2)(2T_1 + T_2 + 2T_3 - \tau_{12}), & t_{11} \le t < t_{12},\\
s_{121} + p_3 \tau_{13} (s_{122} - 2s_{23} \tau_{13} + \tau_{13}^3), & t_{12} \le t < t_{13},\\
s_{131} + p_4 \tau_{14} [s_{132} + 2\tau_{14}^2 - 3(T_1 + 2T_2)\tau_{14}], & t_{13} \le t < t_{14},\\
s_{141} - p_3 \tau_{15} (4T_1^2 - 6T_1 \tau_{15} + 4\tau_{15}^2 - \tau_{15}^3), & t_{14} \le t < t_{15},
\end{cases} \tag{5}
$$

where $p_3 = \dfrac{1}{24}k, p_4 = \dfrac{1}{12}kT_1,$

$$
\begin{aligned}
&s_{11} = p_3 T_1^4,\\
&s_{21} = s_{11} + p_4 T_2 (2T_1^2 + 3T_1 T_2 + 2T_2^2),\\
&s_{22} = 4T_1^3 + 12T_1 T_2 (T_1 + T_2),\\
&s_{23} = 6T_1 (T_1 + 2T_2),\\
&s_{31} = s_{21} + p_4 T_2 (2T_1^2 + 3T_1 T_2 + 2T_2^2),\\
&s_{41} = s_{31} + p_3 T_1^2 (13T_1^2 + 24T_1 T_2 + 12T_2^2),\\
&s_{42} = 12T_1 [2T_1 + 3T_1 T_2 + T_2^2 + 2T_3 (T_1 + T_2)],\\
&s_{51} = s_{41} + 6p_4 T_2 (T_1 + T_2)(T_3 + T_2 + 2T_1),\\
&s_{52} = 22T_1^2 + 30T_1 T_2 + 6T_2^2 + 12(T_1 + T_2)T_3,\\
&s_{61} = s_{51} + p_3 T_1^2 (35T_1^2 + 48T_1 T_2 + 24T_2 T_3 + 12T_2^2),\\
&s_{62} = 44T_1^3 + 72T_1^2 T_2 + 24T_1 T_2^2 + 24T_1 (T_1 + T_2)T_3,\\
&s_7 = s_6 + p_4 T_2 (22T_1^2 + 33T_1 T_2 +\\
&\qquad 12T_3 T_1 + 12T_2 T_3 + 10T_2^2),\\
&s_{81} = s_{71} + p_3 T_1^2 (47T_1^2 + 72T_1 T_2 +\\
&\qquad 24T_3 T_1 + 24T_2 T_3 + 24T_2^2),\\
&s_{82} = 48T_1^3 + 72T_1^2 T_2 + 24T_1 (T_1 + T_1)T_3 + 24T_1 T_2^2,\\
&s_{91} = s_{81} + 12p_4 T_4 (T_1 + T_2)(T_3 + T_2 + 2T_1),\\
&s_{92} = 22T_1^2 + 36T_1 T_2 + 12T_2^2 + 12(T_1 + T_2)T_3,\\
&s_{101} = s_{91} + p_3 T_1^2 (47T_1^2 + 72T_1 T_2 +\\
&\qquad 24T_3 T_1 + 24T_2 T_3 + 24T_2^2),\\
&s_{102} = 44T_1^3 + 60T_1^2 T_2 + 12T_1 T_2^2 + 24T_1 (T_1 + T_2)T_3 - s_{23},\\
&s_{111} = s_{101} + p_4 T_2 (22T_1^2 + 33T_1 T_2 +\\
&\qquad 12T_3 T_1 + 12T_2 T_3 + 10T_2^2),\\
&s_{121} = s_{111} + p_3 T_1^2 (35T_1^2 + 48T_1 T_2 +\\
&\qquad 24T_3 T_1 + 24T_2 T_3 + 12T_2^2),\\
&s_{122} = 24T_1^3 + 36T_1^2 T_2 + 12T_1 T_2^2,\\
&s_{131} = s_{121} + 6p_4 T_3 (T_1 + T_2)(T_3 + T_2 + 2T_1),,\\
&s_{132} = 2T_1^2 + 6T_1 T_2 + 6T_2^2,\\
&s_{141} = s_{131} + p_3 T_1^2 (13T_1^2 + 24T_1 T_2 + 12T_2^2).
\end{aligned}
$$

2.2 Smooth S-curve speed profile

The inputs to the smooth S-curve feedrate generation algorithm are the jerk change time, the jerk constant time, the jerk zero time, the total distance of travel (L), the control loop sampling period (T_s), the initial, commanded, and final feedrates (f_s, F, f_e, respectively. For simplicity, the f_s and f_e are assumed to be zero), the allowable acceleration magnitudes (a_{max}), and the allowable feedrate (v_{max}).

The reqired value of jerk derivative k should not be larger than the achievable value for the given acceleration, jerk change time, jerk constant change time, and jerk zero time. Based on Eq. (3) and Eq. (4), k can be expressed as

$$
k = \min\left(\frac{v_{max}}{T_1 (T_1 + T_2)(T_2 + T_3 + 2T_1)}, \frac{a_{max}}{T_1 (T_1 + T_2)} \right). \tag{6}
$$

In order to generate a feedrate profile, it is necessary to check if the path is a normal block or a short block. The normal block includes acceleration zone, constant-speed zone, and deceleration zone, while the short block includes only acceleration zone and deceleration zone. Eq. (7) needs to be satisfied for a normal block, otherwise the block is a short block:

$$
L > kT_1 (T_1 + T_2)(2T_1 + T_2 + T_3)(4T_1 + 2T_2 + T_3). \tag{7}
$$

For the normal block, we can obtain the feedrate profile as shown in Fig. 1. The feedrate reaches the desired feedrate F and the acceleration reaches the desired acceleration. There are two types of short block. The first one is short block type-I, where the acceleration reaches the desired acceleration and the speed does not reach the desired feedrate. The second one is short block type-II, where the acceleration does not reach the desired acceleration and the feedrate does not reach the desired feedrate, T_3 is zero. type-I short block should satisfy Eq. (8). If neither Eq. (7) nor Eq. (8) is satisfied, the block is type-II. For the short block, the length of the path is shorter than the length needed for the actual speed to reach the desired feedrate F from zero and to change back from the desired feedrate F to zero. It is therefore impossible for short block to reach the desired feedrate, which is F:

$$\begin{cases} L < kT_1(T_1+T_2)(2T_1+T_2+T_3)(4T_1+2T_2+T_3), \\ L \geq 2kT_1(T_1+T_2)(2T_1+T_2)^2. \end{cases} \tag{8}$$

3 Normal Block Speed Profile Generation

In practice, the value of interpolation time is not a multiple of the value of sampled time. Therefore, the low speed zone called “tail” appears in the interpolation, which is shown in Fig. 3. Where v_L represents the low speed. In order to get rid of the “tail”, CHEN, et al[12–13], recalculated the acceleration, jerk, and start velocity when entering into the deceleration zone. Firstly, in each interpolation period, the feedrate for the next period is predicted ceaselessly, the distance of the deceleration zone for the next period is calculated, and the remaining distance in current period is also calculated. The distance for the next period of the deceleration zone is compared with the remaining distance for the next period to determine whether it enters into the deceleration zone and whether the acceleration, jerk, and feedrate need to be recomputed. In this paper, a new method of feedrate profile generation is proposed based on recalculating the feedrate without recalculating the remaining distance, the distance of the deceleration zone for the next period, the acceleration, jerk, and start velocity. With this method, the number of interpolation steps for constant speed zone is calculated; then the jerk derivation, jerk, acceleration, and feedrate are recomputed; finally, the number of interpolation steps for each region is used to determine the region reached. The normal block speed profile generation is shown in Fig. 1.

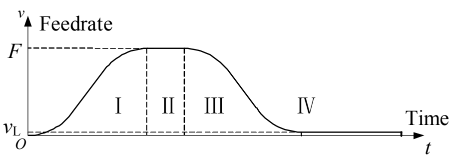


Fig. 3. Tail appearance in acceleration and deceleration

3.1 Determination of the numbers of interpolation steps for each region

Given the numbers of interpolation steps for all regions (except the constant-speed region) specified, the total distance of travel L is calculated from Eq. (5), shown as

$$L = kT_s^4 n_1(n_1+n_2)(2n_1+n_2+n_3)(4n_1+2n_2+n_3+n_4). \tag{9}$$

Then the number of interpolation step for constant-speed region is calculated as follows:

$$n_4 = \left[\frac{L}{kT_s^4 n_1(n_1+n_2)(2n_1+n_2+n_3)}+1\right] - 4n_1 - 2n_2 - n_3. \tag{10}$$

The numbers of interpolation steps for different regions are expressed as follows:

$$\begin{cases} N_1 = n_1,\ N_2 = n_2,\ N_3 = n_1,\ N_4 = n_3,\ N_5 = n_1, \\ N_6 = n_2,\ N_7 = n_1,\ N_8 = n_4,\ N_9 = n_1,\ N_{10} = n_2, \\ N_{11} = n_1,\ N_{12} = n_3,\ N_{13} = n_1,\ N_{14} = n_2,\ N_{15} = n_1. \end{cases} \tag{11}$$

3.2 Readjustment of jerk derivative, acceleration, and constant feedrate values

After the number of interpolation steps for different regions is determined, jerk derivative, acceleration, and constant feedrate values are readjusted so that the number of interpolation steps remains unchanged.

The expression of L in Eq. (9) is used to readjust the value of jerk derivative k. The acceleration and feedrate values will also be adjusted based on Eq. (3) and Eq. (4).

The jerk derivative value can be recalculated based on Eq. (9) as follows:

$$k' = \frac{L}{n_1 T_s^4 (n_1+n_2)(2n_1+n_2+n_3)(4n_1+2n_2+n_3+n_4)}. \tag{12}$$

The acceleration value can be obtained:

$$a' = k' n_1 (n_1+n_2) T_s^2. \tag{13}$$

Then the feedrate value is

$$F' = k' n_1 (n_1+n_2)(2n_1+n_2+n_3) T_s^3. \tag{14}$$

The readjusted values of jerk, acceleration and feedrate should not be larger than the desired values. Considering Eq. (13), Eq. (14), and $k' \leq k$, we have

$$\begin{cases} k' \leq k, \\ a' \leq a, \\ F' \leq F. \end{cases} \tag{15}$$

For the machining, the feedrate can’t change too drastically. Therefore, it is necessary to check the percentage feedrate variation η:

$$\eta=\left|\frac{F-F'}{F}\right|, \tag{16}$$

then $\eta<\dfrac{1}{4n_1+2n_2+n_3+n_4}$.

For normal block, the value of $4n_1+2n_2+n_3+n_4$ is much larger than 1 so that the feedrate variation can be neglected. For short block, the length of the path is shorter than the required length for the actual speed to change from zero to the desired feedrate F and to change back from F to zero. It is therefore impossible for the actual speed to reach the desired feedrate, which is F.

3.3 Discretization of feedrate

The s_{1n} in Eq. (5) can be written as

$$s_{1n}=\frac{1}{24}kt_1^4=\frac{1}{24}k'n^4T_s^4. \tag{17}$$

Therefore, the position increment Δs during each sampling time in region 1 is calculated as follows:

$$\Delta s=s_{1n+1}-s_{1n}=\frac{1}{24}k'(n+1)^4T_s^4-\frac{1}{24}k'n^4T_s^4,$$

where $\Delta s=fT_s$ and $0\le n<n_1$, the feedrate is achieved as follows:

$$f=\frac{1}{24}k'(2n+1)(2n^2+2n+1)T_s^3. \tag{18}$$

The discretization of feedrate for each region can be calculated from

$$f(t)=\begin{cases} p_5(2n+1)(2n^3+2n+1), & 0\le n<n_1, n\in N,\\ 2p_5n_1(r_1+6n^2+6n), & 0\le n<n_2,\\ p_5(r_{21}+4r_{22}n+6r_{23}n^2-4n^3), & 0\le n<n_1,\\ 12p_5r_{31}(r_{32}+2n+1), & 0\le n<n_3,\\ p_5(r_{41}+4r_{42}n-4n^3-6n^2-1), & 0\le n<n_1,\\ 2p_5n_1(r_{51}+6r_{52}n-6n^2-2), & 0\le n<n_2,\\ p_5(r_{61}+4r_{62}n-6r_{63}n^2+4n^3), & 0\le n<n_1,\\ 24p_5r_{31}(2n_1+n_2+n_3), & 0\le n<n_4,\\ p_5(r_{71}-4n^3-6n^2-4n), & 0\le n<n_1,\\ 2p_5n_1(r_{81}-6n_1n-6n^2-6n), & 0\le n<n_2,\\ p_5(r_{91}-4r_{92}n-6r_{93}n^2+4n^3+1), & 0\le n<n_1,\\ 12p_5r_{31}(r_{101}-2n-1), & 0\le n<n_2,\\ p_5(r_{111}-4r_{112}n+6n^2+4n^3), & 0\le n<n_1,\\ 2p_5n_1(r_{121}-6r_{122}n+6n^2), & 0\le n<n_2,\\ p_5(r_{23}-2n)(r_{131}-2r_{23}n+2n^2), & 0\le n<n_1. \end{cases} \tag{19}$$

where $p_5=\dfrac{1}{24}k'T_s^3$,

$$\begin{aligned}
r_{11}&=2n_1^2+6n_1n+3n_1+2,\\
r_{21}&=2(3n_1+2n_1^2+2)n_1+12(n_1+n_2+1)n_1n_2-1,\\
r_{22}&=3n_1+6n_1n_2+2n_1^2-1,\\
r_{23}&=2n_1-1,\\
r_{31}&=n_1(n_1+n_2),\\
r_{32}&=2n_1+n_2,\\
r_{41}&=12[(n_2+2n_3+1)n_2+(3n_2+2n_3+3)n_1]n_1,\\
r_{42}&=6n_1+6n_2-1,\\
r_{51}&=(22n_1+3)n_1+6(5n_1+n_2+1)n_2+\\
&\quad 12(n_2+n_1)n_3,\\
r_{52}&=n_1+2n_2-1,\\
r_{61}&=4(6n_2^2+6n_2n_3-1)n_1+2(6n_3+\\
&\quad 36n_2+22n_1+3)n_1^2+1,\\
r_{62}&=3n_1^2-3n_1+1,\\
r_{63}&=2n_1+1,\\
r_{71}&=48n_1^3+72n_1^2n_2+24n_1n_2^2+\\
&\quad 24n_3n_1^2+24n_1n_2n_3-1,\\
r_{81}&=22n_1^2+3n_1+12n_1n_3+36n_1n_2+\\
&\quad 12n_2n_3+12n_2^2-2,\\
r_{91}&=12(5n_1+n_2+2n_3-1)n_1n_2+\\
&\quad 2(12n_3+22n_1-3)n_1^2-4n_1,\\
r_{92}&=6n_1n_2+3n_1^2+3n_1-1,\\
r_{93}&=n_1-1,\\
r_{101}&=2n_1+n_2+2n_3,\\
r_{111}&=12n_1n_2^2-12n_1n_2+1+36n_2n_1^2-12n_1^2+24n_1^3,\\
r_{112}&=6n_1n_2+6n_1^2+1,\\
r_{121}&=6n_2^2-6n_2+6n_1n_2-3n_1+2n_1^2+2,\\
r_{122}&=n_1+2n_2+1,\\
r_{131}&=2n_1^2-2n_1+1.
\end{aligned}$$

4 Short Block Speed Profile Generation

4.1 Short block type-I

For short block type-I, there is not any constant-speed region, as shown in Fig. 4. T_4 is zero, therefore, the displacement becomes

$$L=kn_1(n_1+n_2)(2n_1+n_2+n_3)(4n_1+2n_2+n_3)T_s^4. \tag{20}$$

For the case $n_3\ge 0$,

$$n_3=\left\lceil\frac{\sqrt{(2n_1+n_2)^2+\dfrac{4L}{kn_1(n_1+n_2)T_s^4}}-3(2n_1+n_2)}{2}+1\right\rceil, \tag{21}$$

$$n_3 > \frac{\sqrt{(2n_1+n_2)^2 + \dfrac{4L}{kn_1(n_1+n_2)T_s^4}} - 3(2n_1+n_2)}{2}. \quad (22)$$

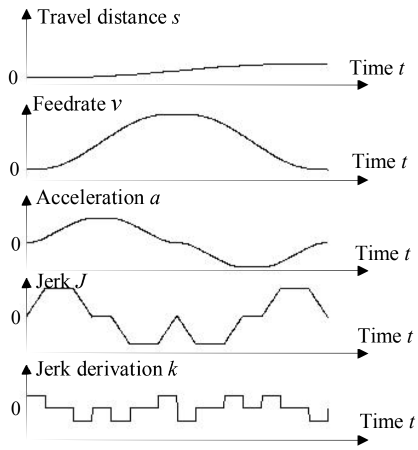


Fig. 4. Short block type-I feedrate profile

The numbers of interpolation steps for different regions are expressed as follows:

$$\begin{cases} N_1 = n_1,\ N_2 = n_2,\ N_3 = n_1,\ N_4 = n_3,\ N_5 = n_1, \\ N_6 = n_2,\ N_7 = n_1,\ N_8 = 0,\ N_9 = n_1,\ N_{10} = n_2, \\ N_{11} = n_1,\ N_{12} = n_3,\ N_{13} = n_1,\ N_{14} = n_2,\ N_{15} = n_1. \end{cases} \quad (23)$$

The jerk derivative value can be recalculated based on Eq. (20) as follows:

$$k' = \frac{L}{n_1(n_1+n_2)(2n_1+n_2+n_3)(4n_1+2n_2+n_3)T_s^4}. \quad (24)$$

The acceleration value can be recalculated as follows:

$$a' = k'n_1(n_1+n_2)T_s^2. \quad (25)$$

The readjusted values of jerk, acceleration and feedrate should not be larger than the desired values. Considering Eq. (21) and Eq. (22), $k' \le k$, we get

$$\begin{cases} k' \le k, \\ a' \le a. \end{cases} \quad (26)$$

The discretization of feedrate for each region can be expressed as Eq. (19). The constant-speed region doesn't exist, so n_4=0. n_3 is obtained by Eq. (21), and the jerk derivative value is expressed as in Eq. (24).

4.2 Short block type-II

For short block type-II, there is no constant-speed region or constant acceleration region, so T_3 and T_4 are zero. Considering the efficiency, the smooth S-curve acc/dec degenerates to S-curve acc/dec. The S-curve is illustrated in Fig. 5.

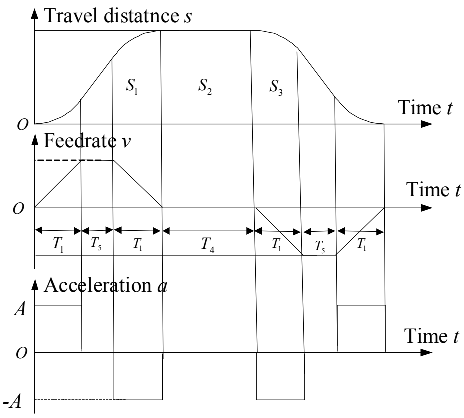


Fig. 5. Kinematic profiles for S-curve acceleration based feedrate generation

The inputs to the S-curve feedrate generation algorithm are the acceleration change time T_1, the acceleration constant time T_5, the total distance of travel (S), the control loop sampling period (T_s), the initial, commanded, and final feedrates (f_s, F, f_e, respectively. For convenience, f_s and f_e are assumed to be zero), the allowable acceleration and deceleration magnitudes (a_{max} and a_{dmax}. For simplicity, we assume that the a_{max} equals to a_{dmax}), and the desired jerk J.

The acceleration profile in Fig. 5 can then be written as

$$v(t) = \begin{cases} p_6\tau_1^2,\ 0<t\le t_1,\ p_6 = 0.5J, \\ p_6T_1(T_1+2\tau_2),\ t_1<t\le t_2, \\ p_6(2T_1T_2+T_1^2+2T_1\tau_3-\tau_3^2),\ t_2<t\le t_3, \\ 2p_6T_1(T_1+T_5)=F,\ t_3<t\le t_4, \\ p_6(2T_1^2+2T_1T_5-\tau_5^2),\ t_4<t\le t_5, \\ p_6T_1(2T_5+T_1-2\tau_6),\ t_5<t\le t_6, \\ p_6(T_1^2-2T_1\tau_7+\tau_7^2),\ t_6<t\le t_7. \end{cases} \quad (27)$$

where t denotes the absolute time, t_i (i=1, 2,⋯, 7) denotes the time boundaries of different regions, J is the jerk value; τ_i ($\tau_i=t-t_{i-1}$ (i=1, 2,⋯, 7)) is the relative parameter time that starts at the beginning of the ith region, as shown in Fig. 5. By integrating Eq. (27) with respect to time, the distance is obtained:

$$s(t) = \begin{cases} p_7\tau_1^3, & 0<t\le t_1, \\ s_1+3p_7T_1(T_1\tau_2+\tau_2^2), & t_1<t\le t_2, \\ s_2+p_7(6T_1T_2\tau_3+3T_1^2+3T_1\tau_3^2-\tau_3^3), & t_2<t\le t_3, \\ s_3+6p_7T_1(T_1+T_5)\tau_4, & t_3<t\le t_4, \\ s_4+p_7[6T_1(T_1+T_5)\tau_5-\tau_5^3], & t_4<t\le t_5, \\ s_5+3p_7T_1[(T_1+2T_5)\tau_6-\tau_6^2], & t_5<t\le t_6, \\ s_6+p_7(3T_1^2\tau_7-3T_1\tau_7^2+\tau_7^3), & t_6<t\le t_7. \end{cases}$$

(28)

where s_i (i=1, 2,$\cdots$, 7) is the displacement reached at the end of the ith region, and

$$p_7 = \frac{1}{6}J,$$
$$s_1 = p_7 T_1^3,$$
$$s_2 = p_7(T_1^3 + 3T_1^2 T_5 + 3T_1 T_5^2),$$
$$s_3 = 3p_7 T_1 (T_1 + T_5)(T_5 + 2T_1),$$
$$s_4 = 3p_7(2T_1^3 + 3T_1^2 T_5 + T_5^2 T_1 + 2T_4 T_1^2 + 2T_1 T_2 T_4),$$
$$s_5 = p_7 T_1 (11T_1^2 + 15T_1 T_5 + 3T_5^2 + 6T_4 T_1 + 6T_2 T_4),$$
$$s_6 = p_7(11T_1^3 + 18T_1^2 T_5 + 6T_5^2 T_1 + 6T_4 T_1^2 + 6T_1 T_2 T_4).$$

The required value of jerk J should not be larger than the achievable value given acceleration, acceleration change time, and the acceleration constant time. Considering Eq. (27) and Eq. (28), we have

$$J = \min\left(\frac{F}{T_1(T_1+T_5)}, \frac{a_{\max}}{T_1}\right). \tag{29}$$

4.2.1 Determination of the number of interpolation steps for each region

Given the numbers of interpolation steps for all regions (except for constant speed region) specified, the total distance of travel S is calculated from Eq. (28) as follows:

$$S = Jn_1 T_s^3 (2n_1 + n_5 + n_4)(n_1 + n_5). \tag{30}$$

The number of the sampled time is

$$n_4 = \left[\frac{S}{Jn_1 T_s^3 (n_1+n_5)} + 1\right] - 2n_1 - n_5. \tag{31}$$

The numbers of interpolation steps for different regions are expressed as follows:

$$\begin{cases} N_1 = n_1, \ \ N_2 = n_5, \ \ N_3 = n_1, \\ \qquad\qquad N_4 = n_4, \\ N_5 = n_1, \ \ N_6 = n_5, \ \ N_7 = n_1. \end{cases} \tag{32}$$

4.2.2 Readjustment of jerk, acceleration and constant feedrate values

After the numbers of interpolation steps for different regions are determined, acceleration and constant feedrate values are readjusted to make the numbers of interpolation steps remain unchanged.

Eq. (33) is used to readjust the value of jerk J. Acceleration and feedrate values will also be adjusted due to Eq. (34) and Eq. (35).

The jerk can be calculated as follows:

$$J' = \frac{S}{n_1(n_1+n_5)(2n_1+n_5+n_4)T_s^3}. \tag{33}$$

The acceleration value can be achieved as follows:

$$a' = J' n_1. \tag{34}$$

The feedrate value can be expressed as

$$F' = \frac{S}{(2n_1+n_5+n_4)T_s}. \tag{35}$$

The readjusted values of jerk, acceleration and feedrate should not be larger than the desired values. Considering Eq. (31), Eq. (33), Eq. (34) and Eq. (35), we have

$$\begin{cases} J' \le J, \\ a' \le a, \\ F' \le F. \end{cases}$$

4.2.3 Discretization of feedrate

The s_{1n} in Eq. (28) can be written as

$$s_{1n} = \frac{1}{6}J' t_1^3 = \frac{1}{6}J' n^3 T_s^3.$$

Therefore, the position increment Δs during each sampling time in region 1 is calculated as follows:

$$\Delta s = s_{1n+1} - s_{1n} = \frac{1}{6}J'(n+1)^3 T_s^3 - \frac{1}{6}J' n^3 T_s^3.$$

where $\Delta s = fT_s$ and $0 \le n < n_1$. Therefore, the feedrate is

$$f = \frac{1}{6}J'(3n^2 + 3n + 1)T_s^2, \quad 0 \le n < n_1. \tag{36}$$

The discretization of feedrate for each region can be obtained by

$$f(t) = \begin{cases} f_{11}(3n^2+3n+1), & 0 \le n < n_1, \\ 3f_{11}n_1(n_1+2n+1), & 0 \le n < n_3, \\ f_{11}[f_{12} - 3(n-2n_1+1)n], & 0 \le n < n_1, \\ 6f_{11}n_1(n_1+n_5), & 0 \le n < n_4, \\ f_{11}[6n_1(n_1+n_5) - 3n^2 - 3n - 1], & 0 \le n < n_1, \\ 3f_{11}n_1(n_1+2n_5-2n-1), & 0 \le n < n_3, \\ f_{11}(3n_1^2 - 3n_1 + 1 - 6n_1 n + 3n^2 + 3n), & 0 \le n < n_1, \end{cases} \tag{37}$$

where $f_{11} = \frac{1}{6}J' T_s^2$, $f_{12} = 3(n_1 + 2n_5 + 1)n_1 - 1$.

5 Simulation and Experiment Results

Five case studies were developed in order to verify the feedrate profile generating efficiency under real-time conditions. The profiles were implemented in an in-house developed CNC[14] running on an Intel pxa270 and TMA320C6713 hardware. The first case is used to demonstrate the advantage of using smooth S-curve feedrate profile over S-curve speed profile. Then profile examples are used to explore smooth S-curve path planning. Finally, the acceleration technique is applied to a surface generated on a five axis machining center.

As shown in Fig. 6, smooth S-curve acc/dec profiles generate smoother feedrate, acceleration, and jerk than S-curve acc/dec, which are widely used in industry machine tool controllers and robot controllers. The two profiles have the same travel length, feedrate, acceleration, and jerk values. For both cases, a linear displacement of 200 mm is programmed with a feedrate of 450 mm/s and an acc/dec value of 4.4 m/s^2. Fig. 6 shows there are no discontinuities in the smooth S-curve position, speed and acceleration, jerk, and acc/dec profiles, because the smooth S-curve are smoother than S-curve acc/dec. Peak jerk dynamics of the smooth S-curve is reduced compared with the S-curve speed profile and no high-energy impulses are present.

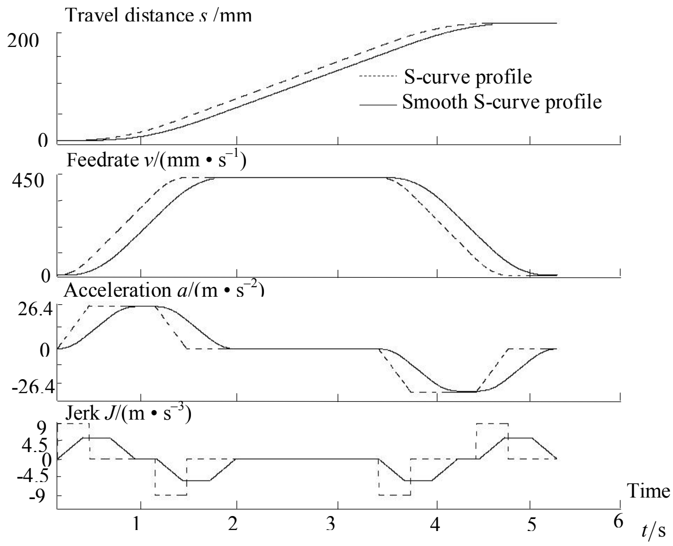


Fig. 6. Comparison of S-curve feedrate and smooth S-curve profiled trajectories

The parameters in the experiment are as follows. The programmed feedrate is 400 mm/s, the maximal acceleration is 2 m/s^2, the jerk change time is 50 ms, the jerk constant time is 75 ms, the Jerk zero time is 50 ms, and the control loop sampling period is 1ms. The kinematic profiles are shown in Fig. 7. From Fig. 7(a)–Fig. 7(c), the travel length is 300 ms, 130 ms, and 100 ms, respectively. From the parameters, we know that, if the travel length is greater than 160 ms, it is the normal block, which is shown in Fig. 7(a). If the travel length is less than 108.9 ms, it is the short block type-II, which is shown in Fig. 7(c). Fig. 7(b) shows the short block type-I with 130 mm travel length.

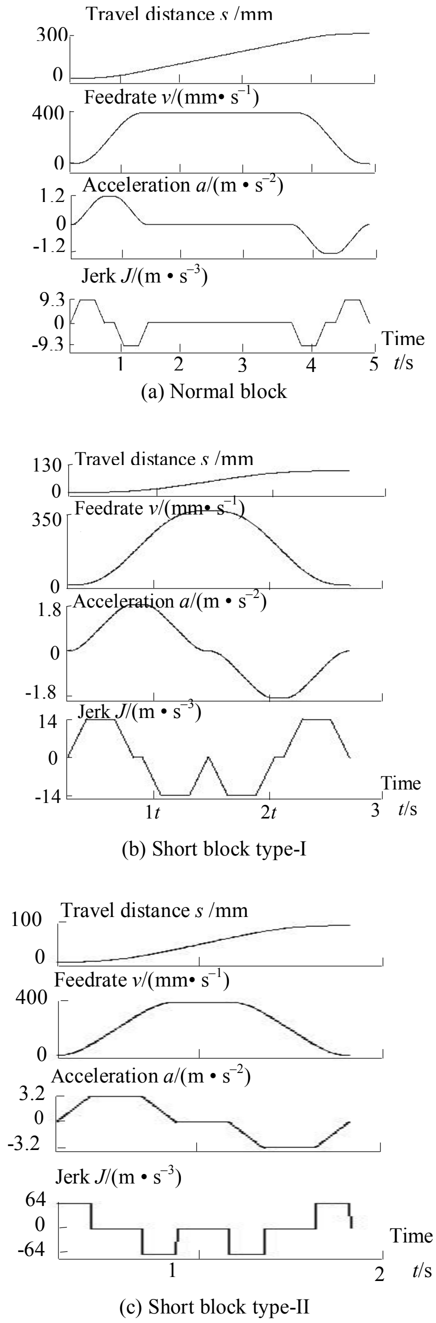
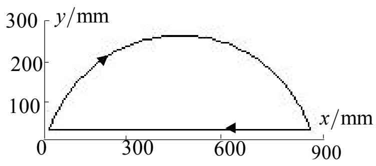
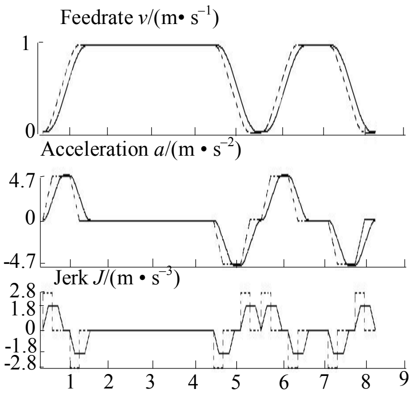


Fig. 7. Kinematic profile of smooth S-curve

In Fig. 8, an example of machining part with smooth S-curve and S-curve acceleration profiling is presented. The tool path is shown in Fig. 8(a). After imposing a smooth S-curve and S-curve acceleration profile to the tool path, for a maximum feedrate of 1 000 mm/s, the obtained velocity, acceleration and jerk profiles are shown in Fig. 8(b). It can be seen that the acceleration, feedrate, and Jerk profile of smooth S-curve in Fig. 8(b) are quite smoother than those of S-curve. The part shown in Fig. 8 is machined on a five axis machining center controller with an in-house developed CNC running on microc/os-II real-time operating system. The CAD model of the part and the generated tool path are shown in Fig. 9(a). The machined part is shown in Fig. 9(b). The machined part shows the acc/dec method proposed in this paper is effective.

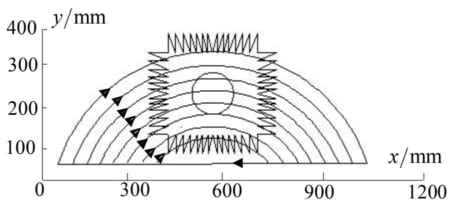


(a) Tool path



(b) Smooth S-curve acceleration profiling along the tool path

Fig. 8. Machined part profile generated smooth S-curve



(a) Tool path

(b) Machined workpiece (c) CNC

Fig. 9. Face surface machined using smooth S-curve.

6 Conclusions

(1) This paper presents a trajectory generation algorithm which employs a smooth S-curve profiling aiming to improve the machinery dynamics by reducing the jerk value. This algorithm reduces the machinery stress by smooth and continuity position, speed, acceleration and jerk. The implementation of the proposed algorithm is based on a TMA320C6713 DSP board showing the feasibility of this feedrate discretization.

(2) In order to generate the feedrate profile, it is necessary to determine if the path is a normal block or a short block. We can get a smooth S-curve acc/dec in normal block, part of a smooth S-curve acc/dec in short block Type-I, and an S-curve acc/dec in short block type-II.

(3) Although promising, the efficiency and the degree of smoothness may decrease if the polynomial feedrate profile is more than three times. Therefore, further research on optimal high degree polynomial profiles for motion smoothness is needed.

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Biographical notes

CHEN Youdong, born in 1973, is currently a lecturer in *Beihang University, China*. He received his PhD degree from *Beihang University, China*, in 2003. His research interests include CNC system, mechachonics control, robotics, control system and embedded system.
Tel: +86-10-82338271; E-mail: chenyd@buaa.edu.cn

WEI Hongxing, born in 1974, is currently an associate professor in *Beihang University, China*. He received his PhD degree from *Harbin Engineering University, China*, in 2001. His main research interests include mechachonics engineering, reconfigurable robot and embedded system.
E-mail: weihongxing@buaa.edu.cn

SUN Kai, born in 1978, is currently a PhD candidate in *Beihang University, China*.
E-mail: kevin_sun_buaa@sohu.com

LIU Miao, born in 1980, is currently a post-doctoral research in *Beihang University, China*.
E-mail: threewaterl@163.com

WANG Tianmiao, born in 1960, is currently a professor in *Beihang University, China*. He received his PhD degree from *Xian Jiaotong University, China*, in 1990. His research interests include intelligent robotics and mechachonics engineering,.
Tel: +86-10-82338271; E-mail: wtm_itm@263.net