Research Article
The Acceleration/Deceleration Control Algorithm Based on Trapezoid-Curve Jerk in CNC Machining

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Abstract: In this study, we put forward an Acc/Dec control algorithm based on trapezoid-curve jerk in order to avoid step change in jerk curve. Moreover, the motion profile smooth control approach based on continuous jerk is developed in details to decrease machine tools impact according to various kinematics constraint conditions, such as the maximum acceleration, the maximum jerk, the machining program segment displacement, the instruction feed rate and so on; Finally, the developed Acc/Dec approach and the traditional linear Acc/Dec approach are compared in the CNC experimental table. The results reveal that the developed approach can achieve more smooth and flexible motion profile, which is helpful to minish machine tools impact and enhance parts machining surface quality.

Keywords: Machine tools impact, smooth control, step change, surface quality trapezoid-curve jerk

INTRODUCTION

It is important to ensure smooth movement and reduce machine tools impact in high precision CNC machining. However, in practical machining the impact and vibration on machine tools worsen cutting process and destroy machining quality. It has been reported that the unsmooth Acc/Dec control in feed movement is one of the main reasons to bring about machine tools impact and vibration (Chen *et al*., 2006).

Consequently, several researchers have developed various Acc/Dec control approach in CNC machining. The jerk profile in the linear Acc/Dec, exponent Acc/Dec approach and the S-shape curve Acc/Dec approach is discontinuous, which leads to flexible impact on machine tools (Shi *et al*., 2007). The excessive jerk still exists due to abrupt change in acceleration profile (Xu *et al*., 2008), which will cause shock to the machine as well as deteriorate the surface accuracy (Zhang *et al*., 2009). Accordingly, Ruo *et al*. (2003) presents optimal S-curve velocity profiles of PTP motion generation for a multiple-axis machine subject to individual axis' maximum velocity, acceleration and jerk constraints. Jiang *et al*. (2011), introduces the feed rate control algorithm based on the trigonometric acceleration-deceleration and machine dynamics conditions. Tseng *et al*. (2009), proposes a parametric interpolator composed of a look-ahead stage and a real-time sampling stage for jerk-limited acceleration planning based on constant jerk. Sung-Ho and Min-Yang (2004), presents a new recursive trajectory generation method to produce exact feed rate trajectory generation through jerk-limited acceleration profiles for the parametric curves. Yih-Fang *et al*. (2010), introduces a look-ahead linear jerk filter to ensure the smooth and accurate motion of a tool with a linear change in jerk during real-time machining. Wan *et al*. (2009) presents a feed rate scheduling and jerk control interpolation algorithm to seek the optimal feed rate by evaluating the tool path ahead.

The CNC Acc/Dec control algorithms mentioned above can reduce impact on machine tools a certain extent. However, the step change in jerk curve will produce flexible impact on machine tools unavoidably. Accordingly, in order to achieve high precision CNC machining, an Acc/Dec approach based on trapezoid-curve jerk is put forward in the study firstly; Secondly, the motion profile smooth control algorithm based on continuous jerk is developed in details to decrease machine tools impact according to various kinematics constraint conditions.

In this study, we put forward an Acc/Dec control algorithm based on trapezoid-curve jerk in order to avoid step change in jerk curve in the study; Moreover, the motion profile smooth control approach based on continuous jerk is developed in details to decrease machine tools impact according to various kinematics constraint conditions, such as the maximum acceleration, the maximum jerk, the machining program segment displacement, the instruction feedrate and so

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on; Finally, the developed Acc/Dec approach and the traditional linear Acc/Dec approach are compared in the CNC experimental table. The results reveal that the developed approach can achieve more smooth and flexible motion profile, which is helpful to minish machine tools impact and enhance parts machining surface quality.

AN ACC/DEC CONTROL APPROACH BASED ON TRAPEZOID-CURVE JERK

The CNC machine tools dynamic model: Suppose the CNC machine tools motion components mass be m, then the relational expression among the servo-actuator driving force F, the cutting force F_c, the friction force F_f and the feeding acceleration a can be obtained:

$$F - F_c - F_f \approx ma \tag{1}$$

Differentiate the Eq. (1):

$$\frac{d(F - F_c - F_f)}{dt} \approx m\frac{da}{dt} = mj \tag{2}$$

where, the jerk j describes the relation between the machine tools response speed and the movement smooth characteristic in theory (Leng *et al.*, 2008).

An Acc/Dec control approach based on trapezoid-curve jerk: A new Acc/Dec control approach based on trapezoid-curve jerk is put forward in the study, where the jerk curve adopts linear Acc/Dec which is first-order continuous. The displacement S, feed rate V and acceleration a curves can be obtained when integrating j curve in turn:

$$S = q_0t^4 + q_1t^3 + q_2t^2 + q_3t + q_4 \tag{3}$$

$$V = 4q_0t^3 + 3q_1t^2 + 2q_2t + q_3 \tag{4}$$

$$a = 12q_0t^2 + 6q_1t + 2q_2 \tag{5}$$

$$j = 24q_0t + 6q_1 \tag{6}$$

As shown in Fig. 1, a whole motion process includes seven segments: AB is acceleration speed-up portion, BC is even speed-up portion, CD is decrease speed-up portion, DE is uniform speed portion, EF is acceleration slowing-down portion, FG is even slowing-down portion and GH is decrease slowing-down portion.

Let the slope coefficient of j curve be l, which is computed through machining experimentations. The q_0, q_1, q_2, q_3 and q_4 value are various in Eq. (3, 4, 5 and 6).
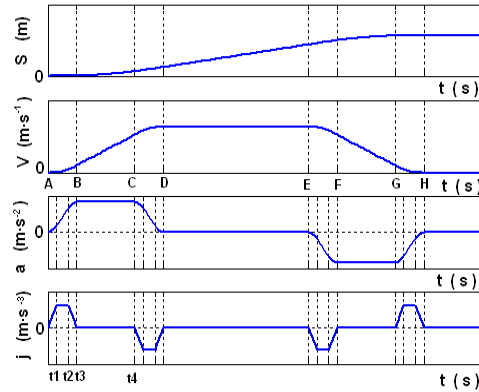

Fig. 1: Acc/Dec approach based on trapezoid-curve jerk

Consequently, the expression of S, V and a are unlike in each segment shown in Fig. 1.
For example, When $t \in [0, t_1)$, the j curve is speed-up:

$$j = lt,$$
$$a = 1/2 * lt^2,$$
$$v = 1/6 * lt^3,$$
$$s = 1/24 * lt^4$$

When $t \in [t_1, t_2)$, the j curve is uniform-speed:

$$j = j_{max},$$
$$a = j_{max}(t - t_1) + 1/2 * lt_1^2,$$
$$v = 1/2 * j_{max}(t - t_1)^2 + 1/6 * lt_1^3,$$
$$s = 1/6 * j_{max}(t - t_1)^3 + 1/24 * lt_1^4$$

As shown in Fig. 1, the jerk j is first-order continuous, which can obtain smooth movement, but make the Acc/Dec process more complicated at the same time. Accordingly, the jerk process algorithm in the introduced Acc/Dec approach should be simplified rationally in order to meet the demand of real-time property in the study. Set an example with AB segment (acceleration speed-up portion) to tell how to simplify operation:

According to the maximum permissible jerk j_{max} and the slope coefficient l of j curve, the time when j accelerates from 0 to j_{max} can be obtained:

$$t_j = \frac{j_{max}}{l} \tag{7}$$

Suppose the CNC system interpolation period be T, then the required period numbers when j accelerates from 0 to j_{max} is as follows:

$$n_1 = \frac{t_j}{T}$$

In order to simplify operation, round-off number to n_1:

$$n_j = round(n_1)$$

So the practical jerk in each interpolation period when j accelerates from 0 to j_{max} can be obtained:

$$j(k) = \frac{k}{n_j} * j_{max} \qquad (8)$$

where, $k = [0, 2, …, n_j]$. In like manner, the practical jerk in each interpolation period when j decelerates from j_{max} to 0, i.e., $t \in [t_2, t_3]$:

$$j(k) = \frac{n_j - k}{n_j} * j_{max} \qquad (9)$$

In AB segment, the needed time t_q when a accelerates from 0 to a_{max} can be obtained:

$$t_q = \frac{a_{max}}{j_{max}} + \frac{j_{max}}{l} \qquad (10)$$

Then the time when j keeps to j_{max} according to Eq. (7) and Eq. (10) can be obtained:

$$t_2 - t_1 = t_q - 2t_j$$

The algorithms mentioned above simplify the calculation of a and j and reduce the Acc/Dec process operation of AB segment (acceleration speed-up portion). Furthermore, the algorithms are appropriate for the other movement segments. With the simplified algorithms, the developed Acc/Dec approach accords with the demand of 4 *ms* interpolation period completely.

MOTION PROFILE SMOOTH PROCESS ALGORITHM BASED ON THE DEVELOPED ACC/DEC APPROACH

All of the motion profile portions shown in Fig. 1 don't always exist in a certain machining program segment. Consequently, the machining program segment Acc/Dec control should be done according to various kinematics constraint conditions, such as the permissible maximum acceleration a_{max}, the maximum permissible jerk j_{max}, the machining program segment displacement S and the instruction feed rate V_c.
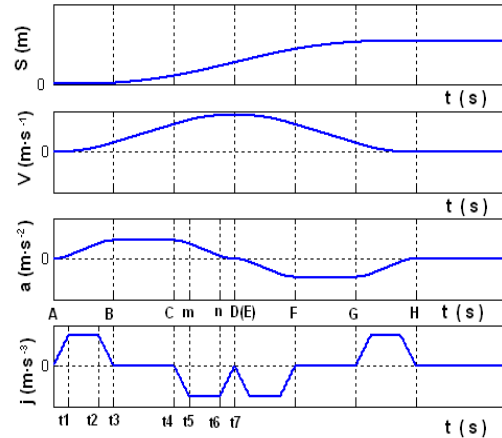

Fig. 2: The motion profile with displacement S_1

Above all, the time that a gets to a_{max} and the time that V gets to V_c should be estimated in CNC interpolation pretreatment. Suppose the time when V accelerates from 0 to V_c be t_v, the time when a accelerates from 0 to a_{max} and decelerates from a_{max} to 0 be t_a, it can be concluded:

$$t_v \approx V_c / a_{max} + a_{max} / j_{max} \qquad (11)$$

$$t_a = (a_{max} / j_{max} + j_{max} / l) \times 2 \qquad (12)$$

The even speed-up portion is needed for velocity to achieve V_c in speed-up process if $t_v > t_a$; The even speed-up portion is unnecessary for velocity to arrive at V_c in speed-up process if $t_v \leq t_a$. The motion profile smooth process algorithm is researched in details according to different conditions.

The motion profile smooth process algorithm if $t_v > t_a$: The even speed-up portion is needed for the velocity to arrive at the instruction feed rate V_c if $t_v > t_a$ in principle. Whereas, whether the velocity arrives at V_c or not is also depended upon the machining program segment displacement S.

The machine tools instantaneous feed rate can arrive at instruction feed rate and acceleration can arrive at maximum if S is long enough (suppose $S \geq S_1$); The acceleration and velocity can't arrive at its maximum or instruction value if S is short enough (suppose $S < S_2$); The acceleration can arrive at maximum but the instantaneous velocity can't get to instruction feed rate if $S_2 \leq S < S_1$. It is noted that the S_1 and S_2 mentioned above are critical values. As shown in Fig. 2, suppose the machining program segment initial point and terminal point velocity be 0 and define the machining program segment displacement as S_1, when the motion acceleration can get to maximum and velocity can get to instruction value exactly; As shown
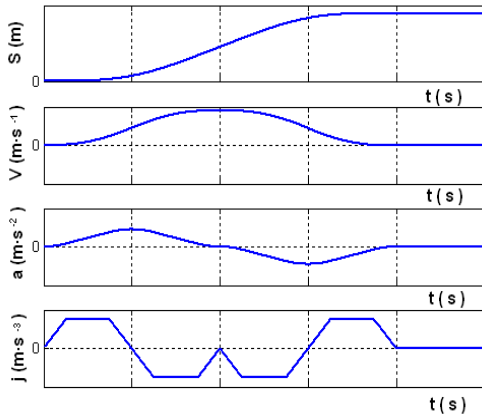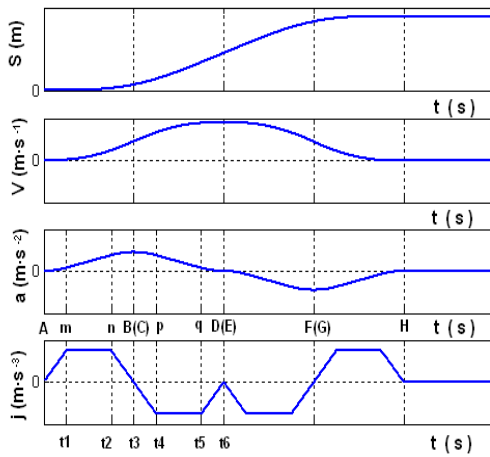
Fig. 3: The motion profile with displacement S_2

Fig. 4: The motion profile with displacement S_3

in Fig. 3, define the machining program segment displacement as S_2, when the motion acceleration can get to maximum exactly.

How to compute S_1? As shown in Fig. 2, the motion profile doesn't include uniform speed portion (DE segment). In other words, the velocity adds from 0 in the motion program segment, arrives at V_c on point D, decreases to 0 in succession on the terminal point. The key to compute displacement S_{AH} from point A to point H is to obtain even speed-up time t_{BC}. The even speed-up time t_{BC} is equal to the even slowing-down time t_{FG} owing to symmetrical characteristic. Because:

$$V_D = \int_{AB} a(t)dt + \int_{BC} a(t)dt + \int_{CD} a(t)dt = V_c \qquad (13)$$

where, suppose the instantaneous velocity on point D be V_D:

Since $\int_{AB} a(t)dt = V_B$,

$$V_B = 1/2 * j_{max}(t_3 - t_2)^2 - 1/6 * l(t_3 - t_2)^3 \qquad (14)$$
$$+ 1/2 * j_{max}(t_2 - t_1)^2 + 1/6 * lt_1^3$$

where,

$$t_1 = t_3 - t_2 = j_{max}/l$$
$$t_2 - t_1 = a_{max}/j_{max} - j_{max}/l.$$

Because

$$\int_{BC} a(t)dt = a_{max} * t_{BC} \qquad (15)$$

The unknown t_{BC} can be concluded according to Eq. (13, 14 and 15), then S_1 will be readily obtained:

$$S_1 = S_{AH} = \int_{AD} V(t)dt + \int_{DH} V(t)dt \qquad (16)$$
$$= 2 * \int_{AD} V(t)dt = 2 * S_{AD}$$

S_2 can be calculated in like manner.

The motion profile smooth process algorithm if $t_v > t_a$: The even speed-up portion isn't needed for the velocity to arrive at the instruction feed rate V_c when $t_v > t_a$. The machining program segments can be divided into two instances according to various displacement: If S is long enough (suppose $S \geq S_3$), the machine tools instantaneous velocity can arrive at instruction feed rate; If S is short enough (suppose $S < S_3$), the machine tools instantaneous velocity can't arrive at instruction feed rate.

As shown in Fig. 4, compute the speed-up time of acceleration with jerk j_{max} firstly:

$$t_{mn} = t_2 - t_1$$

Then S_3 can be concluded:

$$S_3 = 2 * \int_{AD} V(t)dt = 2 * S_{AD} \qquad (17)$$

The machining program segments can be divided into two instances owing to S_3.

- $S \geq S_3$: As shown in Fig. 5, the machining program segment motion profile includes five portions only and doesn't involve even speed-up segment and even slowing-down segment. Accordingly, the Acc/Dec process is same but the uniform speed segment motion time varies for various displacements S.

- $S < S_3$: Because the machining program segment displacement is much less, the acceleration can't
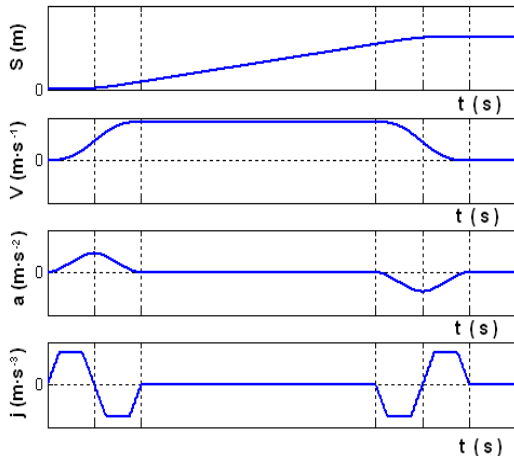
Fig. 5: The motion profile when $S \geq S_3$

get to maximum and velocity can't get to instruction value, the motion profile includes four portions only and doesn't involve uniform speed segment, even speed-up segment and even slowing-down segment.

ACC/DEC CONTROL EXPERIMENTAL ON THE CNC TABLE

The CNC experimental table hardware structure is shown in Fig. 6. The CNC controller is made up of personal computer and DSP movement control card SEED-DEC2812. And the Acc/Dec control, interpolation, position control is carried out on SEED-DEC2812. Especially, the operating system (RTOS)-UC/OS-II is introduced to SEED-DEC2812 to meet the demands of CNC system multitask and real-time property. Both the interpolation period and sampling period of the CNC table are 4 *ms*.

- Adopt the developed Acc/Dec approach based on trapezoid-curve jerk and the main kinematics parameters are defined as follows:

v_c = 15 mm/S,
a_{max} = 300 mm/s²
j_{max} = 20 m/S³
l = 400 m/S⁴

Let the X axis table move forward 15mm and then countermove 15mm. The displacement curve, velocity curve and acceleration curve is shown in Fig. 7.

- Adopt the conventional linear Acc/Dec approach and the main kinematics parameters are defined as follows:

v_c = 15 mm/S,
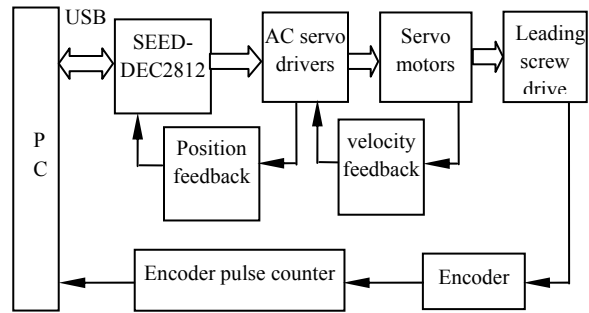a_{max} = 300 mm/s²

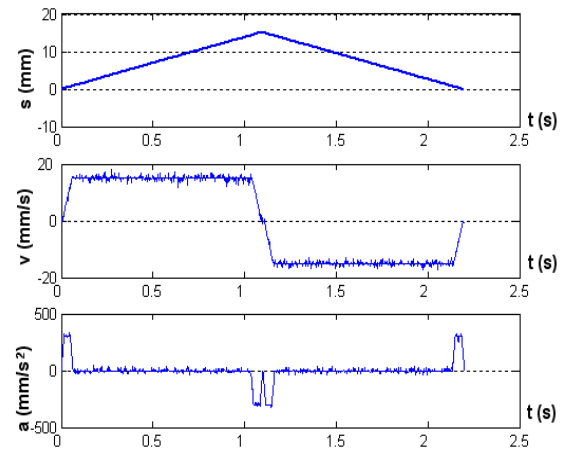Fig. 6: The CNC table hardware structure

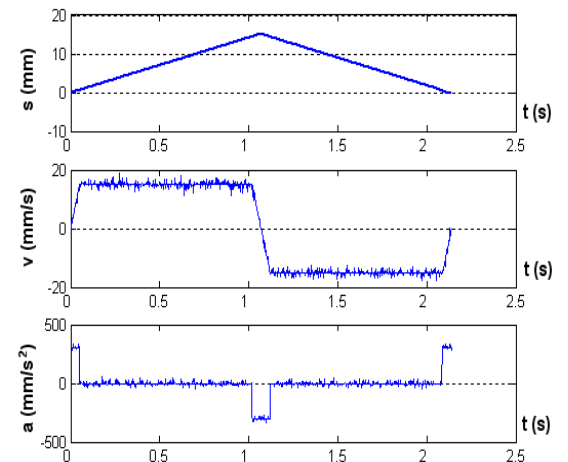Fig. 7: Adopting the developed Acc/Dec approach

Fig. 8: Adopting the linear Acc/Dec approach

The displacement curve, velocity curve and acceleration curve is shown in Fig. 8. Compare the developed Acc/Dec approach and the linear Acc/Dec approach through velocity and acceleration curve: as shown in Fig. 9, the data1 curve represents the developed Acc/Dec approach, while the data2 curve represents the linear Acc/Dec approach.
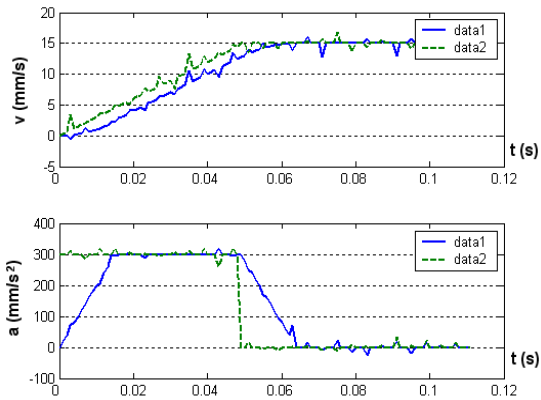
Fig. 9: Compare the two Acc/Dec approaches

Experimentation results: It can be seen from Fig. 7, 8 and 9 that the developed Acc/Dec approach can achieve more smooth and flexible motion profile, but need more run time. In particular, the run time when adopting the introduced Acc/Dec approach is 2.26 s in the experimentation, while the run time when adopting the linear Acc/Dec approach is 2.19 s.

CONCLUSION

It is important to ensure smooth movement and reduce machine tools impact in high precision CNC machining. The CNC machine tools dynamic model is set up to analyze the cause of machine impact in the study, then a Acc/Dec approach based on trapezoid-curve jerk is put forward which can ensure that the jerk is first-order continuous; Moreover, the motion profile smooth control algorithm based on continuous jerk is developed in details according to various kinematics constraint conditions; Finally, the experimentation results reveal that the developed approach can achieve more smooth and flexible motion profile, which is helpful to reduce machine tools impact and enhance parts machining surface quality. In sum, the developed approach avoids flexible impact on machine tools produced by step change jerk and achieves smooth motion profile, which is significant to high accuracy CNC machining.

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