Research on flexible control algorithm for acceleration/deceleration in heavy-duty motion

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Abstract. An algorithm for acceleration/deceleration control is proposed in this paper to improve the flexibility of the heavy-duty motion system. The algorithm is based on the five-segment S-type acceleration/deceleration curve. During the acceleration switching time, a circular arc is used to smooth the curve, and the running time of each stage could be reasonably allocated by cyclic iteration. A parameter is defined to quantify the degree of flexibility of the acceleration/deceleration process to match the actual project. This paper will build the model to compare the good and bad point of different algorithms. The result shows that the vibration and impact during the acceleration and deceleration process can be effectively reduced, which means that the flexibility of the system has been greatly improved.

1. Introduction
In heavy-duty motion system, large impacts can be caused by small acceleration changes that reduce the stability and reliability of the system, that is the flexibility of the system which can be expressed by the changing rate of acceleration [1]. The system can be more flexible by using appropriate acceleration/deceleration curve, therefore reduce the vibration and impact of the system and improve its flexibility.

Since KIM D I [2] advocated the flexible control algorithm in 1994 for the first time, various flexible control algorithms for acceleration/deceleration curves including linear, exponential, trigonometric, polynomial and S-curve have been developed [3-7] in recent years. Based on the S-curve, Tzyy-Chyang Lu [8] further demonstrated an improved five-segment S-type acceleration/deceleration curve, which achieved faster response. Chaozhi Huang also proposed a kind of algorithm based on continuous jerk [9]. However, little attention has been devoted to the heavy-duty motion system and previous algorithm were too complex to apply to this condition. This paper aims to propose a relatively simple algorithm for this condition.

The algorithm is based on the five-segment S-curve [10], a circular arc of the standard circle is used to smooth the acceleration transition section, and the radius of the transition arc is defined as the variable parameter to quantify the flexibility of the algorithm, therefore one can design proper algorithm considering the actual requests. The method makes the jerk continuous, the acceleration process is smooth, the system is more flexible, and the flexibility is controllable, which has high applicability to engineering practice.
2. Flexible acceleration and deceleration algorithm design

In heavy-duty motion systems, flexible control is to make the force of the system change gently. The jerk reflects the flexibility of the system \cite{11}. This paper aims to design an algorithm to reduce short-term impact caused by changing acceleration, and gain higher flexibility without reducing the original performance of the system. The algorithm will be introduced in the following three parts: the original S-type curve, the arc smooth design and the displacement compensation design.

2.1. Five-segment S-type acceleration/deceleration curve

The five-segment S-type acceleration/deceleration algorithm is shown in Figure 1.

\textbf{Figure 1.} The variation of jerk(J), acceleration(A), velocity(V) and displacement(S) with time of five-segment S-type acceleration/deceleration curve.

The five-segment S-curve acceleration/deceleration algorithm is based on jerk variation \cite{12}. The mathematical expression of jerk (J) is shown in Equation (1), By integrating the jerk successively, the acceleration(A), velocity(V) and displacement(S) curves can be obtained as Equation (2) shows.

\[
J(t) = \begin{cases} 
J_m & 0 \leq t < t_1 \\
-J_m & t_1 \leq t < t_2 \\
0 & t_2 \leq t < t_3 \\
-J_m & t_3 \leq t < t_4 \\
J_m & t_4 \leq t \leq t_5 
\end{cases} 
\]  

\[
A(t) = \int_0^t J(t) \, dt \\
V(t) = \int_0^t A(t) \, dt \\
S(t) = \int_0^t V(t) \, dt
\]  

The five-segment S-curve lacks a constant acceleration transition phase, with large acceleration changes and small flexibility, impacts the system during speed switching and reduces system stability. By smoothing the acceleration transformation points and improving the flexibility of the curve, better dynamic performance can be obtained.

2.2. Smoothing design with circular arc

Commonly used smoothing methods include linear interpolation, polynomial interpolation, and spline interpolation. This paper uses circular interpolation. The arc can realize the smooth connection between any slopes. The algorithm is simple. Only by controlling one parameter, can one design the different flexible selection matching different working conditions.
Figure 2. Smoothing process between the increasing acceleration section (Sec.1) and the decreasing acceleration section (Sec.2).

Figure 3. Smoothing process between the decreasing acceleration section (Sec.2) and the uniform speed section (Sec.3).

Figure 2 and Figure 3 show the smoothing processes. The jerk of Sec.1 (the slope of the line $AB$) is $k_1$, Sec.2 (the slope of the line $BC$) is $k_2$, EOF is the interpolated arc. The length of the line segment $OE/OF$ is the radius $r$ of the interpolation arc. The centre point of the arc(O) is located on the $\angle ABC$’s angle bisector $BJ$, the slope of $BJ$ is $k$, then we have Equation 3 to calculate it.

$$\frac{k - k_1}{1 + kk_1} = \frac{k - k_2}{1 + kk_2}$$

(3)

$k_1$ and $k_2$ is given by the original system, when the radius $r$ is determined, The entire curve is also uniquely determined by the geometric relationship. When the radius $r$ is adjusted, the length of EOF changes accordingly. The larger the radius, the longer the arc length, the smoother the curve. The system is more flexible, but it will also lose more displacement and takes more time to finish the motion. Let $\phi=\angle EOF$, then (in radians) using Equation 4 to calculate it.

$$\phi = \pi - (\arctan k_2 - \arctan k_1)$$

(4)

The time of the speed switching point $E(t_E)$ and $F(t_F)$ are calculated as Equation 5 shows.
Define a parameter $\delta$ used to evaluate the degree of flexibility of the curve, that is, the slewing rate of the acceleration's direction. The calculation formula is: how much the direction of acceleration changes per unit time (characterized by angle). That is what we have in Equation 6.

$$
\Delta t = t_f - t_e
$$

$$
\delta = \frac{\varphi}{\Delta t} = \frac{\pi - (\arctan k_2 - \arctan k_1)}{r \tan \frac{\varphi}{2} \left[ \cos(\arctan |k_1|) - \cos(\arctan |k_2|) \right]}
$$

Taking $\delta$ as the basis for selecting flexibility, after the working condition is determined, the parameter is only related to the radius $r$ of the selected smooth arc. Considering the needs of the actual working conditions, different $\delta$ can be selected to obtain the acceleration/deceleration curves with both flexibility and quick response. The rest of the smoothing processes are basically the same as it.

Considering the green area in Figure 2 and Figure 3 we can easily know that some displacement is lost during the smooth process, then the compensation is required.

### 2.3. Compensation design for the missing displacement

In order to compensate more efficiently, the displacement compensation is performed by the uniform velocity section which of the highest speed. The specific method is as shown in Figure 4 below. In order to maximize the performance of the motor, the smooth curve of the plan can be improved to make the maximum accelerations equal (the ordinates of $B$ and $H$ are equal), as $A'E'HF'C'$ (the red one) planned.

![Figure 4. Curve comparison before and after compensation.](image)

When the original curve $AECF$ (the blue one) is translated in the $AE$ direction for a distance equal to $EE'$, the smooth arc parts will overlap, therefore the two planning curves have the same flexibility, and the maximum values of jerk and acceleration are unchanged.
After the acceleration/deceleration process ends, the maximum speed will increase, and increased value is \( \Delta v_m \) which can be calculate by Equation 7, the system achieves higher ending speeds, quicker response, faster displacement compensation, more accurate positioning, and higher motor efficiency.

\[
\Delta v_m = \frac{1}{2} (y_{H'} - y_{H}) (x_{AC'} - x_{AC})
\]

\( y_{H'}, y_{H} \): Maximum value of new \( H' \) and old \( H \) curves, \( x_{AC'}, x_{AC} \): Length of line segments \( AC' , AC \).

While the S curve itself has no speed or acceleration during the starting and ending time, there is no special need to do the smooth interpolation, we will only deal with the speed transformation during the movement. The final compensation method is based on simulation iteration. The design steps are as follows.

Firstly, we smooth the original five-segment S-curve by using the algorithm introduced above, then calculating the displacement \( S' \) and the maximum speed \( v' \) of the newly acceleration/deceleration curve. Secondly, calculating the displacement difference by subtracting the original displacement \( S \) and \( S' \), and the uniform velocity time \( t' \) is showed in Equation 8.

\[
t' = \frac{S - S'}{v'}
\]

Finally we can get the optimal path planning curve showed below in Figure 5. We can easily find that the uniform velocity time is reduced a lot but it will take less time to finish the requested displacement.

![Figure 5. Curve comparison before and after optimization.](image)

If the displacement required by the acceleration/deceleration process is greater than the actual required displacement, or the required time is longer than the actual required time, or the displacement compensation still fails to meet the operational requirements within the specified time, then in no way can the method meet the requirements. In this case, you should consider using a better performing motor to meet the operating requirements.

In summary, the new acceleration and deceleration curve does not reduce the original positioning accuracy and control accuracy of the system, and can also achieve higher speed response and smoother running flexibility, guarantee the accuracy and speed requirements during the motion. The overall acceleration/deceleration path planning curve is shown in Figure 6.
Figure 6. The variation of acceleration(A), velocity(V) and displacement(S) with time of the optimized five-segment S-type acceleration-deceleration curve.

3. Simulation results

To compare the effects using different acceleration/deceleration curve including trapezoidal curve, seven-segment S-type curve and five-segment S-curve, we use speed and current double closed loop control, and SVPWM(Space Vector Pulse Width Modulation) control strategy, by inputting different acceleration/deceleration curves to build the model which is showed in Figure 7. Judging the performance of the method used by observing the output torque of PMSM (permanent magnet synchronous motor) and the speed synchronization performance.

The motor model used in this experiment is a model of J-GK6000 series servo motor provided by Wuhan Huazhong Numerical Control System, Inc. The main parameters are shown in Table 1.

| Rated output torque | Maximum output torque | Rated speed | Rated voltage | Rated current | Rated efficiency |
|---------------------|------------------------|-------------|---------------|---------------|-----------------|
| 33.7Nm              | 67.4Nm                 | 3000rpm     | 380V AC       | 22.5A         | 80%             |

The control algorithm used in the simulation model is designed as follows in Figure 7.

In addition, we design two acceleration/deceleration curve using different flexibility showed in Figure 8. Through the Equation (6), we can figure out that $\delta_1=11.57$ for the blue one and $\delta_2=2.78$ for the red one, the red one is more flexible by comparison.
Figure 8. Curve comparison before and after optimization.

After inputting different curves, the results of each experiment are as follows in Figure 9 and Figure 10.

Figure 9. Trapezoidal, seven-segment S-type, five-segment S-curve output torque.
Figure 10. Optimized output torque of the five-segment S-curve ($r=100,400\,\text{mm/s}^2$).

Table 2. Comparison of output parameters of each curve.

| Item                      | Trapezoidal | Seven-segment S | Five-segment S | Optimized S($r=100\,\text{mm/s}^2$) | Optimized S($r=400\,\text{mm/s}^2$) |
|---------------------------|-------------|-----------------|----------------|-------------------------------------|-------------------------------------|
| Maximum output force/kN   | 30.57       | 29.6            | 31.89          | 31.36                               | 28.04                               |
| Positioning accuracy/mm   | 1.5         | 1.6             | 2.5            | 0.5                                 | 0                                   |
| Synchronization accuracy/mm| 6.932      | 6.934           | 7.552          | 7.408                               | 6.400                               |
| Maximum Velocity/(mm/s²)  | 499.5       | 484.9           | 547.6          | 613.4                               | 579.9                               |

Comparing the test results showed above in Table 2, it can be seen that the output force by the trapezoidal acceleration/deceleration method will have two cliff-like jumps, which may cause instability of the system. The flexibility of the seven-segment S-shaped curve is better than that of the five-segment, however, when we use the optimized five-segment S-type acceleration and deceleration curve and select the appropriate $\delta$, the performance of the system will be greatly improved. The maximum output torque is reduced and the system is more flexible. At the same time, the system maintains good positioning accuracy and synchronization control accuracy.

4. Conclusions
As the simulation results shows, the newly designed acceleration/deceleration control curve does improve the flexibility of the original system without reduce its performance or requirements. The structure of the algorithm is relatively simple and easy to implement. The acceleration and speed are smooth in the whole running time. By adjusting the parameter $\delta$, it is possible to design control algorithms with different flexibility. However, the results do not imply the optimization for the starting and ending time, and can not be used to deal with the sudden change of instantaneous force. However, these problems could be solved if we consider the complexity of the actual working condition, thus we will do some experiment in the near future to prove its validity.

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