A Segment Planning Method for Random Angle Compensation of Rotating Cylinder

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Abstract

In this article, a segment planning method has been proposed especially for the requirement of the random compensating angle in the rotating cylinder transmission system. Firstly, the article has established the constraint condition of the angle compensation according to the position correcting principle of the rotating cylinder, and proposed the segment planning method composed by rough compensation and finish compensation, designed the work mechanism of the controller in different segments. The study has derived the function of S shape acceleration and deceleration process based on the segment planning method, defined the planning coefficient which effects the segmentation and the dynamic characteristics of the cylinder, proved the feasible region of the planning coefficient is 0.58~0.70, and provide the optimized method of the planning coefficient in feasible region based on the basic idea of the compensating method. Simulation results show that this method can both get a gentle and symmetrical acceleration-deceleration curve and abundant finish compensating time for diverse initial velocity and compensating angle.

Key words: ROTATING CYLINDER, RANDOM ANGLE, COMPENSATING METHOD, SEGMENT PLANNING

1. Introduction

The Roll-to-Roll drum winding transmission system has been widely used in the production lines of papermaking, printing, textile, steel rolling and semiconductor package. In recent years, the drum winding transmission has been recognized as one of the most important technologies to cut costs. The characteristics of high efficiency and low cost have greatly promoted it’s applications in the production of flexible thin film products such as paper sheet [1]. In the equipment of winding transmission, it needs to make a dynamic angle compensation to correct the position of the thin film products during the rotation period of the cylinder. Since the position of the monolithic membrane attached to the cylindrical surface is random and the position deviation is uncertain, it is particularly important for the position correcting process of the drum winding transmission system to have an angel compensation method which can adapt to a wide range of adjustment. The angle compensation of the drum has usually been actualized through the accuracy control of the rotating angle by servo motor. As the drum has been continually rotating in the winding transmission process, it needs to make an accelerating and decelerating control of the drum to actualize the dynamic angle compensation in the continually rotating process.

At present, the researches on acceleration and deceleration mainly based on the S shape velocity control algorithm for the target of reducing the shock and vibration in the acceleration and deceleration process [2-4], but ignored the accuracy control of the angle in the velocity change process. Such as, Zhu et al. pre computed the velocity boundary points of each section, and achieved the subsequent velocity control parameters through the comparison of the real-time velocity and target velocity [5]. Li et al. proposed a 5 sections type of the S shape acceleration and deceleration control method, and provided the expressions of the Jerk (rate of acceleration change), acceleration, velocity and displacement [6]. Xu et al. proposed a polynomial acceleration and deceleration controlling method which can assure the continuity of the Jerk and acceleration [7, 8]. He et al. proposed a nested prospective processing algorithm of the S shape acceleration and deceleration and established the velocity planning model according to the symmetry of the S shape acceleration and deceleration curve [9]. Chen et al. proposed a discrete control algorithm of the S shape acceleration and deceleration and gave the velocity iterative formula of the straight line and S shape acceleration and deceleration [10, 11]. The above researches about acceleration and deceleration mainly concentrated in the controlling of velocity and acceleration. The existed methods have seldom been used in the dynamic angle compensation of the rotating body. This article has proposed a segment planning method for random angle compensation based on acceleration and deceleration, studied the determination of the planning coefficient to make sure the velocity curve is gentle and the finish segment compensating time is appropriating in different initial velocity and compensating angle.

2. Angle compensation principle of the rotating cylinder

The rotating cylinder is composed of cylinder body, servo motor, encoder, and visual system position detector and compensation controller. A vacuum cup is attached on the cylinder surface of the drum to adsorb the flexible thin film sheet. The rotating cylinder is drove by servo motor to actualize the spin velocity control. The encoder is installed on the central shaft to real-time feedback the actual position of the cylinder. The visual system can detective the geometrical center and get the position deviation of the thin film sheet which is adsorbed on the cylinder surface. The compensation controller receives the position deviation from the detector and carries out the angle compensation through acceleration and deceleration of the servo motor.

The work mechanism of the rotating cylinder during a cycle is shown in Figure 1.The point O on the drum is the reference point for angle accurate control, the phase point G is the initial point of the work cycle. The rotating cylinder goes through 5 functional areas during a cycle, finishes different processing technologies respectively in the production of thin film sheet.

In uniform velocity area EA, the cylinder rotates at an initial and constant speed ω_0, when point O arrives at the phase point G, the phase value of the controller is cleared zero, and the vacuum cup adsorbs a piece of thin film sheet.

In calculation area AB, when point O arrives at phase point A, the visual system detector captures the image of the thin film sheet and get the angle deviation β between the geometric center of the sheet and point O, and send the initial velocity ω_0 and compensation value β to the compensation controller, then the controller calculates and stores the start parameters of the acceleration and deceleration angle compensation.

In the compensation area BC, the servo motor starts the angle compensation process by acceleration and deceleration, and the controller carries out the calculation of the subsequent motion parameters, the compensation period T is constant. Figure.1 shows the angle that the geometric center of the sheet lags behind the point O is β, so the compensatory movement is firstly acceleration then deceleration. The compensation process must satisfy the constraint condition as Formula (1) shows

$$\begin{cases} \theta - \theta_0 = \beta \\ \omega_e = \omega_0 \end{cases} \tag{1}$$

Where, θ is the actually turning angle during the compensation period, θ_0 is the virtual reference angle that the cylinder rotates at a constant speed ω_0 during T , ω_e is the ending speed of the compensation process.

In interchange area CD, the center of the sheet arrives at phase point R with initial velocity ω_0 , and accomplishes the interchange of the sheet at the given time.

In reply area DE, the rotating cylinder carries out the negative angle compensation with first deceleration then acceleration process to make sure that the actually turning angle is consistent with the virtual reference angle and the point O replies to initial point G with initial velocity ω_0 , then start the next rotating cycle.

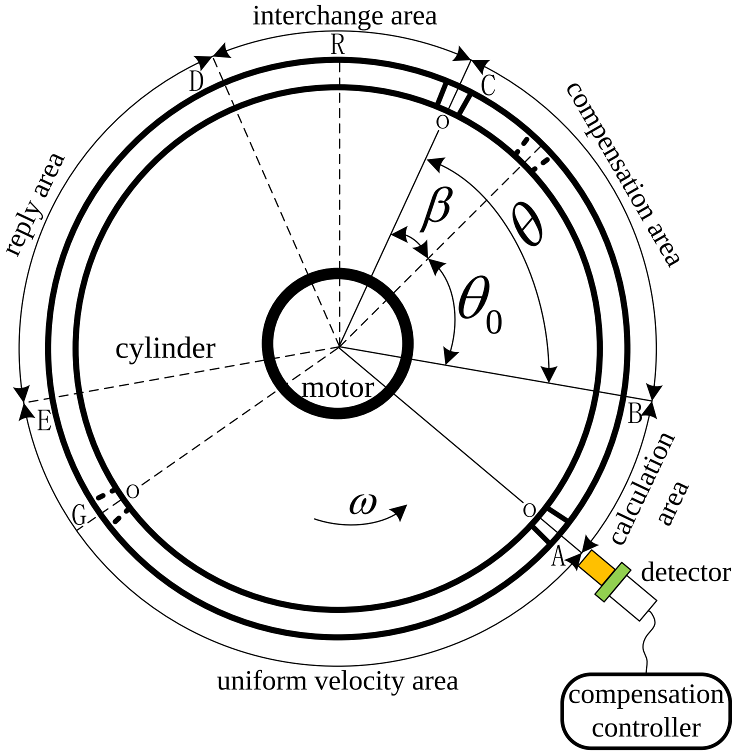

Figure 1. Work mechanism of the rotating cylinder

3. The segment planning method for angle compensation

3.1 The principle of segment planning

In order to analysis the parameter adaptability and the acceleration and deceleration performance of the segment planning method for rotating cylinder angle compensation. This article defined the planning coefficient k_T which means the proportion of rough compensation time in full compensation period and the checking coefficient k_θ which means the proportion of rough compensation turning angle in the full compensation angel β . The basic principle of segment planning is to choose the appropriate planning coefficient k_T and make sure that the k_T can be as small as possible while the k_θ can be as big as possible. So that there is abundant time for finish compensation to check and adjust the turning angle and the acceleration and deceleration curve must be gentle and smooth.

3.2 The basic planning function

The segment planning method for angle compensation divided the S shape acceleration and deceleration process into 6 sections.

As shown in Figure 2, the sections respectively are increasing acceleration section T_1 , constant acceleration section T_2 , decreasing acceleration section T_3 , constant velocity section T_4 , increasing deceleration section T_5 and increasing deceleration section T_6 . We regard the deceleration point e as the cut-off point of the rough acceleration and finish acceleration. Where, T_1 □ T_4 is rough compensation segment and T_5 T_6 is finish compensation segment.

According to the principle of rotating cylinder angle compensation, the S shape acceleration and deceleration process must satisfy the constraint condition as Formula (2) shows

$$\begin{cases} \sum_{i=1}^{6} T_i = T \\ \sum_{i=1}^{6} \theta_{T_i} = \theta \end{cases} \tag{2}$$

Where, T_i is the time period of section i , θ_{T_i} is the turning angle of section i .

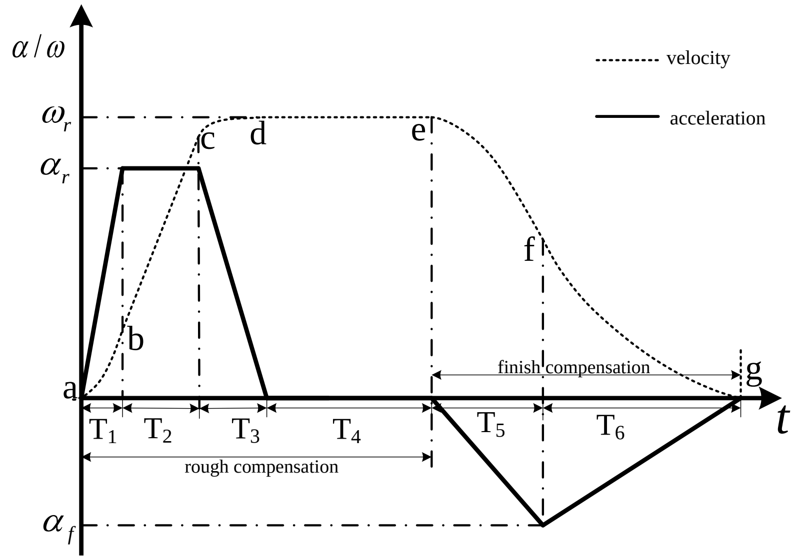

Figure 2. The curves of planning velocity and acceleration

According to the definition of planning coefficient k_T and the checking coefficient k_θ, we can get

$$\sum_{i=1}^{4} T_i = k_T T \tag{3}$$

$$\sum_{i=1}^{4} \theta_{T_i} = k_\theta \theta \tag{4}$$

Also, as the limitation of the servo motor driving power and cylinder rotary inertia, we can get

$$\begin{cases} \omega_i \le \omega_{\max} \\ \alpha_i \le \alpha_{\max} \\ J_i \le J \end{cases} \tag{5}$$

Where, ω_i is the rotational speed of section i, $\omega_{\max}$ is the allowed maximum rotational speed, α_i is the acceleration of section i, $\alpha_{\max}$ is the allowed maximum acceleration, J_i is the Jerk of section i, J is the allowed maximum Jerk.

We can get the segmented function of the acceleration by Figure 2

$$\alpha_i = \begin{cases} J_r t_1 & (0 < t_1 \le T_1) \\ J_r T_1 & (0 < t_2 \le T_2) \\ J_r T_1 - J_r t_3 & (0 < t_3 \le T_3) \\ 0 & (0 < t_4 \le T_4) \\ -J_{f_5} t_5 & (0 < t_5 \le T_5) \\ -J_{f_5} T_5 + J_{f_6} t_6 & (0 < t_6 \le T_6) \end{cases} \tag{6}$$

Where t_i ($i = 1, 2, 3, 4, 5, 6$) is the time span within section i, J_r is the Jerk of rough compensation segment, J_{f_5} is the Jerk of section 5 in finish compensation segment, J_{f_6} is the Jerk of section 6 in finish compensation segment.

According to the acceleration integrating principle, we can get the function of real-time rotational speed

$$\omega_{t_i} = \omega_{T_{i-1}} + \int_0^{t_i} \alpha_i dt \tag{7}$$

Combining Formulas (6) (7), we can get the function expansion of rotational speed in section i.

$$\omega_{t_i} = \begin{cases} \omega_0 + \frac{1}{2} J_r t_1^2 & (0 < t_1 \le T_1) \\ \omega_0 + \frac{1}{2} J_r T_1^2 + J_r T_1 t_2 & (0 < t_2 \le T_2) \\ \omega_0 + \frac{1}{2} J_r T_1^2 + J_r T_1 T_2 + J_r T_1 t_3 - \frac{1}{2} J_r t_3^2 & (0 < t_3 \le T_3) \\ \omega_0 + \frac{1}{2} J_r T_1^2 + J_r T_1 T_2 + J_r T_1 T_3 - \frac{1}{2} J_r T_3^2 & (0 < t_4 \le T_4) \\ \omega_0 + \frac{1}{2} J_r T_1^2 + J_r T_1 T_2 + J_r T_1 T_3 - \frac{1}{2} J_r T_3^2 - \frac{1}{2} J_{f_1} t_5^2 & (0 < t_5 \le T_5) \\ \omega_0 + \frac{1}{2} J_r T_1^2 + J_r T_1 T_2 + J_r T_1 T_3 - \frac{1}{2} J_r T_3^2 - \frac{1}{2} J_{f_1} T_5^2 - J_{f_1} T_5 t_6 + \frac{1}{2} J_{f_2} t_6^2 & (0 < t_6 \le T_6) \end{cases} \tag{8}$$

According to the rotational speed integrating principle, we can get the function of real-time turning angle

$$\theta_{t_i} = \int_0^{t_i} \omega_i dt \tag{9}$$

Combining Formulas (8) (9), we can get the function expansion of turning angle in section i

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$$\theta_{t_i} = \begin{cases} \omega_0 t_1 + \frac{1}{6} J_r t_1^3 & (0 < t_1 \le T_1) \\ \omega_0 t_2 + \frac{1}{2} J_r T_1^2 t_2 + \frac{1}{2} J_r T_1 t_2^2 & (0 < t_2 \le T_2) \\ \omega_0 t_3 + \frac{1}{2} J_r T_1^2 t_3 + J_r T_1 T_2 t_3 + \frac{1}{2} J_r T_1 t_3^2 - \frac{1}{6} J_r t_3^3 & (0 < t_3 \le T_3) \\ \omega_0 t_4 + \frac{1}{2} J_r T_1^2 t_4 + J_r T_1 T_2 t_4 + J_r T_1 T_3 t_4 - \frac{1}{2} J_r T_3^2 t_4 & (0 < t_4 \le T_4) \\ \omega_0 t_5 + \frac{1}{2} J_r T_1^2 t_5 + J_r T_1 T_2 t_5 + J_r T_1 T_3 t_5 - \frac{1}{2} J_r T_3^2 t_5 - \frac{1}{6} J_{f5} t_5^3 & (0 < t_5 \le T_5) \\ \omega_0 t_6 + \frac{1}{2} J_r T_1^2 t_6 + J_r T_1 T_2 t_6 + J_r T_1 T_3 t_6 - \frac{1}{2} J_r T_3^2 t_6 - \frac{1}{2} J_{f5} T_5^2 t_6 - \frac{1}{2} J_{f5} T_5 t_6^2 + \frac{1}{6} J_{f6} t_6^3 & (0 < t_6 \le T_6) \end{cases} \tag{10}$$

Formulas (6) (8) (10)give out the segmented function to calculate the real-time acceleration, rotational speed, turning angle of each section during the angle compensation process based on acceleration and deceleration. Substituting parameters in the functions above, the curve of the S shape acceleration and deceleration for angle compensation can be generated.

3.3 The selection of planning coefficient

The data of segment planning method has been calculated and stored in τ unit, the time period T_i can be represented by τ , so we defined

$$T_i = k_i \tau \tag{11}$$

According to the rotational speed constraint condition described in Formula (1), combining Formulas (8) (11), we can get

$$J_r (k_1 k_2 + k_1^2) - \frac{1}{2} J_{f5} (k_5^2 + 2k_5 k_6) + \frac{1}{2} J_{f6} k_6^2 = 0 \tag{12}$$

According to the turning angle constraint condition described in Formula (1) and the definition of checking coefficient described in Formula (4), combining Formulas (3) (10) (11), we can get

$$J_r \tau^3 (\frac{3}{2} k_1^2 k_2 + k_1^3 + \frac{1}{2} k_1 k_2^2 + k_1^2 k_4 + k_1 k_2 k_4) = \omega_0 T (k_\theta - k_T) + k_\theta \beta \tag{13}$$

$$\tau^3 [J_r (k_5 + k_6)(k_1 k_2 + k_1^2) - \frac{1}{6} J_{f5} (k_5^3 + 3k_5^2 k_6 + 3k_5 k_6^2) + \frac{1}{6} J_{f6} k_6^3] = \omega_0 T (k_T - k_\theta) + (1 - k_\theta) \beta \tag{14}$$

It can be found from Formulas (13) (14) that the effect of planning coefficient on motion parameters relates to the initial rotational speed ω_0 and compensating angle β .

According to the working requirement of the rotating cylinder, we made the following assumptions for each section:

$$\begin{cases} T_3 = T_1, \ T_2 = 2T_1, \ T_4 = T_1 + T_2 + T_3 \\ T_6 = T_5 \end{cases} \tag{15}$$

According to the constraint condition of compensating time length described in Formula (2), combining Formula (3) (11) (15), we can get

$$k_1 = \frac{k_T T}{8\tau}, \quad k_5 = \frac{(1 - k_T) T}{2\tau} \tag{16}$$

From the above formulas we can solve the time period of each section T_i and the amount of each step k_i, substitute them into Formulas (12) (13) (14), we can get

$$3k_T^2 J_r - 16(1 - k_T)^2 J_f = 0 \tag{17}$$

$$J_r (12k_T^2 T^3 - 3k_T^3 T^3) - 32 J_f (1 - k_T)^3 T^3 = 256\beta \tag{18}$$

Formulas (17) (18) are the constraint condition of rotational speed and compensating angle which include the planning coefficient k_T. Solving Formulas (17) (18), we can get the Jerk of rough compensation segment and finish compensation segment.

$$\begin{cases} J_r = \dfrac{256\beta}{3k_T^3 T^3 + 6k_T^2 T^3} \\ J_f = \dfrac{16\beta}{T^3 (2 + k_T)(1 - k_T)^2} \end{cases} \tag{19}$$

According to $\alpha = Jt$, we can get the actual maximum acceleration of rough compensation segment and finish compensation segment.

$$\begin{cases} \alpha_r = \dfrac{32\beta}{3k_T^2 T^2 + 6k_T T^2} \\ \alpha_f = \dfrac{8\beta}{T^2 (2 - k_T - k_T^2)} \end{cases} \tag{20}$$

Combining Formulas (13) (19), we can get the checking coefficient

$$k_\theta = \frac{k_T^2 \omega_0 T + 2k_T \omega_0 T + 3k_T \beta}{(k_T + 2)(\omega_0 T + \beta)} \tag{21}$$

From Formulas (19) (20) (21), we can find that both the acceleration and Jerk are the functions of planning coefficient k_T and compensating angle β , also the checking coefficient k_θ relates to the initial rotational speed ω_0 .

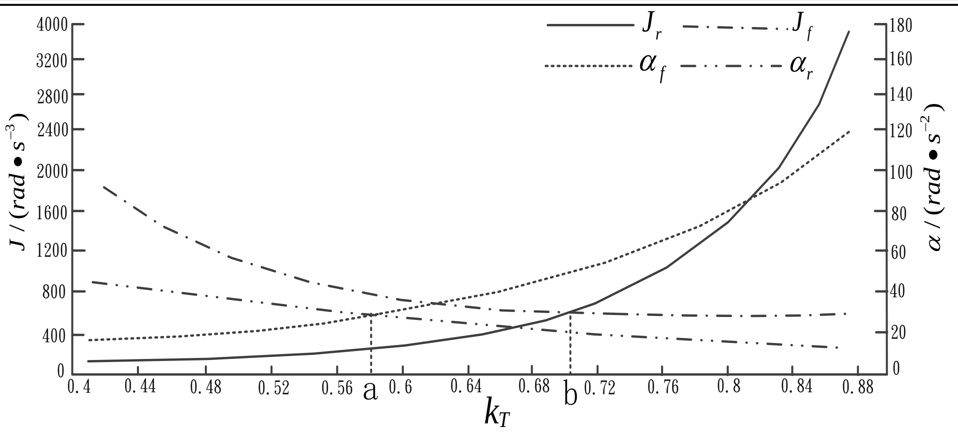

Figure 3. The relation curves of $J-k_T$ and $\alpha-k_T$

Figure 3 shows that both J_r and the actually maximum acceleration α_r decreases with the increase of k_T in the rough compensation segment, while both J_f and the actually maximum acceleration α_f increase with the increasing of k_T in the finish compensation segment. The intersection point of actually maximum acceleration α_r and α_f is $a=0.58$, while the intersection point of J_r and J_f is $b=0.7$ .While $k_T\in[0.58,0.7]$, the acceleration and Jerk are smaller both in rough segment and finish segment.

Considering the random of initial rotational speed ω_0 and the compensating angle β, we defined formula $\mu=\beta/\omega_0$ as the weight factor of the angle compensation, so Formula (21) can be transformed as

$$k_\theta=\frac{k_T^2T+2k_TT+3k_T\mu}{(k_T+2)(T+\mu)} \tag{22}$$

Taking partial derivative of k_θ with respect to μ

$$\frac{\partial k_\theta}{\partial\mu}=\frac{k_TT(1-k_T)}{(k_T+2)(T+\mu)^2} \tag{23}$$

Taking partial derivative of k_θ with respect to k_T

$$\frac{\partial k_\theta}{\partial k_T}=\frac{2k_TT+T+2\mu}{(k_T+2)^2(T+\mu)^2} \tag{24}$$

As $k_T<1$, so both Formula (23) and Formula (24) are constant larger than zero, that means the checking coefficient k_θ increases with the increasing of k_T and μ . The range of rotational speed and compensating angle this article studied respectively are $\omega_0\in[\pi/3,4\pi]$ and $\beta\in[0,\pi/3]$, so the range of weight factor is $\mu\in[0,1]$. For the random input of (β,ω_0) within the scope of μ, while $k_T\in[0.58,0.7]$, according to Formula (22) we can get that the range of checking coefficient is $k_\theta\in[0.58,0.752]$, which satisfies the basic requirement of segment planning method. This proves that, $k_T\in[0.58,0.7]$ is the feasible region of planning coefficient, and the actually calculating k_T will be selected from the feasible region.

According to the basic principle of segment planning method, we defined the optimizing operator of k_T

$$\upsilon=k_\theta-k_T=\frac{k_T\beta(1-k_T)}{(k_T+2)(\omega_0T+\beta)} \tag{25}$$

Substituting μ into the optimizing operator, we can get

$$\upsilon=\frac{k_T(1-k_T)}{(k_T+2)(\frac{T}{\mu}+1)} \tag{26}$$

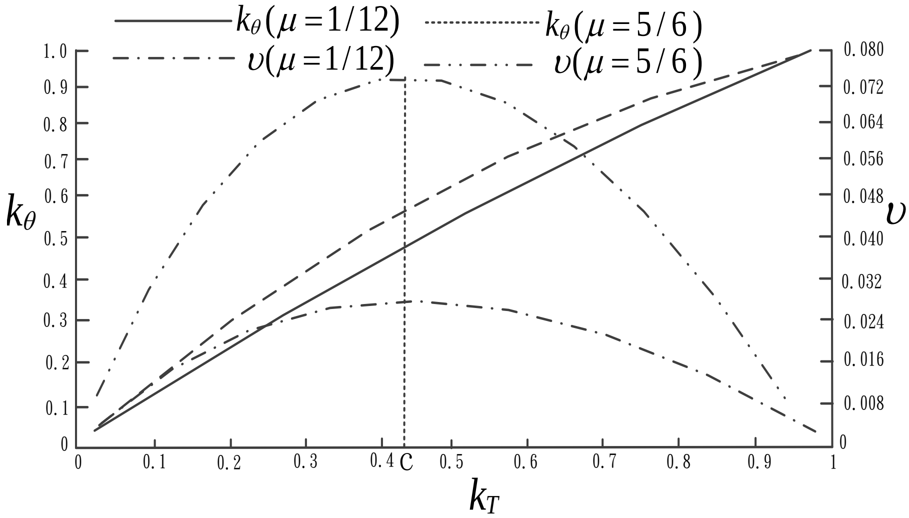

Figure 4. The relation curves of $k_\theta - k_T$ and $\upsilon - k_T$

Figure 4 shows that the $k_\theta - k_T$ curves with different (β,ω_0) input have the same starting point and ending point k_θ increases with the increasing of k_T, and μ is smaller the linearity of the $k_\theta - k_T$ curve is better.

The optimizing operator monotone increases within the feasible region of planning coefficient and gets the maximum value at point C. For actually input of (β,ω_0), The principle of planning coefficient optimizing is to search k_T within the feasible region, when υ gets the maximum value and satisfies the condition of $J_r \le J_{\max}$ and $\alpha_f \le \alpha_{\max}$, we can get the planning coefficient k_{T_0} which can be used is actually calculating.

3.4 The realization of segment planning method

According to the above theoretical derivation, Figure 5 gives out the realizing method of segment planning for angle compensation by acceleration and deceleration. In Figure 5, F(9) means the Formula (9), and the following F(x) are the same.

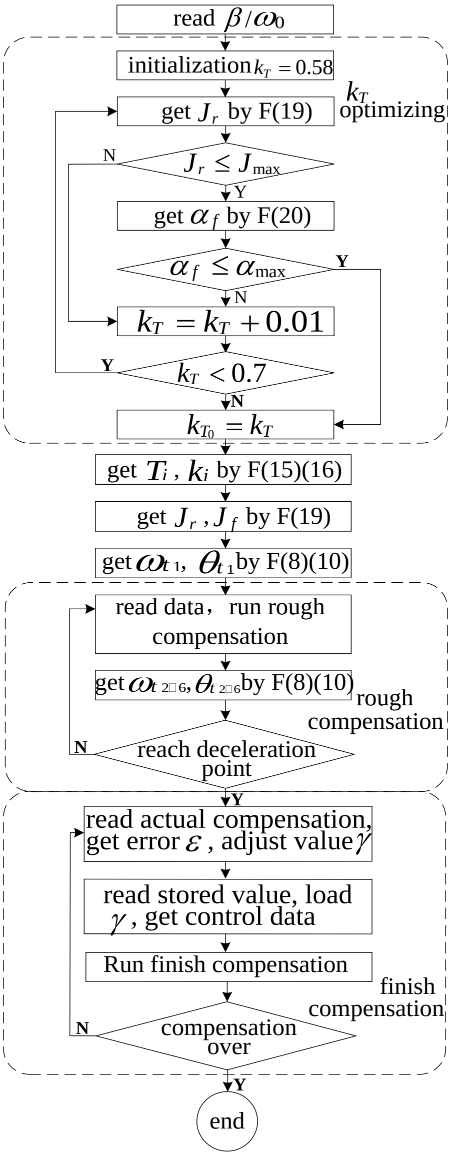

Figure 5. The flow chart of segment planning method

4. Simulation and Verification

This article simulated the segment planning method by MATLAB programming, verified the acceleration and deceleration performance during the angle compensation process. Simulating parameters are: compensating time period $T = 400ms$, tiny step time period $\tau = 2ms$, the allowed Jerk $J_{\max} = 800 rad / s^3$, the allowed acceleration $\alpha_{\max} = 40 rad / s^2$, pulse equivalency $D = 20000 pulse / rad$, the integrating error of rough compensation $\varepsilon = 150 pulse$, the amount of loading steps $n = 10$. We selected 4 groups (β, ω_0) input with different weight factor and planning coefficients, simulated the rotational curves and compensating curves in the process of angle compensation based on acceleration and deceleration.

The (β, ω_0, k_T) inputs of the curves are shown in Table 1.

Table 1. The (β, ω_0, k_T) inputs of the curves

Curves	β	ω_0	k_T
C1	$\pi / 3$	$\pi / 3$	k_{T_0}
C2	$\pi / 3$	$\pi / 3$	0.4
C3	$5\pi / 2$	$\pi / 9$	k_{T_0}
C4	$5\pi / 2$	$\pi / 9$	0.8

R is the reference turning angle that the cylinder runs with the constant initial speed ω_0 in the compensating time period T .

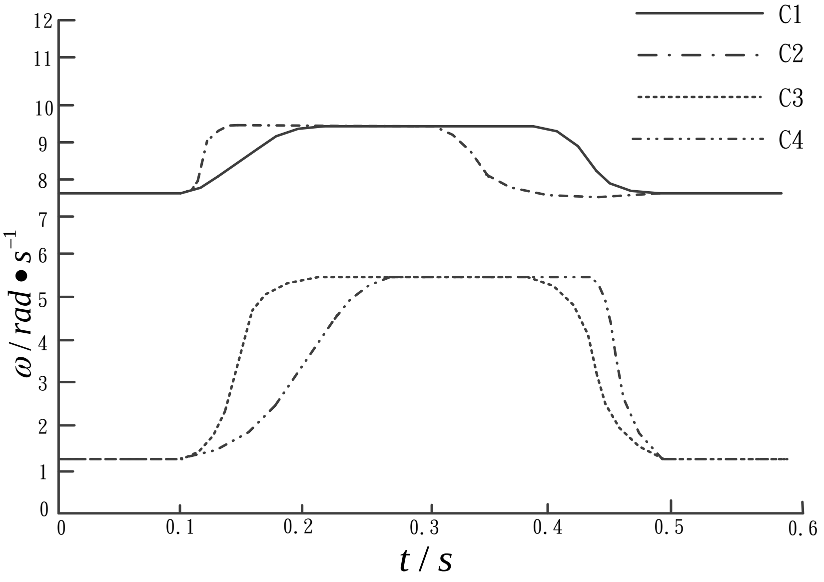

Figure 6. The rotational speed in compensating process

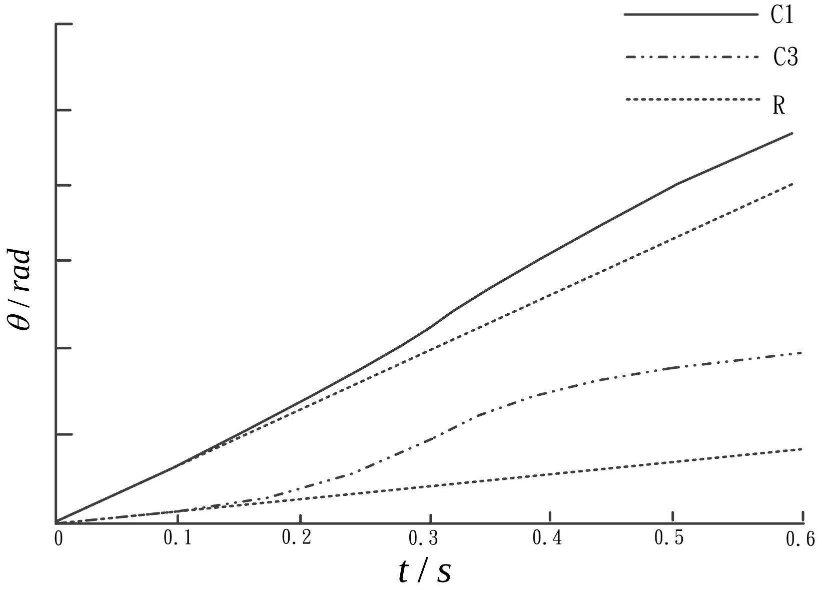

Figure 7. The turning angle in compensating process

In Figure 6 and Figure 7, the simulating results show that, the rotational speed and turning angle curves have no sudden change in the compensating process for (β,ω_0) inputs with different weight factor μ.The cylinder finishes the angle compensation with gentle and smooth S shape acceleration-deceleration curve and replies to the initial rotational speed ω_0.

The acceleration-deceleration curves are gentle and symmetrical when the planning coefficient k_T is selected by the optimization method this article introduced. While k_T is selected out of the feasible region, sudden change appears in the speed curves. When $k_T = 0.4$, the acceleration curve is too steep and the acceleration is too high with low system stability. While $k_T = 0.8$, the finish compensating time is short, and the deceleration curve is too steep with low compensating accuracy.

5. Conclusions

(1) This article has proposed a segment planning method for random angle compensation. Result shows that this method can get both better acceleration-deceleration performance and high compensation accuracy for different initial speed and compensating angle, which can well satisfy the requirement of random angle compensation.

(2) The planning coefficient k_T has been defined and the optimization method of k_T has been given out based on the segment planning principle including the rough compensation segment and the finish compensation segment. The analysis shows that the planning coefficient selected by optimization method can get a gentle and symmetrical acceleration-deceleration curve meanwhile ensure abundant and proper finish compensating time to attain the compensation accuracy.

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