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Research of High-Precision Control Method for Rotary Flying Shear

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Abstract:

In the high-speed operation, we should not only accurately cut the cut point on the material according to the production requirements to complete the cut, and but also ensure the relative speed matching between the cut blade and the material in the cut process to protect the cut blade. As a result, there is extremely high requirement for the control accuracy of the rotary flying shear. In this paper, through the physical analysis of the cut process, the motion law of the rotary flying shear and the motion track of the cut blade are obtained, and a complete control method of the rotary flying shear is put forward by combining the control theory analysis with the motion track of the cut blade. This method fully meets the control requirements when the cut blades are in different positions in the cut process, and can significantly improve the speed and position control accuracy of flying shears, providing a good foundation for the optimization of control parameters of rotary flying shears with different structures.

Keywords*:Rotary flying shear,Cut blade,Cut angle, Cut point,Cut-to-length.*

I. INTRODUCTION

Flying shear is one of the most important equipment in metallurgical field, which is used to cut the metal materialsin motion. Rotary flying shear is a common structure of flying shear, with advantages including simple structure, high cut speed and high control precision. Therefore, it has been widely used [1].

Rotary flying shear driven by motor is mainly used for head-tail cut and cut-to-length of produced materials. In the process of cut, it is necessary to accurately maintain relative matching between the cut blade speed and the material speed to protect the cut blade, and to control the cut blade position to accurately cut the cut point on the material to achieve accurate cut-to-length [1,2]. To ensure the control accuracy, many complex control methods have been proposed and applied to the cut control process of flying shears [2-13]. Most of these control methods focus on solving some specific problems in the control process of flying shears or meeting the application of flying shears in a specific scene, which have certain limitations and have limited effect on improving the overall control accuracy of flying shears.

In this paper, the working principle of rotary flying shear is introduced. Through the physical analysis of the cut process, the motion law of the rotary flying shear and the complete motion track of the cut blade are obtained [14-17]. A complete control method of the rotary flying shear is put forward by analyzing the

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trajectory of cut blade combined with control theory. This method refines the cut control process of flying shears, fully meets the control requirements when the cut blades are in different positions in the cut process. It can greatly improve the speed and position control accuracy of flying shears, and is suitable for the control of rotary flying shears with different structural forms, providing a solid foundation for the control process analysis and control parameter optimization of rotary flying shears with different structural forms.

II. ANALYSIS OF CUT PROCESS OF FLYING SHEAR

No matter what kind of structure the rotary flying shear is, its basic working principle is that the motor drives the cut blade to make a circular motion through the gearbox, as shown in Fig. 1 below. The running track of the cut blades in the cut process is an approximate circle. During the rotation of the flying shear, when the upper cut blade is at the lowest point, the lower cut blade is at the highest point. The upper and lower cut blades cross each other to completely cut the material.

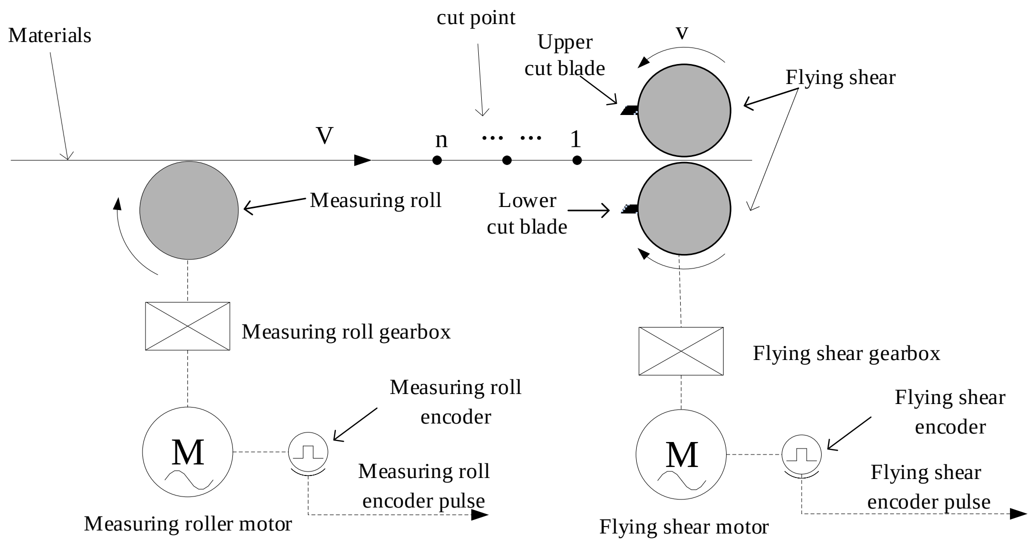

Fig.1 Schematic diagram of arrangement of equipment related to rotary flying shear control

Generally, the position where the upper and lower cut blades of the flying shear are completely staggered, that is, the lowest point of the upper cut blade, is called the cut point of the flying shear. The cut blade angle of the flying shear is artificially calibrated to 0° every time it passes the cut point, so the cut blade angle changes from 0° to 360° every time the flying shear finishes cut, as shown in Fig. 2 below. During the cut process, to ensure the safety of the cut blades without damaging the materials, it is necessary to ensure that the relative speed between them is 0 when the cut blades contact the materials. Observing the cut process of the flying shear, it is found that the cut blade only touches the material within a certain angle range around the cut point, namely the cut angle.

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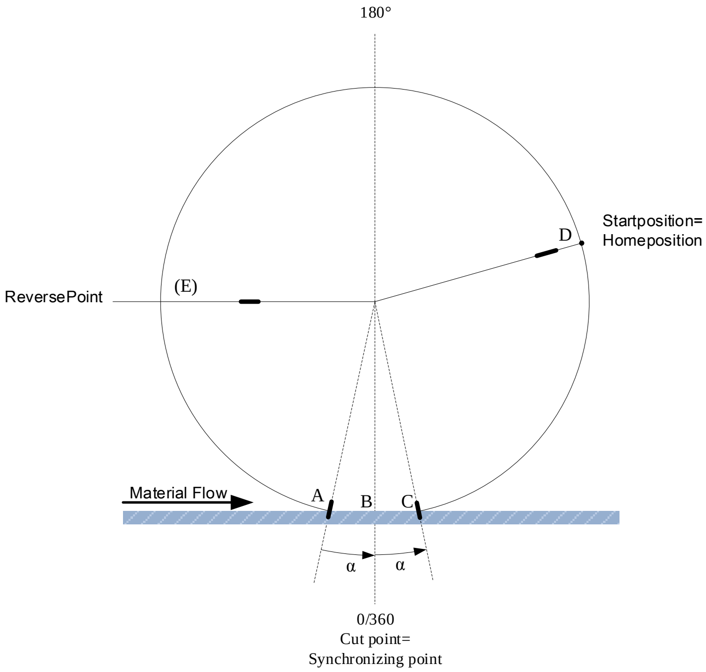

Fig.2 Schematic diagram of cut angle

The cut angle is related to the overlap between the upper and lower cut blades of the flying shear, the thickness of the material and the rotation radius of the cut blade. Its calculation formula is as follows:

$$\alpha = \arccos\left(\frac{R-0.5\times(MD+MU)}{R}\right) \tag{1}$$

Wherein: α is the cut angle; R is the rotation radius of the cut blade; MD is the material thickness; MU is the overlap between the upper and lower cut blades.

During normal production, the cut blade stops at a fixed position, such as position D in Fig. 2 above. The material runs at a fixed speed V. When the first cut point on the material reaches the set position, as shown in Fig. 1 above, the flying shear enters the starting and acceleration process. The cut blade of the flying shear starts from the starting position and accelerates to the same speed as the material, and then intersects with the first cut point on the material at the cut point B to complete the first cut. Then, it comes to the cut-to-length process. When the cut blade and the last cut point on the material pass through the cut point B at the same time, the cut action is completed. The flying shear starts to brake, and it comes to the stopping process. When the cut blade completely stops at the reverse position E, the cut blade retreating process is started to control the cut blade to turn backward to the starting position D and then stop.

We divide the circular area crossed by the cut blade in the cut process into several continuous parts with the cut angle, cut point, starting position and reverse position as the boundary, as shown in Fig. 3 below.

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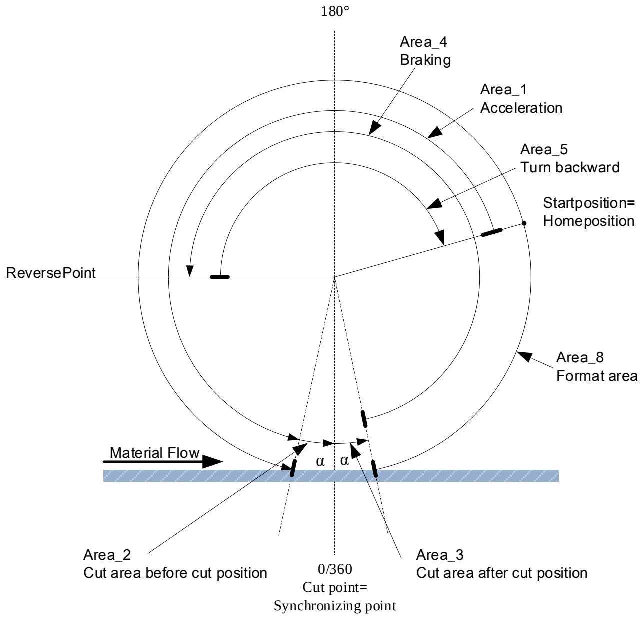

Fig.3 Schematic diagram of cut blade movement track in the cut process of rotary flying shear

Area 1 is the starting and acceleration area, where the flying shear starts and accelerates from the starting position. When reaching the front cut angle, the horizontal component speed of the cut blade must reach the running speed V of the material.

Area 2 is the cut area before cut point. The flying shear must have accelerated to the material speed V before entering this area to ensure normal cut.

Area 3 is the cut area after cut point. After cut, the cut blade is ready to separate from the material. In this area, the cut blade speed should be consistent with the material speed or even slightly ahead of it.

Area 8 is the format area. In this area, the cut blade and the material are completely separated, and the cut of different lengths can be realized mainly by adjusting the speed of flying shear in this area.

Area 4 is the braking area. After the cut is finished and the cut blade leaves the rear cut angle, the braking of flying shear is started, so that the cut blade can stop at the reverse position.

Area 5 is the back area of flying shears. After the flying shear stops at the reverse position,it turns backward to the starting position and stop, waiting for the next cut command.

Combined with the above analysis, it can be seen that the whole process of flying shear is to control the rotating speed of flying shear according to the distance from the cut point on the material to the flying shear and the angle of the cut blade. As shown in Fig. 1, the angle of the cut blade is calculated by the flying shear encoder, and the distance from the cut point on the material to the cut point B of the flying shear is calculated by the measuring roll encoder.

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The measuring roll is set in front of the flying shear. When the cut point reaches the set position, the count value of the measuring roll encoder is cleared. Then, in the following cut process, the distance value from the next cut point to the flying shear can be calculated by using the cumulative value of the measuring roll encoder. The calculation formula is as follows:

$$l' = L - I_1 \times \frac{\pi \times D_1}{i_1 \times n_1} (2)$$

Where: l' is the distance value from the next cut point to the flying shear; L is the setpoint of the cut length; I1 is the cumulative value of the measuring roll encoder; D1 is the diameter of the measuring roll; i1 is the gear ratio of measuring roll; n1 is the number of pulses per revolution of the measuring roll encoder.

III. THE SPEED & ANGLE CONTROL OF THE CUT BLADE IN AREA 1

The starting process of flying shear is shown in area 1 of Fig. 3 above. When the first cut point on the material reaches the set position, the flying shear is started, so that the cut blade meets the first cut point on the material at the front cut angle (360-α), and the horizontal speed component of the cut blade of the flying shear is consistent with the material running speed V. Then, the starting time of flying shear, the speed setpoint in the acceleration process and the angle control of the cut blade are the keys of the control process.

3.1 Starting Time and Speed Setpoint Calculation

The material speed is V. To ensure that the horizontal speed component of the cut blade is consistent with the material speed during cut, the speed of the cut blade should be V/(cosα) when it reaches the front cut angle. When the cut blade runs from the start position (fixed angle β) to the front cut angle (angle 360-α), the speed rises from 0 to V/(cosα), then the acceleration of flying shear in this area can be calculated as follows:

$$a_1 = \frac{V^2 \times 360}{4\pi R \times \cos^2 \alpha \times (360 - \alpha - \beta)} (3)$$

Where: a1 is the acceleration setpoint of flying shear in area 1; V is the actual linear speed of the material; α is the cut angle; β is the angle of the start position of the cut blade; R is the rotation radius of the cut blade.

In this process, the distance that the material travels is:

$$l = \frac{4\pi R \times \cos \alpha \times (360 - \alpha - \beta)}{360} (4)$$

When the flying shear starts, the distance from the first cut point of the material to the cut point B of the flying shear is calculated as follows.

$$l_1' = l + \sin \alpha = \frac{4\pi R \times \cos \alpha \times (360 - \alpha - \beta)}{360} + \sin \alpha (5)$$

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Wherein: l_1' is the distance from the first cut point on the material to the cut point B of the flying shear when the flying shear starts; α is the cut angle; β is the angle of the start position of the cut blade; R is the rotation radius of the cut blade.

When the control system judges that the actual distance from the first cut point to the flying shear is less than the valuel_1', the flying shear will start immediately.

After the flying shear is started, the measuring roll is used to calculate the remaining distance l' from the first cut point to the flying shear in real time, and the speed setpoint value of the flying shear during acceleration is calculated as follows:

$$v_1 = \frac{l' - \sin\alpha}{\mathrm{V}} \times \mathrm{a}_1 (6)$$

Wherein: v_1 is the speed setpoint of flying shear in area 1; l' is the remaining distance from the first cut point to the flying shear; a1 is the acceleration setpoint of flying shear during acceleration process; V is the actual linear speed of the material; α is the cut angle.

3.2. Angle Control of Cut Blade

Accurate cut of the first cut point on the material is the key step in high-precision cut control of flying shear. To ensure the cut control accuracy of the first cut, the position of the cut blade must be controlled in real time by the position of the first cut point on the material. The above formulas determine the acceleration of the flying shear. The speed setpoint is calculated according to the distance from the next cut point to the flying shear, and is used to control the cut blade position of the flying shear. This method is an open-loop control of the cut blade position, and the control accuracy is difficult to guarantee.

3.2.1Calculation of the angle setpoint of the cut blade according to the distance from the first cut point to the flying shear:

According to the foregoing analysis, combined with Fig. 3 above, we can get the calculation formula of the angle setpoint of cut blade as follows:

$$\theta = \frac{360 \times a_1 \times (l' - \sin\alpha)^2}{4\pi R \times V^2} + \beta (7)$$

Where: θ is the angle setpoint of the cut blade, and β < θ < 360-α is satisfied; a1 is the acceleration setpoint of flying shear during acceleration process; l' is the distance from the first cut point to the flying shear; R is the rotation radius of the cut blade; α is the cut angle; β is the angle of start position; V is the actual linear speed of the material.

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3.2.2Closed-loop control of cut blade angle:

The difference between the angle setpoint and the actual angle of the flying shear is used as the adjustment quantity to control the position of the cut blade in the acceleration area in a closed loop. To prevent the speed oscillation caused by the position control of the cut blade, the proportion regulator is selected as the position controller, and the output of the controller is superimposed as additional speed into the flying shear speed setpoint calculated earlier as the final setpoint of flying shear speed. The control flow is shown in Fig. 4 below.

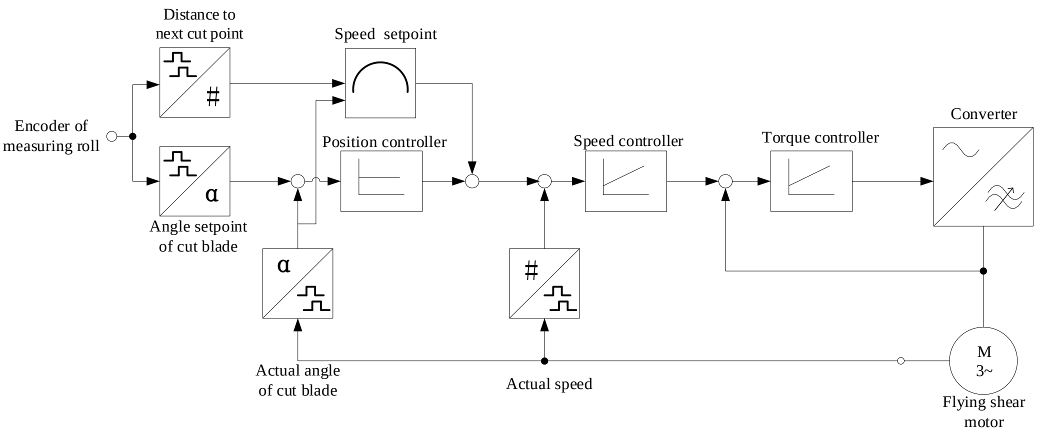

Fig. 4 Schematic diagram of cut control flow of flying shear

IV. CALCULATION OF SPEED SETPOINT OF FLYING SHEAR IN AREA 2 AND 3

As shown in area 2 and area 3 of Fig. 3 above, the material runs horizontally, while the cut blade rotates along an arc. Within the cut angle, the speed of the material and the cut blade of the flying shear are kept the same. Strictly speaking, the speed in the horizontal direction is kept the same. Then, the speed setpoint of flying shear in the cut area is calculated as follows:

$$v2(v3)=V/(\cos\theta) \quad (8)$$

Where: v2 is the flying shear speed setpoint within front cut angle; V3 is the flying shear speed setpoint within the rear cut angle; V is the actual linear speed of the material; θ is the actual angle of flying shear, and 0<θ<α or 360-α<θ<360 is satisfied (α is the cut angle).

The acceleration setpoint of flying shear in the cut area is:

$$a_2(a_3)=\frac{V^2\times(-\sin\theta)}{R\times\cos^3\theta}(9)$$

Where: a2 is the acceleration setpoint of flying shear within front cut angle; a3 is the acceleration setpoint of flying shear within the rear cut angle; V is the actual linear speed of the material; θ is the actual angle of flying shear, and 0<θ<α or 360-α<θ<360 is satisfied (α is the cut angle); R is the rotation radius of the cut blade.

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V. CALCULATION OF SPEED SETPOINT OF FLYING SHEAR IN AREA 8

During multi-cuts, the cut-to-length of the material can be realized by controlling the speed of the flying shear in the format area 8 as shown in Fig. 3 above.

As shown in Fig. 5 below, in the process of cut-to-length, if the material cut length L and the material running speed V are constant, then the time Tofeach cut-to-length processis constant and $T = L/V$. During each cut-to-length process, the cut blade of flying shear rotates from 0° to 360°. The running length of the cut blade is the circumference of the circular track, and the flying shear speed must reach the material running speed V at the beginning and end of each cut-to-length process.

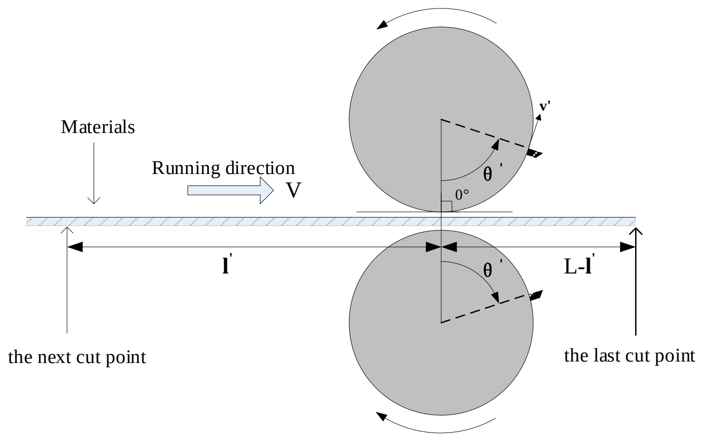

Fig. 5 Schematic diagram of the relationship among the distance value of the next cut point, the cut blade angle and the cut blade speed in cut-to-length process

To sum up, a cut-to-length process is to control the flying shear speed vto make cut blade rotates from 0°to 360° during the time T when the material runs at the speed V, and to ensure that the flying shear speed is V at the beginning and end of the cut-to-length process.

Fig. 6 and Fig. 7 show the relationship between flying shear speed and cutting length L during the cut-to-length process. The area below the dotted lineis equal to the total cutting length value L=VT. The area of shaded area 3 is equal to the running length of the cut blade in the cut area after cut point $(2\pi R \times \alpha/360)$; the area of shaded area 2 is equal to the running length of the cut blade in the cut area before cut point $(2\pi R \times \alpha/360)$; the area of shaded area 8 is equal to the running length of the cut blade in the format area. The sum area of the shaded areas is equal to the running length of the cut blade in a whole cut process, namely the circumference $2\pi R$ of the rotating circle of the cut blade.

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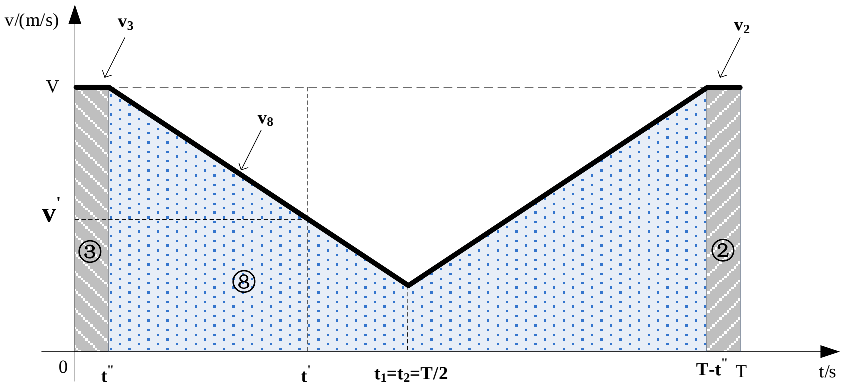

Fig. 6 Schematic diagram of flying shear speed setpoint curve when there is no need to stop during cut-to-length process

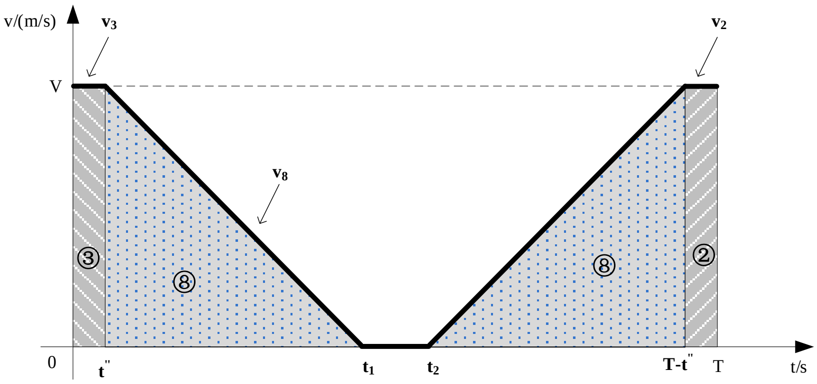

Fig. 7 Schematic diagram of flying shear speed setpoint curve when it is necessary to stop during cut-to-length process

Combined with the above analysis, it can be seen that in the process of cut-to-length, if the acceleration of the flying shear has been determined, when the flying shear rotates to any position in the format area, the distance from the next cut point to the flying shear, the elapsed time of this cut-to-length process, the angle and the speed of the flying shear are in one-to-one correspondence. Therefore, as long as the acceleration of the flying shear in the format area are determined and the distance value of the next cut point is calculated by the measuring roll encoder, the angle setpoint and the speed setpoint of the flying shear can be calculated.

5.1. Calculation of the Acceleration of Flying Shear

From the perspective of protecting mechanical equipment, under the condition of meeting the control requirements, we should strive to avoid excessive acceleration and deceleration process of flying shear. When the cut-to-length process needs to adjust the speed of the flying shear, the best control strategy is to keep the absolute values of acceleration and deceleration consistent, and try to ensure the smooth acceleration and deceleration curve of the flying shear, as shown in Fig. 6 and Fig. 7.

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As can be seen from the previous analysis, during cut-to-length process, when the material maintains speed V and runs for a distance of L, the running length of cut blade is 2πR (where R is the rotation radius of the cut blade). Because the thickness of the produced material and the overlap of the cut blade are much smaller than the rotation radius of the cut blade, the calculated cut angle is generally smaller (below 15 degrees). Then, the speed of the flying shear within the cut angleis approximately equal to V.

As shown in Fig. 6, when the cut length setpoint $L \leq 2\pi R \times (2-\alpha/180)$, the flying shear will decelerate first and then accelerate, or accelerate first and then decelerate, without stopping in the middle. The acceleration and deceleration switching point is at T/2 time of a cut-to-length process, and the acceleration is switched from A to-A. The calculation formula is:

$$t_1 = t_2 = T/2(10)$$

$$A = \frac{(2\pi R - L)}{(\frac{L}{2} - \frac{\alpha}{180} \times \pi R)^2} \times V^2(11)$$

As shown in Fig. 7, when the cut length setpoint $L > 2\pi R \times (2-\alpha/180)$, the flying shear first decelerates until it stops and then accelerates after a period of time. The acceleration is switched from A to 0 at t1 and from 0 to-A at t2. The calculation formulas of t1, t2 and A are as follows:

$$t_1 = \pi R \times \frac{(2-\frac{\alpha}{180})}{V}(12)$$

$$t_2 = \frac{L}{V} - \pi R \times \frac{(2-\frac{\alpha}{180})}{V}(13)$$

$$A = \frac{-V^2}{2\pi R \times (1-\frac{\alpha}{180})}(14)$$

In the above formulas, L is the cut length setpoint; V is the actual linear speed of the material; R is the rotation radius of the cut blade; α is the cut angle; T(=L/V) is the time of a single cut-to-length process; A is the acceleration of flying shear; t1 is the time of the first speed switching point in theformat area; t2 is the time of the second speed switching point in theformat area.

5.2. Calculation of the Speed Setpoint According to the Distance Value of the Next Cut Point:

According to the distance l' from the next cut point to the flying shear, the elapsed time $t' = (L - l')/V$ of this cut-to-length process can be calculated, wherein L is the cut length setpoint; V is the actual speed of the material. According to the foregoing analysis, combined with Fig. 6 and Fig. 7, the calculation formula of the flying shear speed setpoint can be obtained as follows:

$$v_8 = \begin{cases} A \times \frac{\left(L - l' - \pi R \times \frac{\alpha}{180}\right)}{V} + V & (t'' < t' < t_1) \\ 0 & (t_1 \leq t' \leq t_2)(15) \\ A \times \frac{\left(l' - \pi R \times \frac{\alpha}{180}\right)}{V} + V & (t_2 < t' < T - t'') \end{cases}$$

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Wherein, v_8 is the speedsetpointof flying shear in the format area; A is the acceleration of flying shear; l' is the distance from the next cut point to the flying shear; R is the rotation radius of the cut blade; α is the cut angle; V is the actual linear speed of the material; L is the cut length setpoint; t' is the elapsed time of this cut-to-length process; t'' $(=\frac{\alpha}{180}\times \pi R/V)$ is the time for the flying shear to rotate through the cut angle; t1 is the time of the first speed switching point in the format area; t2 is the time of the second speed switching point in the format area; T(=L/V) is the time of a single cut-to-length process.

5.3. Closed-Loop Control of Cut Blade Angle in Format Area

To ensure the control accuracy of cut-to-length, the cut blade position of flying shear must be controlled in real time by the position of the cut point on the material. See the above Fig. 4 for the control flow. According to the foregoing analysis, combined with Fig. 6 and Fig. 7, the calculation formula of angle setpoint value can be obtained as follows:

$$\theta = \begin{cases} [L - l' + \frac{1}{2}A \times \frac{\left(L - l' - \pi R \times \frac{\alpha}{180}\right)^2}{V^2}] \times \frac{180}{\pi R} & (t'' < t' < t_1) \\ 180 & (t_1 \le t' \le t_2) \\ 360 - [l' + \frac{1}{2}A \times \frac{\left(l' - \pi R \times \frac{\alpha}{180}\right)^2}{V^2}] \times \frac{180}{\pi R} & (t_2 < t' < T - t'') \end{cases} \quad (16)$$

Wherein, θ is the angle setpoint of cut blade, and α<θ<360-α is satisfied; L is the cut length setpoint; l' is the distance from the next cut point to the flying shear; A is the acceleration of flying shear; R is the rotation radius of the cut blade; α is the cut angle; V is the actual linear speed of the material; t' is the elapsed time of this cut-to-length process; t'' $(=\frac{\alpha}{180}\times \pi R/V)$is the time for the flying shear to rotate through the cut angle; t1 is the time of the first speed switching point in the format area; t2 is the time of the second speed switching point in the format area; T(=L/V) is the time of a single cut-to-length process.

VI. SPEED CONTROL OF FLYING SHEAR IN AREA 4 AND 5

After the last cut, the cut blade leaves the rear cut angle and immediately enters the stop control process. At this time, because the cut blade is separated from the material, its speed will not affect the material, so the angle of the reverse position is directly used as the angle setpoint, and the position of the cut blade is closed-loop controlled by a P regulator. When the reverse position is reached, the angle of the starting position is used as the angle setpoint to control the cut blade to turn backward to the starting position and then stop. The flow charts of these two control processes are shown in Fig. 8 below.

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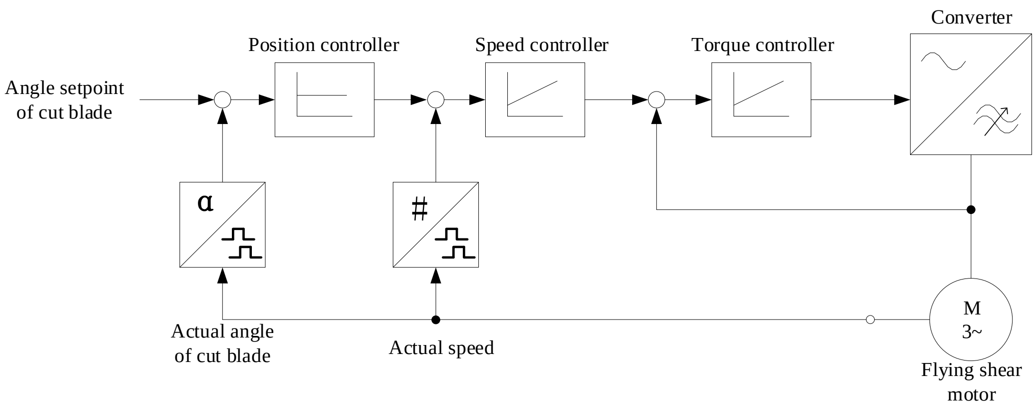

Fig. 8 Schematic diagram of braking control flow of flying shear

The starting position is generally set relatively close to the rear cut angle to ensure enough starting distance. For high-speed flying shears, the speed is very high when passing the rear cut angle,and the braking distance of flying shears is very short when they stop directly at the starting position, which leads to the high energy fed back in an instant. In this case, it is vitally necessary to set the reverse position. We should lengthen the high-speed braking distance of the flying shear, so as to reduce the impact of the feedback energy on the rectifier device.

For low-speed flying shears, because of the low-cut speed, the feedback energy is limited when directly stopping at the starting position after cut, so it is unnecessary to set the reverse position.

VII. CONCLUSION

In this paper, the complete cut process of the rotary flying shear is analyzed. By calculating the cut angle, the time point when the cut blade bites and breaks off steel can be accurately determined. The working track of the cut blade is divided into several continuous parts, and the control characteristics of each part are analyzed. The calculation formulas of the speed and acceleration of the cut blade in each part are given, thus realizing the high-precision control of the flying shear.

The rotary flying shear control system developed according to this algorithm has been applied in cold rolling production line such as tandem cold rolling mill, continuous annealing line, continuous galvanizing line, etc. Among them, the high-speed cut of 300m/min is realized in the tandem cold rolling mill, and the control effect is satisfactory. The control accuracy of cut-to-length can reach ±1 mm.

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