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METHOD FOR AUTOMATIC CONTROL OF CUTTING SPEED OF A LONGITUDINAL ROADHEADER TAKING INTO CONSIDERATION THE TEMPERATURE LOAD

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With a continuous development of the power engineering industry, the longitudinal roadheader has become one of the most important machinery items. However, the traditional method for automatic control of cutting speed regulation of the longitudinal roadheader is unstable because of its poor ability of calculating the temperature load on the cutting part. Therefore, a method for the cutting speed control is proposed, which takes into account the temperature load on the cutting part, thus optimizing this problem. A mathematical model of the cutting head of the longitudinal roadheader is constructed based on two displacements: vertical and horizontal. A thermal conductivity formula is used to calculate the temperature load on the cutting part. A PID controller is selected as a basis for automatic control. In comparison with two other methods, the control cycle of our design is found to be the most stable. Therefore, the proposed method for automatic control over the cutting speed of the longitudinal roadheader is quite promising.

Keywords: longitudinal roadheader, automatic control, fuzzy controller, temperature load.

INTRODUCTION

At present, the main functions of the roadheader widely used in coal mines include: cutting the coal and rock, transporting the coal blocks, and supporting the spray and dust removal. It is among the important equipment in coal mining, whose operation relies on a number of theorems including the law of the lever in physics [1, 2]. It plays a significant role in roadway excavation and coal face layout, greatly enhancing the excavation efficiency, reducing the labor intensity and improving the working conditions. The roadheaders worldwide are developing towards automation, intelligence, information and unmanned operation. There are advanced roadheaders available in other countries, they offer automatic detection of the working conditions and faults, automatic adjustment of the motor power, monitoring of the cutting section and direction of tunneling, etc. The main development trend is to design a mechatronic system. In the level of automation, the gap between the domestic and foreign roadheaders is still large. The theoretical research on the roadheader automation has been started in China, so the development of a new domestic roadheader is among the key projects in the China's coal industry.

Although roadheaders have been widely used in mining by now, considering the continuous development of social economy, the progress of science and technology and the continuous improvement of people's living standards, the demand for roadheader machinery will be higher, which would inevitably require an increase in the mining intensity. Therefore, it is necessary to improve the working efficiency of the roadheader and, more importantly, it is

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required that the tunnel construction should develop towards safer and more secure operation, higher quality, labor-saving, higher efficiency and better comfort. Although the traditional roadheader is a sufficiently mechanized construction tool that meets the above requirements to a certain extent, it is still operated manually. With high labor intensity and poor comfort of drivers, there are a large number of casualties caused by accidents, and the labor productivity is low. According to the surveys of the current practices, the construction quality and safety largely depend on human factors. According to the available literature, the overbreak volume of highway engineering worldwide is generally controlled at 10-25%, which leads to an increase of roadway support and backfill workload, waste of lining materials, and greatly increases the cost of the roadway construction, which is obviously uneconomical [3]. Therefore, it is more reasonable and correct to strengthen the automation function of the roadheader and install such devices as advanced detection sensors, infrared positioning facilities, etc., on the longitudinal roadheader. On the other hand, automatic control is an important direction of the development of all machinery and also an important benchmark to evaluate the performance of a machine. The more comprehensive is the monitoring of the environment, the more convenient the operation, the higher the production efficiency, and the lower the accident rate. At present, the development of a driverless automatic roadheader is one of the important goals for the roadheader designers aimed at an eventual driverless operation.

At present, the automated roadheaders at home and abroad are few, so the shape of the roadway section mainly depends on human factors, with low cutting accuracy and precision. In the case of over- or underexcavation, additional efforts are required or the shape of the roadway has to be changed resulting in an increased excavation cost. For example, the research on the dynamics and kinematics of a driving machine is not sufficient. The main aspect of the kinematics research is only focused on the influence of the cantilever swing angle and the cylinder stroke on the section size. The research on the mechanism of the influence of the speed and acceleration of the cantilever and the cylinder on the section formation are insufficient, while it must not be ignored [4].

In addition, the research on the mechanical characteristics of the driving machine is not comprehensive both in China and abroad. Compared with the maturity of the research by the cutting load simulation, the consideration of the interaction between cantilever inertia force and various mechanisms in the study of the relationship between the cutting force and the cutting head speed is not systematic. Moreover, the most commonly used hydraulic system on the roadheader is still limited to manual operation, without any automatic control, and its research is lacking. The research on the cutting speed control theory of the longitudinal roadheader including the temperature load of the cutting part into consideration is also limited. The problems listed above need to be solved one by one with great efforts of researchers.

DESIGN OF THE METHOD FOR AUTOMATIC CONTROL OF THE CUTTING SPEED REGULATION OF A LONGITUDINAL ROADHEADER INCLUDING THE CUTTING TEMPERATURE LOAD

In this study, in order to ensure an effective design of the automatic control method for cutting speed adjustment of a longitudinal axial roadheader, which takes into account the temperature load of the cutting part, the temperature load is closely related to the physics of the binding force caused by the object that cannot freely expand and contract when the temperature changes due to the external or mutual constraints among the parts. The whole design process is shown in Fig. 1.

It can be seen from Fig. 1 that the proposed scheme of automatic control of the cutting speed of the longitudinal roadheader compensates for the shortcomings of the traditional control methods. The scope of research presented in this study is as follows:

A. This paper analyzes the cutting mechanism and the working process of the roadheader, establishes a mathematical model of the cutting head, establishes a geometric relationship between the center space coordinate of the cutting head and the length of the oil cylinder and the cantilever swing angle, and plans the cutting process path of a standard shape of the cutting section.

B. The temperature load of the cutting head is calculated as one of the control objects of the automatic control method.

C. An automatic speed controller of the cutting mechanism is designed, and a mathematical model of the control system is constructed; a PID control model is established in Simulink.

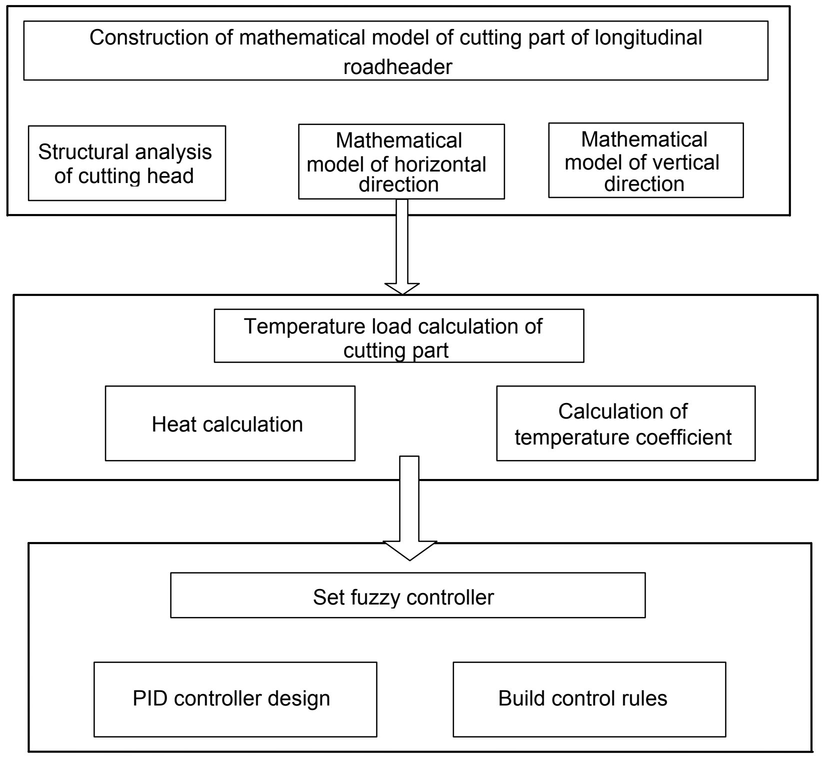

Fig. 1. Flow chart of the method for automatic control of the cutting speed regulation of a longitudinal roadheader considering the temperature load of the cutting part.

Through the above parts, the design process of the control method for automatic speed regulation is completed.

Construction of Mathematical Model of Cutting Part of Longitudinal Roadheader

The cutting part is the executive mechanism that directly cuts the coal and rock in the working face and performs the roadway excavation. Therefore, the cutting capacity, the structural form, the operation and other important factors of the working mechanism have a great influence on the driving efficiency, the production capacity and stability of the roadheader body [5, 6]. A hydraulic drive can provide a wide range of speed regulation and it easy to control. The volume of motor oil is smaller than that of the motor with the same torque output, but the overload capacity of the hydraulic system is very low. For the driving condition with a large hardness variation of the working object (coal rock), the adaptability and reliability are poor. Therefore, the working mechanism of the vertical shaft roadheader is mostly driven by the motor.

The cutting part of the roadheader is arranged at the front end of the roadheader, which is generally composed of a cantilever, a cutting head, a motor, coupling, a reducer, etc.. The cantilever of some roadheaders has an expansion mechanism, which can make the cantilever expand longitudinally. Other roadheaders do not have any expansion mechanisms. In the cutting condition, the cutting head would enter the cutting tunnel section only by the weight of the machine itself; the cutting head and the cantilever are connected by the coupling. The rotation of the cutting head with the cantilever axis is driven by the motor, which is connected with the reducer and the coupling. The motor, the reducer and the accelerator are all installed in the cantilever. On the one hand, this design can make the structure of the working mechanism more compact. It can be seen from the literature that the cutting head of the roadheader swings in the vertical and horizontal planes to complete the task of section cutting. Therefore, in order to achieve an ideal control

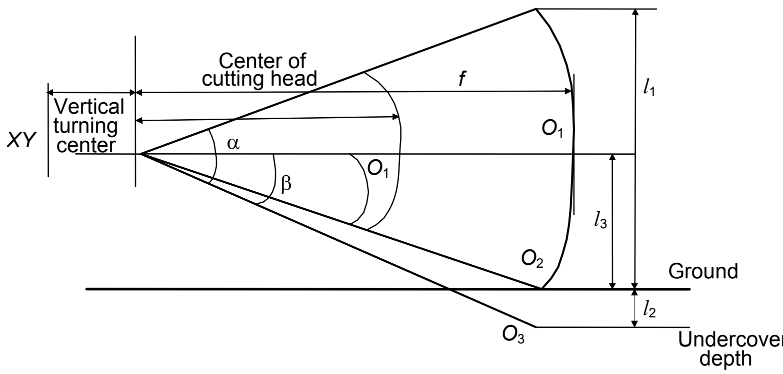

Fig. 2. Analysis diagram of vertical swing of cutting head.

effect, it is necessary to have a deep understanding of the movement state of the cutting head in the vertical and horizontal planes and analyze its mathematical model (Fig. 2).

As shown in Fig. 2, the hinge point between the lifting cylinder and the frame is designated by X, the hinge point between the lifting cylinder and the cantilever is designated by Y, the projection position of the cutting head center on the roadway section is designated by O_1, XY (lifting cylinder length) is designated by d_1, O_1Y (cantilever axis) is in the horizontal plane, $\angle XO_2Y$ is designated by o, the center line projection of the rotary table in the vertical plane is designated by O_2, and the vertical rotation center of the cantilever is designated by α_0, The projection of the center line of the rotary table in the vertical plane is designated by O_3, and the vertical rotation center of the cantilever is designated by O_2, then we obtain

$$\angle YO_2O_3 = \angle Y^{'}O_2O^{'}_3 = \angle Y^{''}O_2O^{''}_3 = \angle Y^{'''}O_2O^{'''}_3 = \alpha_0. \tag{1}$$

This is determined by the installation position and the specific size of the working parts and has nothing to do with the variation of the cantilever angle around point O_2. Both d_1 and α_0 change as β changes. The cantilever angle of the cutting head is $\beta_1, \beta_2, \beta_3$ when driving at the highest level, floor and undercover, respectively, and the heights of O_3 from the ground in these three cases are l_1, l_2, l_3, respectively. Symbol f stands for the cantilever length, O_3 is the height from the ground when the cantilever axis is l_4 in the horizontal position. Figure 1 also presents the specific parameters and dimensions of the roadheader. The mathematical model can be written as follows:

$$\beta = \arcsin\frac{l - l_4}{d} + \alpha_0, \tag{2}$$

$$\beta = \arcsin\frac{l - l_4}{d} - \alpha_0, \tag{3}$$

$$d_1 = \sqrt{O_2X^2 + O_2Y^2 - 2 \cdot O_2X \cdot O_2Y\cos(\alpha_0 + \beta)}. \tag{4}$$

In the above formula, when $l_4 < l \le l_1$, formula (2) holds; when $l_3 \le l \le l_4$, formula (3) holds. The above formulas represent the mathematical model of the cutting part in the vertical swing. In order to ensure the reliability of the automatic control method design and increase the mathematical model of the horizontal trend, the specific horizontal swing analysis diagram is shown in Fig. 3.

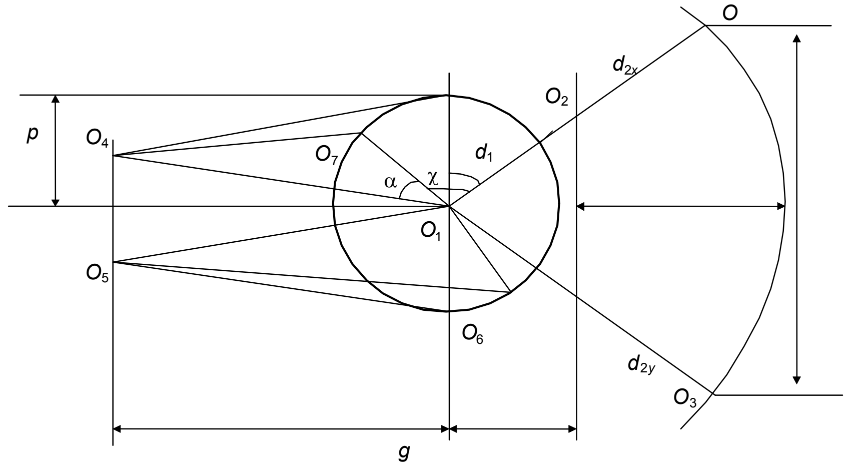

Fig. 3. Analysis of horizontal swing of cutting head.

Figure 3 is a schematic diagram of the cantilever horizontal swing analysis. On the premise that the centerline of the roadway coincides with O_1O_2, the position of each hinge point of the roadheader and the relevant parameters are shown in Fig. 3. The horizontal rotation center is recorded as O_1, the point of projection of the vertical rotation center in the horizontal plane is designated by O_2, and the horizontal distance between O_1 and O_2 is d_1. The length of the axis of the cutting head projected into the horizontal plane is designated by O_2O_3, the angle of the cutting head in the vertical plane is designated by α_0, the linear relationship is $O_2O_3 = d\cos\alpha_0$, and the width of the roadway is designated by g. When the cutting head is in the middle position, the angle between the roadway center line and the cantilever can be designated by δ at any time. The distance between the center line of the cutting head and the centerline of the roadway can be designated by p, d_{2x} and d_{2y}, which respectively represent the length of the left and right rotary cylinders. If the angle of the cantilever swinging to the left in the horizontal plane of the roadway is δ, then:

$$\beta = \arcsin\frac{g}{d\cos\alpha + p}. \tag{5}$$

The position of the horizontal swing mechanism can be expressed by the length of two swing cylinders. In this state, the corresponding lengths of a pair of horizontal swing cylinders are respectively

$$d_{2x} = \sqrt{O_4O_1^2 + O_1O_7^2 - 2\cdot O_4O_1\cdot O_1O_7\cos(\chi-\delta)} \text{ and} \tag{6}$$

$$d_{2y} = \sqrt{O_4O_1^2 + O_1O_7^2 - 2\cdot O_4O_1\cdot O_1O_7\cos(\chi+\delta)}. \tag{7}$$

Through the above formula, the mathematical model of the cutting part of the longitudinal axis roadheader is built, and this is the design basis of the cutting speed regulation automatic control method.

Calculation of Temperature Load of Cutting Part

According to the empirical formula [7, 8] of the bearing friction torque derived by Palmgren, the calculation formula of the friction heat generated by the rolling element under an external load is as follows:

$$s_i = 1.04 \cdot n \cdot r_i \,. \tag{8}$$

In the above formula, the friction heat generated by the rolling element under the external load is set as s_i ; r_i is the friction torque generated by the external load; n is the rotation speed of the bearing. If the above formula is integrated, then

$$q_i = \mu e v_i \,. \tag{9}$$

In (9), q_i is the friction heat generated by the rolling element under the action of an external load; μ is the friction coefficient between the rolling element and the inner and outer rings; v_i is the relative sliding speed between the rolling element and the inner and outer rings; e is the contact load between the rolling element and the inner and outer rings. The above formulas (8) and (9) are the friction heat generated by the cutting head under the external load. In the course of a daily use, an appropriate lubricating oil is often added to it. Therefore, in this design, the friction heat generated by the spin sliding of the cutting head and the friction heat generated by the viscous friction of the lubricant are calculated.

The sliding caused by the rolling body axial rotation along the inner and outer raceways is called spin sliding. The calculation formula of the friction heat generated by the spin sliding is given by

$$s_j = 1.04 \cdot n \cdot r_j \,, \tag{10}$$

where s_j and r_j are the friction heat and the friction torque generated by the rolling body spin sliding, respectively. The choice of a lubricating oil (grease) and a lubrication method has an important influence on the temperature field of the bearing. Because of the function of the lubricating oil (grease) and the incompressibility of the liquid, the lubricating oil film formed between the roller and the inner and outer rings would buffer and absorb the vibration, which can reduce the friction factor in the course of the bearing motion.

$$s_{\mathrm{oli}} = 1.04 \cdot n \cdot r_{\mathrm{oli}} \,, \tag{11}$$

where s_{oli} is the friction heat generated by the viscous friction of the lubricant and r_{oli} is the friction torque generated by the viscous friction of the lubricant. Through the above formula, the heat of the cutting head is calculated. In this calculation process, the fluidization heat coefficient is added to obtain the temperature load of the cutting part. A convective heat transfer coefficient is an important parameter in the calculation of the temperature load, but it is difficult to calculate. Its value is generally determined by an approximate algorithm and an empirical formula, which is closely related to the characteristic parameters of the lubricating oil (grease), the lubricating oil characteristic parameters of gears in the cutting section, the size parameters, the rotation parameters and the material characteristics of the bearings [9]. In this study, a calculation method is used to estimate the convective heat transfer coefficient in the heat transfer of the rolling bearing. The formula is as follows:

$$\partial = 0.332 \frac{w_f}{D_h} (G_i \cdot P_i)^{\frac{1}{4}} \,, \tag{12}$$

where w is the material thermal conductivity; D is the bearing inner diameter; h is the lubrication index, G_i is the Reynolds number; P_i is the Prandtl number of the lubricating oil (grease). The convective heat transfer coefficient can be of three types: the natural convective heat transfer coefficient between the cylindrical surface of the bearing seat and the fluid air, the forced convective heat transfer coefficient between the outer surface of the shaft and the lubricating oil, and the forced convective heat transfer coefficient between the lubricating oil and the bearing. This makes the calculation method more accurate and optimizes Harris' rough estimation method [10]. The calculation method of the convective heat transfer coefficient is as follows:

$$\partial = 0.175 \frac{w_f}{Q} \sqrt{\frac{Q \wp U}{i} \sqrt{\frac{U}{Q}}} \Big/ \ln\left(1 + \frac{U}{Q}\right) \tag{13}$$

where w_f is the thermal conductivity of the lubricant, i is the kinematic viscosity of the lubricant, U is the gap between the inner race and the cylindrical surface of the cage; Q is the radius of the inner race of the cage in the calculation of the convective heat transfer coefficient of the fluid between the inner race and the cylindrical surface of the cage. In the calculation of the convective heat transfer coefficient of the fluid between the outer ring and the cylindrical surface of the cage, Q is the raceway radius of the outer ring, $\wp$ is the angular velocity of the outer ring. Through this formula, the temperature load coefficient of the cutting head can be obtained. The specific formula is as follows:

$$\partial = 0.53 \frac{w_f}{D} (G_i \cdot P_i)^{\frac{1}{4}}. \tag{14}$$

In the above formula, D is set as the outer diameter of the bearing. The forced convection heat transfer coefficient ∂_2 between the external surface of the cutting head and the lubricating oil is obtained by the formula

$$\partial_2 = 0.11 \frac{w}{d} (0.5 G_i \cdot P_i)^{0.35}, \tag{15}$$

where w is the thermal conductivity of the material; d is the inner diameter of the bearing. By integrating formulas (14) and (15), the temperature load calculation formula is obtained as follows:

$$\partial_3 = 0.0986 \left[\frac{n}{v} \left(1 + \frac{H_w}{H_m} \right) \right]^{\frac{1}{2}} ko^{\frac{1}{3}}, \tag{16}$$

where H_w is the rolling element diameter, H_m is the average bearing diameter, n is the bearing rotational speed, and v is the lubricant kinematic viscosity; and ko is the maximum bearing volume. The temperature load of the cutting head is calculated by the above formula and included into the mathematical model of the cutting head as the object of automatic control.

Set Fuzzy Controller

Using the above design part as the control object of the automatic control method, in order to control the effectiveness in the controller design part, it is necessary to obtain some parameters of the roadheader (see Table 1).

According to the parameters shown in Table 1, a respective PID speed controller is set. The PID controller, as the earliest practical controller, has a history of more than 70 years. It is composed of a proportional unit, an integral unit and a differential unit through a linear combination to control the controlled object. Because of its simplicity and ease of understanding, strong robustness, and good adaptability, no need for an accurate system model and other preconditions, it has become the most widely used industrial controller [11-13]. In this part, the PID controller compares the collected load current and the rated current of the cutting motor, and then takes the difference as a new input. Through a linear combination of the proportional unit, the integral unit and the differential unit, the input current

TABLE 1. Some Roadheader Parameters

Number	Name	Number	Name
1	Cutting rotary cylinder–rod diameter, mm	11	Total volume of two chambers from electro-hydraulic proportional valve to rotary hydraulic cylinder, mm
2	Cutting rotary cylinder–cylinder inner diameter, mm	12	Cutting lifting cylinder–cylinder inner diameter, mm
3	Cutting rotary cylinder–cylinder outer diameter, mm	13	Cutting lift cylinder–cylinder outer diameter, mm
4	Cut swing cylinder–stroke, mm	14	Cut lift cylinder–stroke, mm
5	Cutting horizontal swing angle range, deg	15	Cutting vertical swing angle range, deg
6	Left extension of cutting head, mm	16	Cutting arm length *L*, mm
7	Total weight, t	17	Distance between hinge point of cutting arm and turning center *e*, mm
8	Turntable mass, kg	18	Cutting arm mass, kg
9	Quality of single rotary hydraulic cylinder	19	Quality of single lifting hydraulic cylinder
10	Total volume of two chambers from electro-hydraulic proportional valve to rotary hydraulic cylinder, l	20	Distance from electro-hydraulic proportional valve to two chambers of lifting hydraulic cylinder

controlling the opening of the throttle valve of the electro-hydraulic proportional directional valve is controlled, so as to control the feed speed of the horizontal rotary oil cylinder. Finally, it controls the horizontal swing speed of the cutting head. Through the PID control, the load current can always be kept near the rated value, and the deviation is not more than 5%, so as to implement the speed control of the cutting mechanism. The relationship between the PID input and output is as follows:

$$s(t) = k_j \left[q(t) + \frac{1}{T_i} q(t)dt + T_d \frac{dr}{dt} \right], \tag{17}$$

where $s(t)$ is the output signal of the regulator; $q(t)$ is the deviation signal, which is the difference between the given quantity and the output quantity; k_j, T_i, T_d are the proportional coefficient, the integral time constant and the differential time constant, respectively [14]. Then the temperature transfer function of the cutting part can be expressed as:

$$G(t) = \frac{F(q)}{P(q)} = k_j \left[1 + \frac{1}{T_i s} + T_d s \right]. \tag{18}$$

In the above formula, $G(t)$ is the transfer function, $F(q)$ is the integral time constant, and $P(q)$ is the differential time constant. At the same time, the transfer ability of the temperature load is controlled. In the above formula, an increase of the proportion coefficient k_j will accelerate the response speed of the system, which would help reduce the static error and eliminate the static error fundamentally; if the k_j is too large, the system will produce an overshoot and an oscillation, but it cannot extend the adjustment control time and destroy the stability of the system; on the contrary, if k_j is too small, the system will move slowly. A simple proportional control is suitable for the

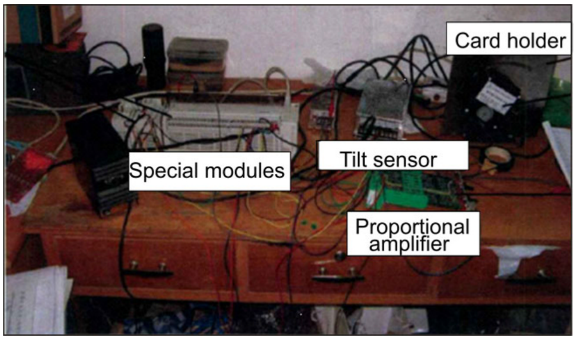

Fig. 4. Experimental environment.

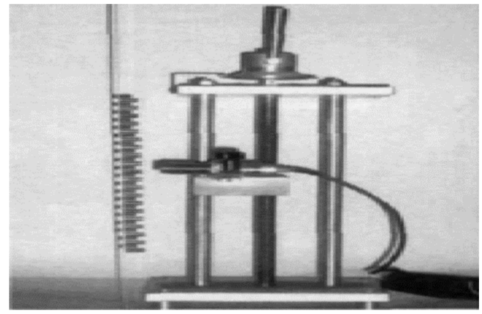

Fig. 5. Swing sensor of cutting head.

situation of a small disturbance, a small lag, a small load change and a certain residual error. When the system is stable, it can reduce the steady-state error, but cannot eliminate it entirely.

Since the PID parameter sets a need for a specific control platform, first of all, use the Simulink toolbox in MATLAB software to build and package the sub-modules and build the PID temperature load control platform [15]. According to the mathematical model of the horizontal swing motion of the cutting head and the mathematical model of the main components, the electro-hydraulic proportional directional valve sub-module, the horizontal swing cylinder sub-module, the swing cylinder stroke and the cantilever horizontal swing angle sub-module, the cantilever horizontal swing angle and the swing speed sub-module are duly established [16]. The main temperature load calculation parameters in the previous section are substituted into the transfer function of the controller for a numerical calculation, and the PID parameters are adjusted in the Simulink environment using a stable boundary method.

SIMULATION TEST

Experimental Environment Setting

Under the premise of complete hardware, the laboratory debugging platform is set up to debug the prepared automatic control experiment platform - Sw7dsc-gppw-c software to write a simple program. The hardware of the control system is connected in series from easy to difficult, and the input and output characteristics of each component of the control system are mastered. Through an off-line simulation and an on-line monitoring and a continuous software improvement and modification the laboratory program of whole control method is finally debugged. The laboratory debugging platform is shown in Figure 4.

As shown in Figure 4, the horizontal swing angle sensor of the rotary table outputs 4 lines, corresponding to two outputs of the positive and negative poles of the power supply and the ground wires. A small test bench is built to simulate the working state of the turntable. The sensor is fixed on the spiral moving bracket, and the sensing tooth with a 5 mm width is replaced by the pin, which is glued to the steel ruler, the pin spacing being 5 mm [17]. The sensitive surface of the swing angle sensor is a quasi pin, and the acting distance is 0–2 mm. The following are the process steps: rotate the handle (the sensor would move up and down relative to the pin), output the square wave pulse signal, input it into the PLC input terminals X0, X1, use on-off to simulate the number of the sensing teeth so as to calculate the distance of the horizontal movement. The motion process of the cutting head is simulated by detecting the induction rack and calling the relevant pulse command (Fig. 5).

As can be seen from Fig. 5, the output of the FX2N-2DA module is connected to the proportional amplifier. The output of the proportional amplifier is connected to a load-sensitive proportional multidirectional valve set. In the experiment, a resistance with the same resistance value (3052) can also be used to replace the load-sensitive proportional multiway directional valve [18]. Observe the lighting conditions of LED A and LED B on the proportional amplifier, and simulate the motion direction of the corresponding cutting head. The electrometer simulates the output voltage of the cutting motor current sensor 1-SV. The ammeter tests the coil current in the socket, which corresponds to

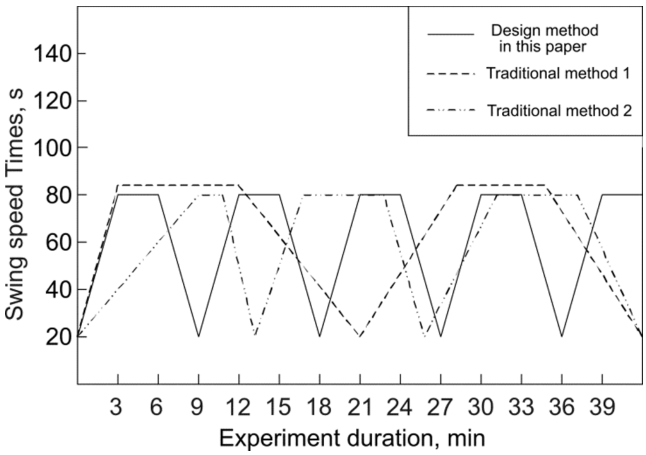

Fig. 6. Results of the first experiment.

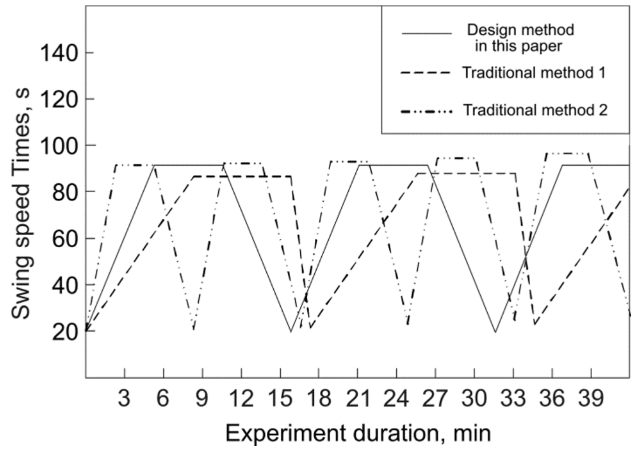

Fig. 7. Results of the second experiment.

the opening of the electro-hydraulic proportional valve port, reflects the cylinder feed speed, and then determines the swing speed of the cutting arm. The above part is the experimental environment of this experiment. An automatic control method and two other traditional control methods are adopted to control the equipment in the experiment, and the control results are compared to demonstrate the effectiveness of the design method discussed in this paper.

Experimental Comparison Parameters

In this experiment, the control accuracy of the cutting head is compared with that of the automatic control method. In order to show the differences between the three automatic control methods in use, the control accuracy is embodied in the swing speed of the cutting head. In this experiment, the working speed of the cutting part is set as "low speed high speed low speed", so as to ensure a stable temperature change of the cutting head, which would affect the use of the roadheader [19]. In this paper, the design method, the traditional method one (fuzzy control method) and the traditional method two (passive control method) are used to automatically control the cutting part of the roadheader, and the control curves are compared. In order to improve the effectiveness of the experiment, three experiments were carried out, and the differences of the three methods in each experiment were obtained.

Analysis of Experimental Results

As can be seen from the experimental results in Fig. 6, the process of automatic control of the design method in this paper is relatively stable, the traditional method 1 has a longer control cycle, the control process is relatively fluctuant, and the loss of the cutting part component is too large. In traditional method 2, the speed is adjusted too fast and there is no buffer time, which can easily cause overheating of the cutting head. Therefore, the design method in this paper in the first experiment has the best effect (as shown in Fig. 6).

As can be seen from the experimental results in Fig. 7, the speed adjustment cycle was partially adjusted. It is evident that the control period of the design method in this paper is relatively stable and there is no fluctuation. Compared with the design method proposed in this paper, the image of the other two methods fluctuates greatly, and the cycle is chaotic, and the acceleration - deceleration process is uneven. Summing up, the method proposed in this paper has demonstrated the strongest control ability in this experiment (as shown in Fig. 7).

As can be seen from the experimental results in Fig. 8, there is an increase in the maximum speed. In this environment, the period of the design method is relatively complete, and the time period is shorter than in the other two methods. The acceleration and deceleration processes are relatively steady, and there is no trend towards a sharp increase or decrease. Combining the results of this experiment with the results of the previous two experiments, we can

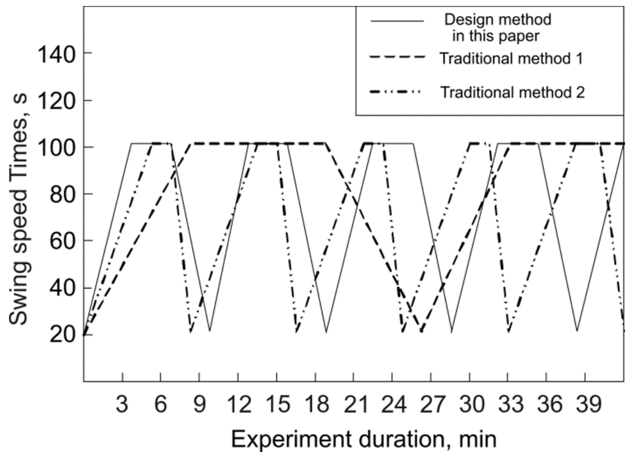

Fig. 8. Results of the third experiment.

see that the method proposed in this paper has the best effect. Because the acceleration and deceleration process is stable, the temperature of the cutting part is also stable, and no overheating will be cased by the loss of the roadheader (as shown in Fig. 8).

CONCLUSIONS

In this paper, the method for an automatic control over the cutting speed regulation of a longitudinal axis roadheader has been studied. Based on the manual and automatic controls, a new method for controlling the roadheader speed regulation has been put forward. With this technology, the roadheader can be used to a great advantage. An automatic cutting control platform with a roadheader has been developed, which can ensure that the cutting head would not exceed the boundary of the roadway during manual cutting. If the geological conditions of the roadway are not complex, the automatic cutting of any roadway section can be directly carried out according to the set path, otherwise, the memory-based cutting can be carried out after the manual demonstration cutting. At the same time, the boundary control method is proposed to ensure that the roadway is cut manually forming quality.

The research results of this paper can make the roadheader fully perform the speed control in the complex and variable environment of the coal roadway, provide an optimal or nearly optimal path to meet the tunneling technology and the geological conditions, control the temperature of the cutting part and avoid the damage of the roadheader caused by overheating. This technology is of an important research significance, it promotes the coal mine underground driving the control equipment to make a qualitative leap, which has a widespread engineering application value. The main results of this study are as follows:

A. A mathematical model of the cutting head has been established. Based on the analysis of the basic structure of the roadheader, the working principle of the cutting mechanism and the spatial movement track of the cutting head, a theoretical model of the cutting head has been constructed, and the cutting process path has been planned according to the standard cutting section shape, which provides a theoretical basis for the next step of the control platform construction.

B. Calculation of the temperature load on the cutting head. This paper has analyzed the control principle of the cutting operation of the traditional manual control roadheaders and proposed a calculation scheme including the temperature load; it has established a space temperature control transfer function of the cutting head and laid the foundation for the automatic controller design in the next step.

C. Design of the cutting mechanism of the controller. This paper has presented a constant-power automatic speed regulation control scheme of the cutting mechanism based on the PID control technology, formulated a mathematical model of the controller, established its PID control model in Simulink, and calculated and analyzed the current step signal, the load step signal and the load sine signal, respectively. The results show that the controller has good dynamic response and control characteristics, which can eliminate the influence of the temperature load variation on the cutting motor.

The research results presented in this paper have a certain practical significance for improving the tunneling efficiency, prolonging the service life of the cutting parts, and achieving safety, efficiency and automation of the tunneling operation. Due to the limited time and conditions, there are still some deficiencies in establishing the automatic cutting and constant-power cutting control of the roadheader section. We believe that the following research and improvements are necessary:

a. According to the response characteristic curve of the cantilever horizontal swing PID control system in this paper, the dynamic characteristics of the cutting part of the roadheader have to be further analyzed, and the related technical parameters, such as the structure and working performance of the controller, optimized.

b. In this paper, the feasibility and effectiveness of the cutting temperature speed regulation control were studied from the perspective of theoretical modeling and simulation analysis only. Practical testing is necessary.

c. As a technology, the method of automatic cutting should be used in all roadheaders.

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REFERENCES

1. E. S. Sadi, O. Ibrahim, Neural Comput. Appl., **31**, No. 4, 1103–1116 (2019).
2. Y. P. Shi, Xia, Y. M. Xia, Q. Tan, *et al*., J. Cent. South. Univ., **26**, No. 9, 2393–2403 (2019).
3. R. Zhang, Y. M. Zhang, L. S. Zhu, *et al*., J. Braz. Soc. Mech. Sci. Eng., **42**, No. 19, 1288–1292 (2020).
4. A. Luis, Q. Rafael, E. S. Tiago, *et al*., J. Strain. Anal. Eng. Design., **53**, No. 8, 602–615. (2018).
5. A. Mustafa, A. Deniz, M. Ş. İmamoğlu, *et al.*, Bull. Eng. Geol. Environ., **78**, No. 4, 2641–2652 (2019).
6. S. D. Qin, H. X. Ge and R. J. Cheng, Phys. Lett. A., **382**, No. 7, 482–488 (2018).
7. R. Luca, S. Francesca and T. Giovanni, Heat Mass Transfer, **54**, No. 6, 1627–1636 (2018).
8. H. Wang and L. J. Guo, Heat Transfer Eng., **40**, Nos. 5–6, 464–475 (2019).
9. L. M. Gian, Heat Transfer Eng., **40**, Nos. 9–10, 695–710 (2019).
10. D. A. Arturo, L. G. Amélie and S. Jérôme, Dev. Cell, **48,** No. 5, 596–598 (2019).
11. H. T. Chen, S. Q. Chang, and A. M. Fan, Int. J. Automot. Technol., **20**, No. 1, 127–135 (2019).
12. K. Nisi, B. Nagaraj and A. Agalya, Int. J. Mach. Lear. Cybern., **10**, No. 8, 2015–2025 (2019).
13. R. Ali, A. Furqan and S. H. Kim, J. Elec. Eng. Technol., **13**, No. 1, 451–459 (2018).
14. B. Kishore, I. Rosdiazli, N. K. Mohd, *et al*., Arab. J. Sci. Eng., **43**, No. 6, 2687–2701 (2018).
15. F. Alessandro, M. Antonio, P. Pietro, *et al*., Int. J. Automot. Technol., **19**, No. 5, 771–781 (2018).
16. H. M. Baskonus, H. Bulut, and T. A. Sulaiman, Appl. Math. Nonlinear Sci., **4**, No. 1, 129–138 (2019).
17. A. Cordero, J. P. Jaiswal, and J. R. Torregrosa, Appl. Math. Nonlinear Sci., **4**, (1), 43–56 (2019).
18. H. Durur, A. Kurt, and O. Tasbozan, Appl. Math. Nonlinear Sci., **5**, (1), 455–460 (2020).
19. F. Erdogan, M. G. Sakar, and O. Saldlr, Appl. Math. Nonlinear Sci., **5**, (1), 425–436 (2020).