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RESEARCH ARTICLE

# A Fuzzy Adaptive PID Control Method for Novel Designed Rail Grinding Equipment

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**ABSTRACT** Rail defects appear in a greater variety and frequency with the rapid development of High-Speed Rail (HSR), which seriously affects the safe operation of trains. Rail grinding is one of the common methods used to eliminate these defects. However, the quality of rail grinding is often limited by the constant power control method. This paper presents a fuzzy adaptive PID control method based on PID control. In this method, a fuzzy rule library of input and output is established according to the experience of experts and grinding operators, and the PID control parameters can be adjusted in real time through the library to achieve the purpose of constant power grinding. Compared with classical PID, the effectiveness of the proposed method was verified by simulation and the rail grinding experiment with the designed equipment. Experimental results showed that the power data of fuzzy adaptive PID control had less fluctuation, which could be basically stabilized at 5KW±0.1KW, and the curve tracking error was reduced by 60.9%. It is concluded that this method can greatly improve the power accuracy and stability of rail grinding.

**INDEX TERMS** HSR, rail grinding, constant grinding power, fuzzy adaptive PID, accuracy and stability.

## I. INTRODUCTION

With With the rapid growth of transportation demands, China is witnessing and experiencing striding development of High-Speed Rail (HSR). In 2019, China's HSR network has had a running distance of 29,000 km, exceeding 60% of the whole world in total [1], [2]. Due to the large passenger flow and the high operating speed of train, the damage to the internal and surface of the rails has become more and more serious [3], [4], [5], which will cause irreversible harm to the rail if not treated in time [6]. Studies have shown that rail grinding can improve rail quality and extend rail life [7], [8], [9]. At present, there are two main types for rail grinding: preventive grinding of the main line and manual grinding of the local scope [10], [11]. The preventive rail grinding of the main line is basically completed by oversize grinding equipment, which has some problems such as difficult scheduling, low flexibility and local grinding blind areas [12], [13], [14]. Manual grinding completed by manually carrying small grinding device is mainly used to overcome these problems. However, it extremely depends on workers' experience, the grinding effect is unstable and the efficiency is low [15]. Therefore, it is necessary to develop a rail grinding equipment with flexible scheduling, stable grinding effect and high efficiency.

Based on this, a new automatic rail grinding equipment is developed. We know that the grinding power is an important parameter in the rail grinding process, and constant grinding power is the premise for ensuring the quality and efficiency of the grinding [16]. Currently, the most classical controlling methods for constant grinding power is Proportional-Integral-Derivative (PID) control strategy [17], [18]. However, it is difficult to get better control effects with fixed PID control parameters for different grinding angles and various

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interferences caused by different rail surface corrosion conditions and defect distributions in the actual rail grinding process. It is necessary to dynamically adjust the PID parameters according to the external load characteristics.

Study have shown that intelligent controller such as fuzzy inference system(FIS) using a set of IF-THEN rules can be used in complex and challenging control situations for its high interpretability and outstanding capability of approximating nonlinear systems [19], [20], [21]. Fuzzy adaptive PID controller embedding the structure of PID controller as well as the human expert knowledge from FIS is found to provide distinguished controlling performance in several researches [22], [23], [24]. Therefore, a constant power control method based on fuzzy adaptive PID for rail grinding was proposed in this paper. In this method, the input and output of the system were fuzzified firstly based on the fuzzy control theory. Then a fuzzy rule library of input and output was established according to the experience of experts and grinding operators. Through the rule library, PID control parameters of the grinding system can be adjusted automatically to adapt to the changes in the actual rail grinding process, achieving optimal control effect of grinding, ensuring the accuracy and quality of the grinding and improving the stability of the railway operation.The main contribution of this paper includes:

(1) A novel rail grinding equipment is developed to validate the performance of the proposed control method under different working conditions.

(2) A constant power control method for rail grinding is proposed by using fuzzy adaptive PID based on dynamics modeling of rail grinding unit, which expands and verifies the adaptability of fuzzy adaptive PID control method in rail grinding field, providing reference and comparison for more advanced control algorithms in the future.

The remainder of the paper is organized as follows. Section 2 presents the configuration of novel rail grinding equipment and the dynamics modeling of rail grinding unit. Section 3 describes the details of the proposed fuzzy adaptive control method. The experiment results and analysis are shown in Section 4. Finally, the conclusion and discussion are drawn in Section 5.

## II. OVERVIEW OF THE NOVEL DESIGNED RAIL GRINDING EQUIPMENT

### A. CONFIGURATION OF THE RAIL GRINDING EQUIPMENT

The novel designed rail grinding equipment is shown in Figure 1, which is composed of a control unit, a motion unit, an alarming unit, a power unit, and several same grinding units that can be combined if needed (for example, two same units on the left and right sides respectively in Figure 1). The control unit controls the start and stop of the grinding equipment and coordinates other modules to complete the grinding task, measures and displays various operation parameters in real time. The alarming unit is designed to display when the equipment is in different states. The motion unit carries the grinding equipment and controls the movement of the

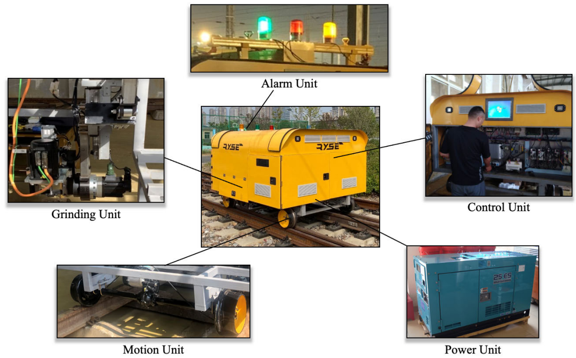


**FIGURE 1.** Configuration of the rail grinding equipment.

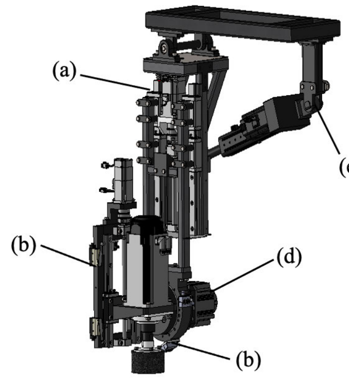


**FIGURE 2.** Rail grinding unit: (a) safety lifting module; (b) feed module; (c)grinding module; (d) angle adjustment module; (e) swing frame module.

grinding equipment on the rails. The grinding unit is the core component of the rail grinding equipment, which is composed of five parts as shown in Figure 2: grinding module, feed module, angle adjustment module, swing frame module, and safety lifting module. The grinding module is driven by the grinding motor, which drives the grinding wheel rotating at a high speed and uses wheel end face to grind the rail. The distance between grinding head and the position of rail to be ground is controlled by the feed module. The swing frame module and angle adjustment module cooperate with each other to adjust the angle of the grinding head relative to the rail. The safety lifting module is mainly used for safety protection.

The core for this rail grinding equipment is constant power control, in which the rail grinding unit is the important actuator. To achieve a better constant power control effect, a dynamic model is established based on the dynamic equation of the rail grinding unit.

### B. THE DYNAMICS MODELING OF RAIL GRINDING UNIT

The relationship between grinding power P and grinding force $F_n$ of the rail grinding mechanism in the operating regulations can be expressed as (1) according to [16]:

$$P = \pi F_n cot\theta_z (R_1 + R_2)\omega_r / 4. \tag{1}$$

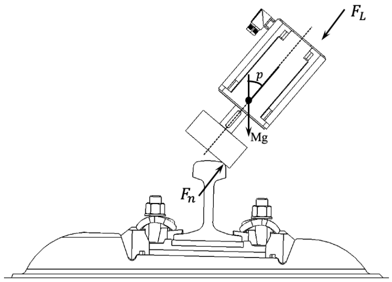


**FIGURE 3.** Schematic diagram of grinding unit model.

Here, $\theta_z$ is half cone angle, $R_1$ is the inner radius of grinding wheel, $R_2$ is the outer radius of grinding wheel, $\omega_r$ is the angular velocity of the grinding wheel. The force conversion from the feed axis to the grinding wheel is shown in Figure 3.

From Figure 3, we can get:

$$F_n = F_L + Mgcos\theta_p - Mgsin\theta_p. \tag{2}$$

Combining (1) and (2), and using incremental form of the Laplace transform it can be written as:

$$\Delta P(s) = \pi\omega_r cot\theta_z (R_1 + R_2)\Delta F_L(s)/4. \tag{3}$$

When the grinding head is in contact with the rail, the acting force is $\Delta F_L$, and the displacement $\Delta x$ is passively generated. Setting the environmental equivalent stiffness as $K_L$, the (3) can be written as:

$$\Delta P(s)/\Delta x(s) = \pi\omega_r cot\theta_z (R_1 + R_2)K_L/4. \tag{4}$$

The relationship between torque $T_L$ and load $F_L$ for the ball screw can be expressed as follows:

$$T_L = F_L P_B/2\pi\eta + (\mu_0 F_L P_B)/6\pi + (J_L + J_B + J_C)\ddot{\theta}. \tag{5}$$

Here, $P_B$ is the pitch of the ball screw, $\eta$ is the mechanical efficiency, $\mu_0$ is the internal friction coefficient of the preload nut, $J_L$ is the load inertia, $J_B$ is the screw inertia, $J_C$ is the coupling inertia, and $\ddot{\theta}$ is the angular acceleration of the feed motor. The conversion equation of servo motor torque $T_L$ and current $I_L$ is:

$$T_L = K_t * I_L. \tag{6}$$

Here, $K_t$ is the torque coefficient. Combining (5) and (6), using incremental form of the Laplace transform it can be written as:

$$K_t\Delta I_L(s) = \Delta F_L(s)(P_B/2\pi\eta + (\mu_0 P_B/6\pi)) + (J_L + J_B + J_C)s^2\Delta\theta(s). \tag{7}$$

If the motor rotates $\theta°$, the feed distance is:

$$x = P_B\theta. \tag{8}$$

Combining the (4), (7) and (8), we can get:

$$\Delta P(s)/\Delta I_L(s) = (K_t\pi\omega_r cot\theta_z(R_1 + R_2)K_L/4) /(K_L(P_B/2\pi\eta + \mu_0 P_B/6\pi) + (J_L + J_B + J_C)s^2/P_B). \tag{9}$$

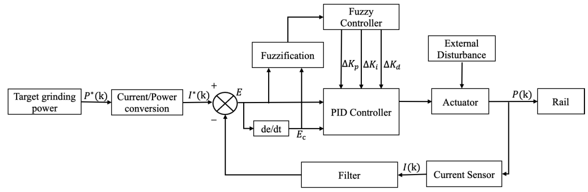


**FIGURE 4.** Structure diagram of fuzzy adaptive PID controller.

## III. DESIGN OF CONSTANT POWER CONTROLLER BASED ON FUZZY ADAPTIVE PID

Here, a classical PID method was firstly used. The governing equation of PID controller is defined as.

$$\mu(t_k) = K_P e(t_k) + K_I\sum_{i=0}^{k} e(t_i)\Delta t_k + (K_D(e(t_k) - e(t_k - 1))/\Delta t_k). \tag{10}$$

Here, $t_k$ is the kth time step; $\mu(t_k)$ is the output in kth time step; $e(t_k)$is the error in kth time step; $\Delta t_k$ is the interval of sampling time in simulation; $K_P \in R$, $K_I \in R$, $K_D \in R$ are the proportional, integral and derivative gain, respectively. $R$ refers to the set point. Since it is difficult to obtain better control effects with fixed PID control parameters in actual grinding process, a constant power control method of rail grinding based on fuzzy adaptive PID is designed in this paper.

### A. FUZZY ADAPTIVE PID CONSTANT POWER CONTROL STRATEGY

The control strategy diagram of the system is shown in Figure 4. Before the grinding operation, the target grinding power $P^*(k)$ is set according to the grinding task that determined by operators, and the target power is converted into the target current according to the current-power conversion formula. Then the controller command is sent to the actuator for the grinding operation. Meanwhile, the current sensor is used to collect the current $I(k)$ in the grinding motor. A strong interaction force is produced by the grinding head and the rail in actual grinding process, resulting in high-frequency vibration of the grinding equipment, which will increase signal noise and signal "burrs". It will seriously affect the stability of the control system if the collected signal is directly fed back to the control system. Therefore, Kalman filter is used to reduce the noise of the collected signal for the advantages of small memory usage and fast calculation speed, and generally does not cause a large signal lag effect [25], [26]. Then the real-time current deviation and the deviation change rate are input into the controller as feedback, and the parameters can be adjusted in real time by fuzzy adaptive PID controller to control the actuator for grinding.

### B. THE INPUT AND OUTPUT OF FUZZY CONTROL

The input of the fuzzy controller is the current deviation E and the deviation change rate $E_C$, and the output is the PID control parameter correction $\Delta K_p$, integral coefficient $\Delta K_i$,

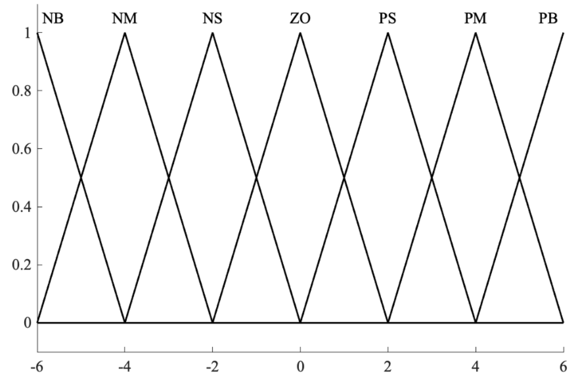


**FIGURE 5.** Fuzzy membership function.

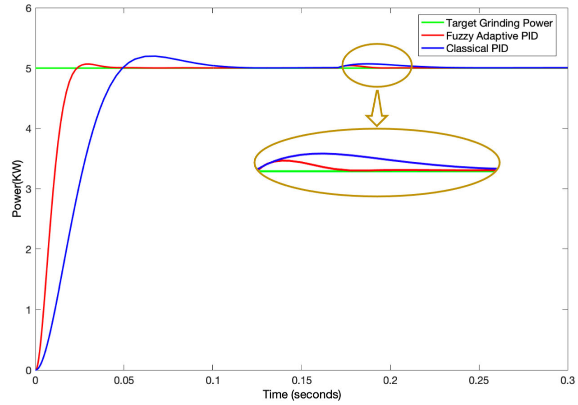


**FIGURE 6.** Fuzzy adaptive PID and classical PID control simulation diagram.

and differential coefficient $\Delta K_d$. The self-tuning parameters are as follows:

$$K_p = K_{p0} + \Delta K_p$$
$$K_i = K_{i0} + \Delta K_i$$
$$K_d = K_{d0} + \Delta K_d. \quad (11)$$

Here, $K_{p0}$, $K_{i0}$ and $K_{d0}$ are the initial values of PID parameters, and $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$ are the modified values obtained by fuzzy inference. The $E$, $E_c$, $\Delta K_p$, $\Delta K_i$, $\Delta K_d$ are divided into seven fuzzy subsets, including $\{NB, NM, NS, ZO, PS, PM, PB\}$. The domain of input variables is:

$$E_c, E = \{-6, -4, -2, 0, 2, 4, 6\}$$

The domain of output variables is:

$$\Delta K_p, \Delta K_i, \Delta K_d = \{-6, -4, -2, 0, 2, 4, 6\}$$

Triangular membership function is used for each linguistic variable of the proposed fuzzy algorithm, as shown in Figure 5.

### C. THE FUZZY CONTROL RULES AND DEFUZZIFICATION

When the PID parameters are adjusted by fuzzy controller, it is necessary to formulate fuzzy rules according to the input $E$ and $E_c$ and the functions of the three PID parameters. According to the experience of the grinding operator, the setting principle is as follows:

(1) If the current deviation $E$ is larger, a large $\Delta K_p$ will be taken to improve the response speed of the system, a moderate $\Delta K_d$ will be taken to avoid large overshoot, and $\Delta K_i$ will be 0 to prevent integral saturation.

(2) If the current deviation $E$ and deviation change rate $E_c$ are moderate, smaller $\Delta K_p$ will be selected to reduce overshoot, the value of $\Delta K_i$ should be appropriate, and a moderate $\Delta K_d$ will be selected to ensure the response speed of the system.

(3) If the current deviation $E$ is small, $\Delta K_p$ and $\Delta K_i$ need to be increased to maintain the stability of the system. Meanwhile, $\Delta K_d$ need to be evaluated according to the deviation rate $E_c$ to improve the anti-interference performance of the system. When $E_c$ is small, larger $\Delta K_d$ is taken, otherwise smaller $\Delta K_d$ is taken.

A fuzzy rule of three parameter correction items $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$ and $E$, $E_c$ is established by combining the setting principle with the basic idea of PID and fuzzy mathematics theory, as shown in Table 1.

The output of the fuzzy controller is a fuzzy set, which needs to be defuzzified to obtain the exact value. The weighted average method is used to defuzzify the fuzzy output, which is as follows:

$$\mu = (\sum_{i=1}^{n} x_i \mu(x_i))/(\sum_{i=1}^{n} \mu(x_i)). \quad (12)$$

Here, $\mu$ is the final output value, $n$ is the number of elements in the output fuzzy domain, $x_i$ is the value of the $i-th$ element in the output fuzzy domain, and $\mu(x_i)$ is the membership degree of the $i-th$ element in the output fuzzy domain.

## IV. EXPERIMENTS

### A. SIMULATIONS

In order to analyze and test the performance of the fuzzy adaptive PID constant power control strategy designed in this paper, the control effect under classical PID control and fuzzy adaptive PID control was simulated through MATLAB/Simulink. According to the (12), set t = 0 time and apply a 5KW step signal to the grinding system. After multiple tests, $K_p = 0.2$, $K_i = 0.005$, $K_d = 1.8$ were selected. Then, a disturbance signal (square wave pulse signal with amplitude of 0.5 and response time of 0.01s) is added at 0.17s, and the system simulation curve was shown in Figure 6.

From the system simulation curve in Figure 6, the system overshoot, rise time and adjustment time of fuzzy adaptive PID control and classical PID control can be calculated respectively. The results are shown in Table 2.

From Table 2, it can be seen that the overshoot of the classical PID control is about 3.65%, the rise time is 0.031s, and the adjustment time is 0.115s. While the adjustment

**TABLE 1.** Fuzzy rules of $\Delta K_p/\Delta K_i/\Delta K_d$.

| E | Ec | | | | | | |
|---|---|---|---|---|---|---|---|
| | NB | NM | NS | ZO | PS | PM | PB |
| NB | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | ZO/ZO/NM | ZO/ZO/PS |
| NM | PB/NB/PS | PB/NB/NS | PM/NM/NB | PS/NS/NM | PS/NS/NM | ZO/ZO/NS | NS/ZO/ZO |
| NS | PM/NB/ZO | PM/NM/NS | PM/NS/NM | PS/NS/NM | ZO/ZO/NS | NS/PS/NS | NS/PS/ZO |
| ZO | PM/NM/ZO | PM/NM/NS | PS/NS/NS | ZO/ZO/NS | NS/PS/NS | NM/PM/NS | NM/PM/ZO |
| PS | PS/NM/ZO | PS/NS/ZO | ZO/ZO/ZO | NS/PS/ZO | NS/PS/ZO | NM/PM/ZO | NM/PB/ZO |
| PM | PS/ZO/PB | ZO/ZO/NS | NS/PS/PS | NM/PS/PS | NM/PM/PS | NM/PB/PS | NB/PB/PB |
| PB | ZO/ZO/PB | ZO/ZO/PM | NM/PS/PM | NM/PM/PM | NM/PM/PS | NB/PB/PS | NB/PB/PB |

**TABLE 2.** Comparison of adjustment parameters between fuzzy adaptive PID and classical PID control.

| Control Method | overshoot(%) | rise time(s) | adjustment time(s) |
|---|---|---|---|
| Classical PID | 3.65 | 0.031 | 0.115 |
| Fuzzy Adaptive PID | 0.51 | 0.016 | 0.051 |

speed of the fuzzy adaptive PID control is reduced actively when it is close to the control target. And the overshoot of fuzzy adaptive control is only 0.51%, the rise time is 0.016s, the adjustment time is 0.051s. Compared with the classical PID control, fuzzy adaptive PID control has a quick response, small overshoot and shorter time to reach steady state. And when the disturbance is added, fuzzy adaptive PID control method has smaller fluctuation range, shorter duration and can be able to balance the system back to steady state more quickly than classical PID control, indicating that the controller has obvious priority of robustness. In general, fuzzy adaptive PID control is obviously better than classical PID control in simulation experiments.

### B. RAIL GRINDING EXPERIMENTS

#### 1) METHOD

The designed rail grinding equipment as shown in Figure 1 was developed to evaluate the performance of the proposed fuzzy adaptive control method. And the grinding parameters were selected as follows: the travel speed was 0.8m/s, the grinding speed was 4000 r/min, the grinding power was 5KW, and the grinding angle range was $-10^\circ \sim 60^\circ$. To reduce the influence caused by the different corrosion degrees of each rail, two adjacent rail sections of the same 50m rail were selected as the experimental objects. Different angles of $-10^\circ$, $0^\circ$, $15^\circ$, $45^\circ$and $60^\circ$ were selected as the test objects on the working profile of the straight rail. The grinding effects of classical PID control and fuzzy adaptive PID control were test respectively, as shown in Figure 7(a). Then the roughness and profile deviation were measured by roughness measuring instrument and portable laser rail profile measuring instrument, as shown in Figure 7(b).

#### 2) RESULTS OF THE EXPERIMENT

The grinding curves are different for various grinding angles. Since the grinding angle of 60°is usually the most severely affected area, the power curve of 60° is selected to display and analyze, as shown in Figure 8.

From Figure 8, it can be seen that the power data of fuzzy adaptive PID control fluctuates less than the classical PID control, which can basically be stabilized at 5KW±0.1KW. The maximum power deviation of classical PID is 246W, the steady-state error is 4.92%. While the maximum power deviation of fuzzy adaptive PID control is 96W, the steady-state error is 1.92%. Compared with the classical PID control, it can be found that the power tracking error of fuzzy adaptive PID control is reduced by 60.9%, which greatly improves the stability of rail grinding. For the other four angles of $-10^\circ$, $0^\circ$, $15^\circ$, $45^\circ$, the roughness and profile deviation are measured as shown in Table 3.


**FIGURE 7.** Rail grinding experiment.

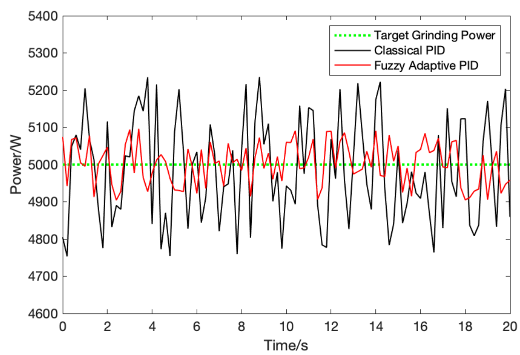


**FIGURE 8.** Power curve with an angle of 60°.

From Table 3, we can see that the effect of classical PID control is close to fuzzy adaptive PID at 0°, which is because the rails generally do not have large defects at 0°. Therefore, classical PID controller can also get good control effect in the test site with relatively fixed conditions. However, the effect of classical PID control is getting worse if the working conditions change, while there is no obvious difference for fuzzy adaptive PID control. The experimental results show that the fuzzy adaptive PID control method has better stability and adaptability than the classical PID control in different working conditions. Simultaneously, the rail surface roughness and longitudinal 20m profile standard deviation are guaranteed to be less than Ra6.0$\mu$m and 0.15mm respectively, indicating that the proposed control method can effectively

**TABLE 3. Comparison of parameters ground by two control algorithms.**

| | angle/° | Steady-state error /% | Surface roughness Ra/$\mu m$ | Longitudinal 20m profile standard deviation/mm |
|---|---|---|---|---|
| Classical PID | -10 | 3.78 | 10.22 | 0.23 |
| | 0 | 2.08 | 5.32 | 0.13 |
| | 15 | 4.56 | 9.21 | 0.19 |
| | 45 | 4.92 | 11.94 | 0.25 |
| Fuzzy Adaptive PID | -10 | 1.93 | 5.31 | 0.09 |
| | 0 | 2.05 | 4.92 | 0.11 |
| | 15 | 1.84 | 4.83 | 0.08 |
| | 45 | 1.96 | 4.71 | 0.13 |

improve consistency of rail surface quality. According to the "Management Measures for HSR Rail Grinding", passengers will not feel uncomfortable and the riding experience is ideal if the surface roughness of the rail is less than Ra6.3$\mu$m and the longitudinal 20m profile standard deviation is less than 0.2mm. From Table 3, it can be shown that the final grinding effect achieved by the fuzzy adaptive PID control in this study meets the acceptance standard of HSR.

## V. CONCLUSION AND DISCUSSION

The rapid development of China's HSR has improved the travelling convenience, optimized the relationship among cities, promoted social and economic prosperity, and enhanced people's living quality [27]. However, the maintenance of high-speed rail has brought huge challenges to line operation, so it is urgent to develop a high-quality and high-efficiency HSR maintenance equipment. An automatic rail grinding equipment was developed, and a constant power control method based on fuzzy adaptive PID was proposed to improve grinding stability and efficiency in this paper. Preliminary experimental results have showed that the proposed fuzzy adaptive PID control method can achieve stable and high-quality grinding effect, meeting the HSR standard.

The equipment does provide a new way for HSR maintenance, and the effectiveness of the fuzzy adaptive PID control method has been verified. With the increasing demand and changed methods for HSR maintenance, more and more new HSR equipment will be developed. There will be some changes for maintenance methods and higher requirements for the corresponding control methods. Some studies have proposed more advanced control methods, such as adaptive neuro-fuzzy control [28], improved genetic algorithm tuning PID control [29], Hybrid PSO-GSA-Tuned PID control [30], etc. In the future, these advanced control methods and experiments on the developed equipment will be carried out to improve the grinding technology and optimize the grinding method continuously, achieving the goal of higher adaptability, higher quality and higher efficiency.

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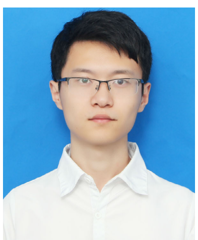

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