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Modelling and Analysis of Step Response Test for Hydraulic Automatic Gauge Control

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The step response for hydraulic automatic gauge control (HAGC) determines the steel rolling speed and the steel sheet thickness in the process of rolling production. In this paper, the step response test process of HAGC was analysed, and a test approach was proposed for it. Based on that, the transfer function model of the step response test was established and simulated by using Matlab. In order to reduce the settling time and the overshoot, an adaptive proportional-integral-derivative (APID) link was presented in order to compensate for the input signal by using back propagation neural networks (BPNN). The experimental results show that the improved step response test model reaches the process requirements of HAGC, eliminates the jitter of the HAGC system at the start-up phase, and has better stability as well as faster response for steel sheet rolling.

Keywords: step response, hydraulic automatic gauge control, proportional-integral-derived controller, artificial neural networks

Highlights

- *Proposed the step response test model of HAGC system.*
- *The working parameters study of the model.*
- *Presented an APID link for signal compensation.*
- *Representation of the stability and the flexibility on step response of the HAGC system.*

0 INTRODUCTION

Sheet gauge is one of the main quality indicators for steel sheet in the process of rolling production. To improve the control precision of sheet gauge, hydraulic automatic gauge control (HAGC) is currently widely used. In the process of HAGC, the step response plays the most important role, because it determines the steel rolling speed and the steel sheet thickness, and accordingly influences steel sheet surface quality. The step response test is a time-domain test method for system dynamic characteristics. It is used to describe the dynamic response process of the control system when the input is a step signal. To achieve uniform thickness of a steel sheet, the step response parameters of the HAGC should be adjusted according to the real-time thickness of steel sheet. However, during the step response process of HAGC, the step response parameters are influenced by the interactions of hydraulic cylinders, servo valves, and various sensors of the system, and the working time is extremely short (no more than 1 second). Consequently, it is of vital importance to model, test, and analyse the step response of HAGC.

In terms of HAGC system design, Wang et al. and Taleb et al. developed a real-time simulator for a hot-rolling mill based on a digital signal processor, which can be used for controlling the hydraulic cylinder in an HAGC system [1] and [2]. Gao et al. proposed a simulated model of 1100 mm rolling mill HAGC system by using position-pressure compound control method [3]. T.S. Tsay presented a command tracking error square control scheme, and designed feedback control systems [4]. To achieve good control effect, many researchers studied the control algorithm of HAGC. Ang et al. and Mitsantisuk et al. researched the general design method of control system with proportional-integral-derived controller (PID) [5] and [6]. Zhang et al., Dou et al. and Chang et al. analysed the PID parameters setting problem [7] to [9]. Their research proved that the PID controller with proper parameters was efficient, but the setting of the PID parameters is the main problem. To achieve the desired strip thickness of the HAGC system, Khosraviet al. and Song et al. proposed a novel fuzzy adaptive PID controller [10] and [11]. The simulation results showed that it was better than traditional PID controller, but sensitive to parameter variations. Wan et al. and Kasprzyczak et al. analysed the main parameters of the hydraulic system and discussed their effects on system stability [12] to [13].

To solve the problem of multivariable parameters adjustment of the PID controller, several authors proposed some intelligent algorithms, such as evolutionary algorithms, particle swarm optimization (PSO), artificial neural networks (ANN) and generalized predictive control method [14] to [18]. The results indicated the intelligent algorithms improved the adaptability of the PID controller. However, the dynamic response process of the controller under step-

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input was not discussed. In the literature, the research put emphasis on the design, analysis and control of HAGC, and few papers studied the step response test of HAGC.

In this paper, the step response test of HAGC is analysed, a test approach is proposed, and a transfer function model of the step response test is established and simulated by using Matlab software. In order to reduce the settling time and the overshoot, an adaptive proportional-integral-derivative (APID) link is presented to compensate for input signal by using back propagation neural networks (BPNN). The experimental results show that the improved step response test model reaches the process requirements of HAGC, eliminates the jitter of the HAGC system at the start-up phase, and has better stability as well as a faster response for steel sheet rolling.

The structure of this paper is organized as follows. Section 1 introduces the parameters and the approach of the step response test of HAGC. Section 2 establishes the step response test model with transfer function. Section 3 simulates the proposed model by using Matlab, and presents the improved model of the step response test by adding an APID link based on BPNN. Section 4 contains the experiments and the analysis of the improved model. Section 5 is devoted to the conclusions.

1 THE STEP RESPONSE TEST OF HAGC

1.1 The Parameters of the Step Response Test

In Fig. 1, the x coordinate value of the response signal curve represents the step response time, and the y coordinate value represents the displacement of the piston rod in the HAGC system. Next, the parameters of the step response test include the rise time t_r, the maximum overshoot M_p, and the settling time t_s. The rise time t_r is the time at which the response signal reaches the first steady-state output, as described in Eq. (1):

$$t_r = t_{0.9} - t_{0.1}, \tag{1}$$

where $t_{0.9}$ is the time at which the response signal is 90% of the first steady-state output, and $t_{0.1}$ is the time at which the response signal is 10% of the first steady-state output.

The difference between the response signal and steady-state output functions as the numerator, and the steady-state output as the denominator, the overshoot as the ratio of them. Next, the maximum overshoot M_p can be calculated by Eq. (2):

$$M_{\mathrm{P}} = \frac{x_o(t_p) - x_o(\infty)}{x_o(\infty)} \times 100\%, \tag{2}$$

where $x_{\mathrm{o}}(t)$ is the displacement of the piston rod at the time t, and t_p is the time at which the response signal reaches the peak.

In the step response process, the settling time t_{s} is also called the transition time, which represents the time at which the HAGC system reaches the steady-state. It is defined as the time at which the value of $x_{\mathrm{o}}(t)$ satisfies Eq. (3):

$$\left| x_{\mathrm{o}}(t)\text{-}x_{\mathrm{o}}(\infty) \right| \le 0.05 x_{\mathrm{o}}(\infty). \tag{3}$$

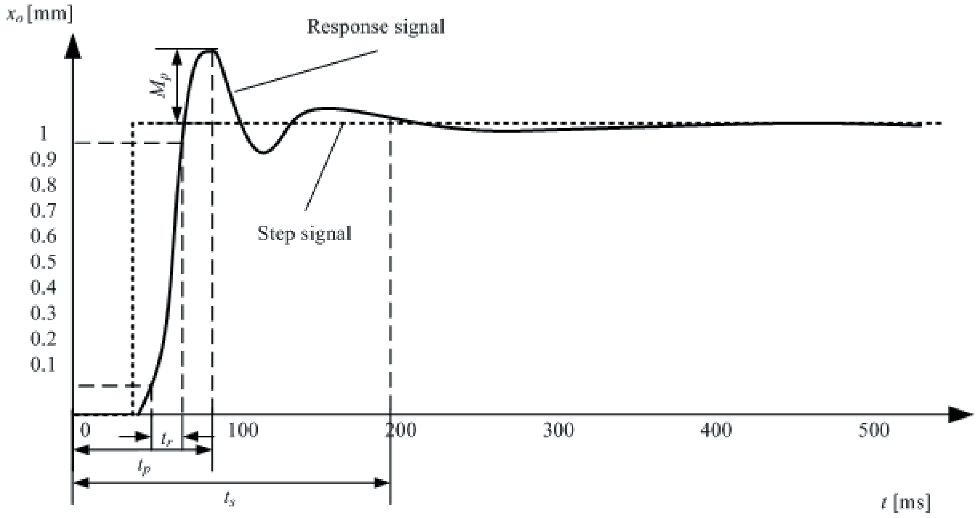

Fig. 1. *The parameters of the step response test*

In the parameters of the step response, the settling time t_s reflects the flexibility of the HAGC system, and the maximum overshoot M_p reflects the stability of HAGC system. In an HAGC system, it is always considered that the shorter of t_s and M_p, the better of the control effect.

1.2 The Approach of the Step Response Test

The main components in the step response process of HAGC are the servo valve, mill cylinder, current sensors, and displacement sensors. In order to simplify the test process, the influence of the hydraulic pipe and hydraulic power components is neglected. Next the approach of the step response test is shown in Fig. 2, and the main test steps are as follows:

Step 1: The displacement of step signal is given to the computer test software. It is converted to a voltage signal by the data acquisition card and is sent to the current sensor (6).

Step 2: The output signal of the data acquisition card is converted to current by the current sensor (6), and then is sent to the servo valve (5) to control the output flow in valve port A.

Step 3: According to the output flow in the valve port A, the piston rod (3) of mill cylinder 2 moves up-down to control the rolling thickness of steel sheet.

Step 4: The real-time displacement of the rolling thickness is measured by the displacement sensor (4), and then is converted to digital signal by the data acquisition card.

Step 5: The acquired digital signal is sent to the computer test software, which will be compared with the input displacement in Step 1 to determine the next input value.

2 MODELLING OF THE STEP RESPONSE TEST

2.1 The Parameters of the Step Response Test

According to Fig. 2, the step response test scheme is established, as shown in Fig. 3. The input signal U_v is the step signal of the expected displacement. The output signal Y_p is the real-time displacement of the mill cylinder, which is converted to the voltage signal U_p by the displacement sensor and fed back to the input port of the servo valve. The difference between U_v and U_p, U_e, is converted to the current signal by the current sensor and is used to drive the servo valve. The piston rod action of the mill cylinder is controlled by the output flow of the servo valve.

If the PID link is neglected and the input signals are sent to drive the servo valve directly, the transfer function of the servo valve is:

$$G_1(s)=\frac{K_{sv}}{\frac{s^2}{\omega_{sv}^2}+\frac{2\xi_{sv}}{\omega_{sv}}s+1}, \tag{4}$$

where K_{sv} is the output flow gain of the servo valve, ω_{sv} is the natural frequency of the servo valve, and ξ_{sv} is the damping radio of the servo valve.

The transfer function of the mill cylinder is:

$$G_2(s)=\frac{\frac{A_c}{KK_{ce}}}{\left(\frac{s}{\omega_r}+1\right)\left(\frac{s^2}{\omega_h^2}+\frac{2\xi_h}{\omega_h}s+1\right)}, \tag{5}$$

where ω_r is the transition frequency of the inertia, and ω_h and ξ_h are the natural frequency and the damping radio of the mill cylinder. K_{ce} is the overall flow-pressure coefficient, K is the load stiffness, and A_c is the effective area of the piston rod of the mill cylinder.

The transfer function of the current sensor is:

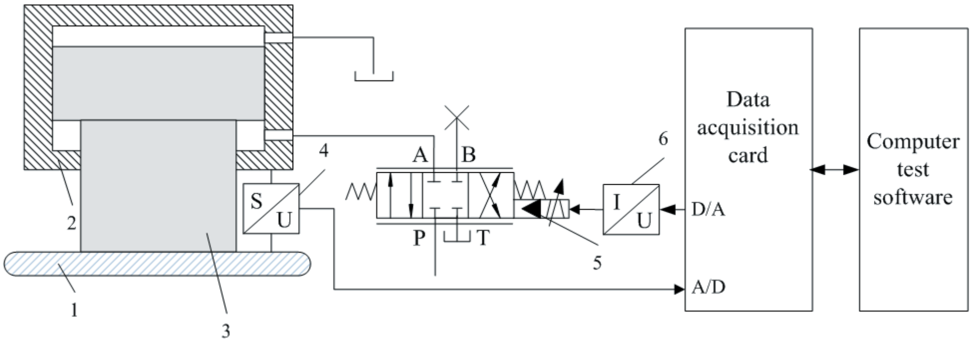

Fig. 2. The step response test of HAGC; 1-Steel sheet, 2-Mill cylinder, 3-Piston rod, 4-Displacement sensor, 5-Servo valve, 6-Current sensor

$$G_3(s) = K_i, \tag{6}$$

where K_i is the gain of current.

The transfer function of the displacement sensor is:

$$H(s) = K_s, \tag{7}$$

where K_s is the feedback coefficient of displacement.

2.2 Adding PID Link

To reduce the settling time and the maximum overshoot of HAGC, some researchers proposed compensating for the input signal by using some algorithms. The signal compensation is implemented by adding a new link to improve the system performance. Because the PID algorithm is flexible, and its parameters can be easily adjusted, it is widely used in control systems. Therefore, based on the step response test scheme, a PID link is added in the step response test scheme between the input signal U_e and the current sensor, as shown in Fig. 3.

The PID algorithm includes a proportional part, an integral part, and a differential part. Consequently, three coefficients, K_p, T_i and T_d, are used in PID controller for the system control, where K_p is the proportional coefficient, T_i is the integral coefficient, and T_d is the derivative coefficient. Therefore, the conventional PID algorithm can be described as:

$$G_4(s) = \frac{U_g}{U_e} = K_p + \frac{1}{T_i s} + T_d s. \tag{8}$$

In terms of Fig. 3 and Eqs. (4) to (8), the overall transfer function model of the step response test with conventional PID algorithm can be described as Eq. (9):

$$G(s)H(s) = \frac{K_{sv}}{\frac{s^2}{\omega_{sv}^2} + \frac{2\xi_{sv}}{\omega_{sv}}s + 1} \cdot \frac{\frac{A_c}{KK_{ce}}}{\left(\frac{s}{\omega_r} + 1\right)\left(\frac{s^2}{\omega_h^2} + \frac{2\xi_h}{\omega_h}s + 1\right)} \cdot K_i K_s \cdot \left(K_p + \frac{1}{T_i s} + T_d s\right). \tag{9}$$

3 SIMULATION AND IMPROVEMENT OF THE STEP RESPONSE TEST

3.1 Simulation of the Step Response Test

To analyse the control effect with and without a PID link in the step response test, the working parameters are loaded to the established transfer function model in the HAGC system, and the step response test is simulated by using the Simulink toolbox in Matlab software. The simulated model with the working parameters is shown in Fig. 4. In the simulated model, a step signal of 1 mm displacement is loaded at the input point, and the output result is shown as the blue dot curve in Fig. 5. In Fig. 5, it can be observed that t_s = 140 ms, M_p = 25 %. However, in the HAGC production process, it is necessary that t_s < 100 ms and M_p < 10 % for steel sheet rolling. Therefore, the settling time and the maximum overshoot are beyond the range of the HAGC requirements, which means the step response test without a PID link cannot be used to drive the HAGC system directly.

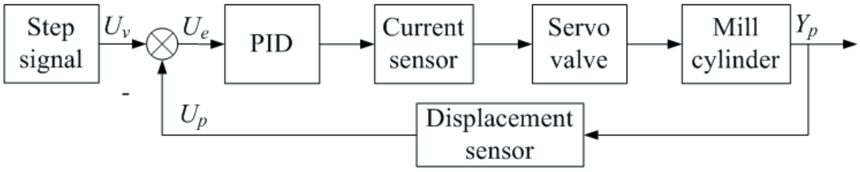

Fig. 3. *The step response test scheme*

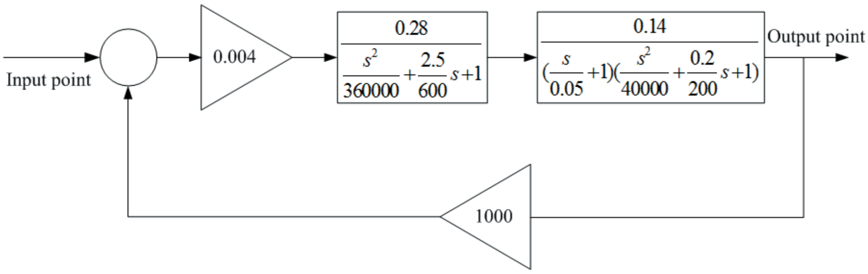

Fig. 4. *The simulated model with working parameters*

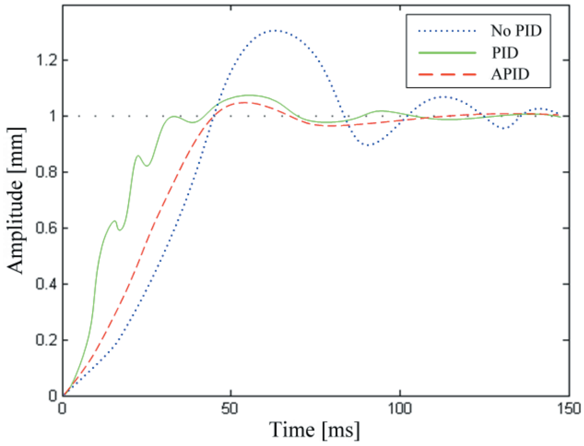

Fig. 5. *The simulated results of the step response test*

By adding the PID link in the established model in Fig. 4, the step response test is simulated with a conventional PID algorithm, and the output result is shown as a green solid curve in Fig. 5. It is found when K_p = 10, T_i = 50, and T_d = 0, the settling time t_s = 80 ms, and the maximum overshoot M_p = 9 %, which meet the process requirements of the HAGC. Moreover, testing shows that increasing K_p and T_d, and decreasing T_i can further reduce the values of t_s and M_p. However, at the same time, it leads to large jitters in the rise time of the step response test, which impairs the stability of the HAGC system.

3.2 Improvement of the Step Response Test

The simulation results of the model with a PID link indicate that the contradiction between the stability and flexibility of the HAGC system cannot be solved by the conventional PID algorithm. This is because the PID parameters of the conventional PID algorithm are constant during the process of the step response test, which cannot be adjusted according to the input and output signals adaptively. In the actual production of steel sheet, because of the interactions of the servo valve, mill cylinder, and sensors in the HAGC system, the step response is a nonlinear time-varying process.

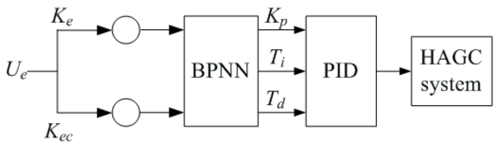

Fig. 6. *The structure of the APID for HAGC system*

As a result, an APID algorithm based on BPNN is proposed. The structure of the APID algorithm is shown in Fig. 6. The error K_e and the error change rate K_{ec} of U_e as the input values of the ANN, and K_p, T_i and T_d as the output values, the BPNN is used to calculate the proper PID parameters by training it with acquired samples.

3.3 Implementation of APID

In recent years, many ANN algorithms have become widely used in both academic research and industrial development. In all ANN algorithms, BPNN is a multi-layer forward-spread network with a minimum mean square deviation learning method. It has been proved that BPNN can map all nonlinear functions with single layers. Therefore, a BPNN is created by using the Neural Networks toolbox in Matlab to implement the APID link of HAGC system. The BPNN is composed of an input layer with 2 neurons (K_e and K_{ec}), a hidden layer with 4 neurons (set in the neural networks toolbox) and an output layer with 3 neurons (K_p, T_i and T_d). The training function is TRAINLM, the adaption learning function is LEARNGDM, and the transfer function is LOGSIG. The samples are collected from the steel sheet production of HAGC system. Table 1 lists 10 sets of the normalized data which are used as the training samples for the built BPNN.

Table 1. *The training samples of the BPNN*

Number	K_e	K_{ec}	K_p	T_i	T_d
1	0.442	0.193	0.056	0.071	0.010
2	0.095	0.794	0.150	0.076	0.093
3	0.119	0.101	0.097	0.070	0.105
4	0.094	0.099	0.620	0.588	0.197
5	0.893	0.545	0.212	0.092	0.081
6	0.792	0.152	0.078	0.063	0.098
7	0.541	0.085	0.038	0.041	0.033
8	0.113	0.125	0.255	0.119	0.100
9	0.867	0.048	0.243	0.008	0.025
10	0.133	0.020	0.135	0.009	0.011

The ability of ANN is generally measured by its mean-squared error (MSE). With the collected data in Table 1, the built BPNN is trained, and the change of the MSE is shown in Fig. 7. It can be seen when the training MSE goal is 0.01; the training times are no more than 500, which indicates that the proposed BPNN is convergent for APID control.

After the BPNN is trained, it can be used to calculate the APID parameters with current values of K_e and K_{ec}. The step response test of HAGC with the APID controller is simulated again by inputting the same values in the conventional PID controller (K_e = 0.326, K_{ec} = 0.247), and the result is shown as the red dashed curve in Fig. 5. In comparing the green solid curve (PID) and the red dash curve (APID), it is obvious that by using the APID algorithm, the step response can not only reach the process requirements of the HAGC, but also eliminate the jitter at the start-up phase, which means the HAGC system has better stability and flexibility with the improved model.

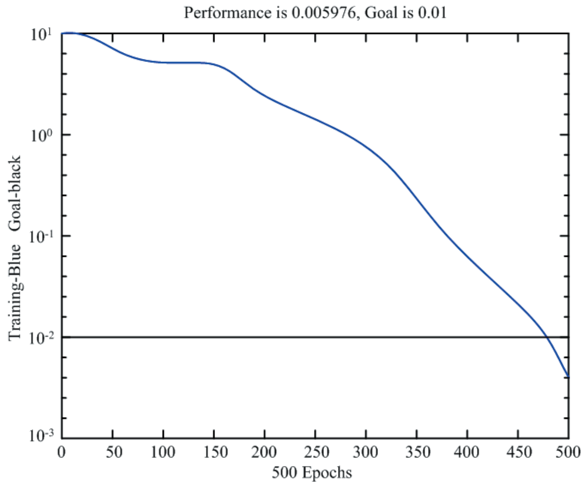

Fig. 7. *The training result of the BPNN*

4 EXPERIMENTAL RESULTS

In order to verify the established step response test model in Section 2 and Section 3, experiments were done with the designed HAGC system of the mill servo cylinder, as shown in Fig. 8. The type of the mill cylinder is C1450-P20N000, the piston rod diameter is 1450 mm, and the stroke length is 10 mm. The embedded computer servo controller receives the acquired signals from the sensors and the servo valves, and sends the calculated results to the HAGC system. The APID algorithm is programmed with Visual C++ and loaded into the HAGC controller. To test step response ability of the HAGC system, the standard step input signals were sent through the HAGC controller, as shown in Fig. 9a. The step response models without PID link, with conventional PID link and with APID link were tested, and the experimental results were shown on the HAGC controller screen, as shown in Fig. 9b. By comparing Fig. 5 and Fig. 9b, it can be determined that there is good agreement between the simulated and the experimental results.

Fig. 8. *The HAGC system*

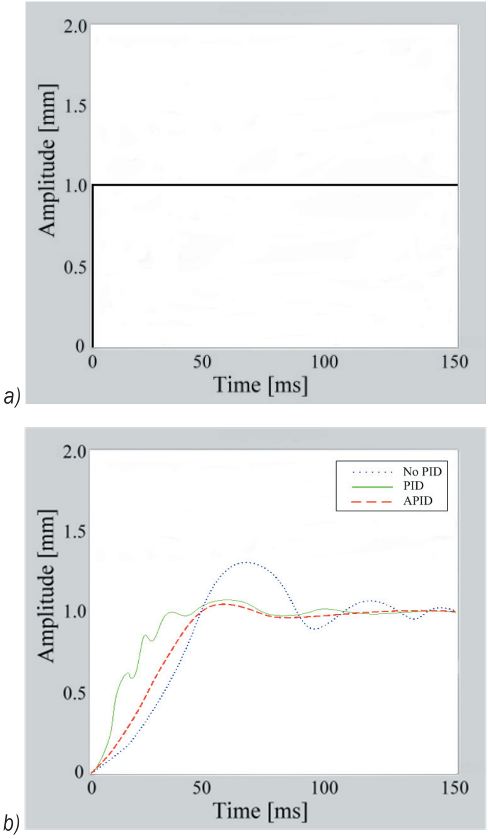

Fig. 9. *The experimental results;*
a) Input signal, b) Step response signals

By using the APID algorithm and conventional PID algorithm, the change of the steel sheet thickness within 100 ms is measured, as shown in Fig. 10. It can be seen that the thickness change in the step response test of HAGC with APID is no more than 0.06 mm, and the surface irregularity has a decreased trend as time passed. The thickness change with conventional PID is about 0.30 mm, far above the value of APID. Consequently, the improved step response test model by using APID link can reduce the settling time and the overshoot, and thus enhance the surface quality of steel sheet in the HAGC system. This indicates the improved step response model is valid, and the experimental results are consistent with the simulated results.

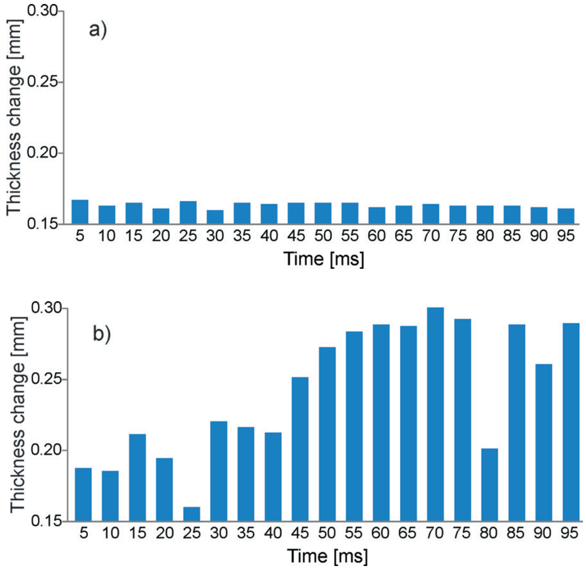

Fig. 10. *The measured thickness change of steel sheet; a) with APID, b) with conventional PID*

5 CONCLUSIONS

In the process of the step response test of HAGC, it is difficult to balance the stability and the flexibility of the system. To improve the control performance of the system, the approach of adding proper link to compensate for the input signal is valid. By adding a PID link, the settling time, and the overshoot can be reduced. However, the conventional PID algorithm also leads to jitters of HAGC at start-up phase. In this paper, based on the established step response test model, the APID link by using BPNN is proposed to improve steel sheet quality. The simulated and experimental results show that the designed step response model with the APID link is useful for overcoming jitters, reducing overshoot and settling time, and accelerating the dynamic response of the HAGC system. Further research to analyse the step response influence of the other components in HAGC systems, such as hydraulic pipes and hydraulic pumps, should be carried out.

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