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Optimization control for the looper's height on continuous pickling titanium plates and strips by microwave heating

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Abstract. Optimal control for design of fuzzy logic controller for by tuning traditional PID parameters-based control strategy was proposed to control the looper's height on continuous pickling titanium plates and strips with an instability and random noise process. The parameters relations between fuzzy controller and PID controller are deeply analyzed. Then the whole output of the fuzzy controller which consists of two sub-controllers, the PI controller and the PD controller is designed using parameters of PID controller tuned by Ziegler-Nichols method. The fuzzy controller is compared with traditional PID by simulation and real engineering application. The results indicate that the dynamic control performances of the looper's height are much better by using fuzzy control strategy. The fuzzy controller is not only the designed simplify, but also the strong effectiveness and feasibility.

1. Introduction
Titanium and its alloy is widely used in aerospace, chemicals, petroleum, metallurgy, shipping, health and daily life due to much properties such as high strength, corrosion-resistant and non-magnetic and so on. Titanium plates and strips are of a very wide range of applications, such as heat exchangers, reaction, synthesizers, and autoclave and titanium tubes and other higher-value products [1]. Titanium and titanium alloy is oxidized in air when heated up 250 °C, which is easily absorbed the elements such as C, O, H, N. Many production processes must be adopted under the blooming mill and finishing from titanium ingots titanium plates and strips. Taking into account the cost of production and operation during the processing, A certain amount of titanium oxide will be produced on the surface of titanium plates and strips due to it is hard to machining in vacuum or protective atmosphere. In order to improve product quality, titanium oxide layer on the surface of the titanium plates and strips are removed through mechanical or chemical methods. Currently oxides and titanium plate surface substrate absorption of harmful substances are remove by used abrasive blasting (or blast) & the pickling process for continuous production process [2].

The continuous pickling of titanium plates and strips is the important part of continuous production of titanium plates and strips by forms of titanium reels, which are far superior to veneer production process technology from many ways such as product quality, production efficiency, energy saving and environmental protection [3]. In continuous pickling, loopers, in ensuring product quality titanium, avoid pulling or pushing titanium band plays a big role, are the entire focus of pickling control. Meanwhile, the looper control is the challenge aspect in the whole automatic control of continuous
pickling as the motor current and torque are time-varying parameters in the looper control system, the amount of looper and the speed, tension of the upper and lower racks strong coupling, and the dynamic response of the looper in the continuous pickling process of titanium plates and strip very high.

2. Looper's height control principle and scheme

Looper's height is closely related to main transmission speed of the upper and lower racks in the titanium Strip continuous pickling. Looper's height control is compared to the actual set point with a given set of corners detected by the encoder. If the actual set angle is greater than a given set point, then the speed of the upper racks is greater than on the rack rate, or tension between racks small. Similarly the speed \( i \) rack is faster than \( i+1 \) if the amount of looper rise with constant tension. The speed of the upper hosting rack will be reduced in order to maintain the same amount of the looper’s height, and to ensure the flow-rate of the titanium plates and strips between the racks to be equal [4,5].

2.1. Looper system model

As Figure 1(a) Shown, the looper’s shape can be approximated by with an arc of a circle [6]. Set looper arc length as \( L \), Its horizontal projection, an effective length of the looper table \( L_0 \), and another set the distance between of the bottom side of the pressing sleeve roller and the top of the height of the looper, \( H \).

\[
\sin \alpha = \frac{L_0/2}{R} = \frac{L_0 \cdot H}{(L_0/2)^2 + H^2}
\]

So, the arc length is expressed as follow:

\[
L = R \cdot 2 \alpha = \frac{(L_0/2)^2 + H^2}{H} \cdot \arcsin \left( \frac{H \cdot L_0}{(L_0/2)^2 + H^2} \right)
\]

Set the looper's length allowance is \( \Delta L = L - L_0 \), it can be obtained that the inverse sine function is approximated by Taylor series expansions of three order:

\[
\Delta L = \frac{c}{L_0} \cdot H^2
\]

So, The function of the looper can transform the increases or decreases of the looper's length of the titanium plates and strips, \( \Delta L \) in the between two exit pressing sleeve roller on continuous pickling production lines into the raise or lower of the looper's height, \( H \) through looper's height is controlled around the set value, to ensure the flow-rate of the titanium plates and strips between the racks to be equal. Equation (3) is justified as a representation of relationships between looper dynamic gain, \( \frac{dH}{dS} \) and the looper's height, \( H \). As shown in Fig.1(b), the horizontal axis is the ratio of the looper's height, \( H \) relative to the effective length of looper table, \( L_0 \). Set the effective length of looper table, \( L_0 = 1350 \text{mm} \), the looper's height ranging between 100 mm and 400 mm. namely, \( H/L_0 \in [0.07, 0.30] \). According to Fig.1(b), the dynamic gain ranges between 0.6 and 2.5, namely, more than 4 Times. From (3), it shows that the titanium plates and strips, looper's height and its length increments is second-order relationship, it also means that equation (13) as a looper's height model is feasible.

Specific to looper control systems, traditional PI controller or PID controller has the following disadvantages: (1) It is difficult to tune parameters accurately and rapidly. Due to the establishment of precise mathematical
model is very difficult [7], the traditional controller parameter cannot be calculated in advance, only have to try and modify continually. Proportion factor, $K_p$, integral time, $T_i$, derivative time, $T_d$ is tuned badly, it will be appeared that the looper will swing instability or the dynamic response will be too slower. (2) The looper's height, $H$ and motor current and torque, tension, and hosting racks of upper and lower are strongly coupling [8]. $K_p, T_i, T_d$ is tuned improperly, and then the performance cannot meet the technical requirements. Therefore, the fuzzy control must be considered because fuzzy logic controller has the following advantages: (1) Do not need to establish precise mathematical models and easy to be realized. (2) The fuzzy controller is ideal one for non-linear controlled process. (3) For the strong-coupling tuned system, it has a better robustness [9].

3. Fuzzy controller design and control

3.1. Fuzzy controller

Titanium plates and strips continuous pickling looper's height, $H$ control to a certain set of looper's height as a benchmark, when the parameter changes in the pickling process, cause exports a rack in the upper and lower rack inlet speed ranges, the integral of velocity difference between the racks. When an error occurs, to adjust the main motor speed of the upper rack is to maintain constant looper [10]. The fuzzy controller is introduced to control looper's height when the amount of deviation is bigger, while the switch to PID control to reduce the loop just put into the dynamic adjustment processes when the amount of deviation is less than a certain threshold value in order to improve control precision in the steady-state.

In actual control, due to the sampling period is very short, it is impossible to complete in a short time fuzzy inference and defuzzification work. Method of using fuzzy control table is adopted in the literature [11, 12], making use of offline design of fuzzy controllers, getting an input output on the domain to the domain of query tables, which is lack of flexibility in the application. Method of using neural networks is selected in the literature [13, 14], requiring a lot of data with network training, but also for solution of complicated coupling calculation, which is inadequacy in applying continuous practice to pickling plates and strips. The structures of conventional fuzzy control is analyzed deeply, and inspired in the literature [15], by analysis of the relationships between fuzzy controller and PID control parameters, so as to simplify the complexity of the design of fuzzy controller, reducing the fuzzy controller design of expert dependency.

The input of the fuzzy controller is looper's height deviation, $e$ and its change rate, $\Delta e$, and the output the setting speed value of the upper pressing sleeve roller. The fuzzy controller consists of two sub-controllers, PI and PD type fuzzy controller. The output of fuzzy controller is the superposition of the two sub-controllers. The benefits of this design are that there are $7^2 = 49$ fuzzy rules when the two input values is chosen, which are far less the rule amount, $7^3 = 343$ of three PID parameters. Additional one input making calculating the amount of complexity is greatly increased. To sum up, this control structure as shown in Fig. 2 as below.

![Figure 2. Block diagram of control structure.](image-url)

The fuzzy controller in the loop $\text{II}$, two sub-controllers are designed with two inputs and one output. Assuming each input variable has two fuzzy values, namely, "positive" and "negative", and output variables three fuzzy values, namely, "positive", "negative" and "zero". The membership function of the fuzzy set “input” and “output” variable is shown in Fig. 3.

There are four linear fuzzy control rules used in the PI and PD fuzzy logic controller in this study:

(1) F-PI:
If $e$ is N and $\Delta e$ is N then $\Delta u_{\text{F-PI}}$ is N
If $e$ is N and $\Delta e$ is P then $\Delta u_{\text{F-PI}}$ is Z
If \( e \) is N and \( \Delta e \) is P then \( \Delta u^{{F.PI}} \) is Z.

If \( e \) is N and \( \Delta e \) is P then \( \Delta u^{{F.PI}} \) is Z.

\[ \text{membership} \]

\[ \text{membership} \]

\[ \text{Figure 3. The input/incremental output of the fuzzy controller, scaled error and rate change of error.} \]

(2) F-PD:

If \( e \) is N and \( \Delta e \) is N then \( \Delta u^{{F.PI}} \) is N

If \( e \) is N and \( \Delta e \) is P then \( \Delta u^{{F.PI}} \) is Z

If \( e \) is N and \( \Delta e \) is P then \( \Delta u^{{F.PI}} \) is Z

The fuzzy set "error" has two members, P (denotes error positive) and N (denotes error negative); and the fuzzy set "rate" has two members, P (denotes error positive) and N (denotes error negative). The fuzzy set "output" has three members, P (denotes error positive), Z (denote out zero) and N (denotes error negative).

Assuming the parameter, \( L = 1 \) in the Fig. 2, then the increment expression of the PI-fuzzy controller outputs is [15]

\[ \Delta U_{F.PI}(k) = \frac{K_{PI}}{4 - 2x(k)} \left[ K_e e(k) + K_{de} \Delta e(k) \right] \]

where

\[ e(k) = y_{sp} - y(k), \quad \Delta e(k) = e(k) - e(k-1) \]

\[ 0 \leq x(k) = \max(K_e \cdot |e(k)|, K_{de} \cdot |\Delta e(k)|) \leq 1. \]

Similarly, the increment expression of the PD-fuzzy controller outputs is

\[ \Delta U_{F.PD}(k) = \frac{K_{PD}}{4 - 2x(k)} \left[ K_e e(k) + K_{de} \Delta e(k) \right] - \frac{K_{PD}}{4 - 2x(k)} \left[ K_e e(k-1) + K_{de} \Delta e(k-1) \right] \]

To sum up, the increment expression of the fuzzy controller outputs is

\[ \Delta U_{F.PD}(k) = \Delta U_{F.PI}(k) + \Delta U_{F.PD}(k) = K_{P}^0(k)e(k) + K_{P}^1(k)e(k-1) + K_{P}^2(k)e(k-2) \]

where

\[ K_{P}^0(k) = \frac{K_{PI} \cdot K_e + K_{PI} \cdot K_{de} + K_{PD} \cdot K_e + K_{PD} \cdot K_{de}}{4 - 2x(k)} \]

\[ K_{P}^1(k) = \left[ \frac{K_{PI} \cdot K_e + K_{PD} \cdot K_{de} + K_{PD} \cdot K_e + K_{PD} \cdot K_{de}}{4 - 2x(k)} \right] \]

\[ K_{P}^2(k) = \frac{K_{PD} \cdot K_{de}}{4 - 2x(k-1)} \]

The increment output expression of the standard discrete PID controller is

\[ \Delta U_{PID}(k) = K_{c} e(k) + K_{c}^1 e(k-1) + K_{c}^2 e(k-2) \]

where

\[ K_{c}^0 = K_c + K_{s} \cdot T_s / T_r + K_{s} \cdot T_s / T_r ; K_{c}^1 = \frac{1}{T_r} ; K_{c}^2 = K_c \cdot T_s / T_r \]

Equations (6) and (8) can be showed that during steady-state operation, namely \( x(k) = 0 \) in the equations (7), (8) and (9) and fuzzy controller of coefficients, \( K_{P}^0(k) \), \( K_{P}^1(k) \), \( K_{P}^2(k) \) as constants in them, respectively, expressed as a constant \( K_{P}^0(\infty), K_{P}^1(\infty), K_{P}^2(\infty) \). Obviously, the fuzzy controller degenerates into linear PID controllers at this present moment, whereas during the dynamic period, the fuzzy controller dynamic is of stronger robustness.
3.2. Fuzzy logic control strategy

The proposed fuzzy logic control strategy is based on the double loops illustrated in Fig. 2. The fuzzy logic control strategy is as follows:

(i) Specify the initial inputs and evaluate. Set \( \tau = 0 \) and while \( \tau = 1 \), do

(ii) Designed with traditional methods of titanium plates and strips continuous pickling looper's height PID controller. Designing traditional PID controllers, and Ziegler-Nichols method of adjusted PID controller parameters respectively PID controller the proportional gain, \( K_p \), integral gain, \( K_i \), and differential gain \( K_d \).

And (10) is calculated PID controller's coefficients \( K_c^0(k) \), \( K_c^1(k) \), \( K_c^2(k) \).

(iii) Establishment of fuzzy adaptive PID control model. According to the accuracy range of the curve of the transition process (usually 2% or 5%) fuzzy controller parameters within, you make fuzzy controller with (i) the PID controller’s corresponding coefficients are equal, that is,

\[
K_c^0(\infty) = K_c^0; K_c^1(\infty) = K_c^1; K_c^2(\infty) = K_c^2 \tag{12}
\]

Meanwhile, taking into account the input variables \( e \times \Delta e \) should as far as possible in the areas \([-1, 1] \times [-1, 1] \), therefore, to select the parameter, \( K_c \) will be should meet

\[
(y_p - y_0) \times K_c = 1 \tag{13}
\]

In this way, simultaneous equations (12) and (13), fuzzy controller parameters, \( K_c, K_d, K_p, K_pd \) will be obtained, and set \( \tau = \tau + 1 \).

(iv) Adaptive, real-time control. According to the closed-loop system response curves to fine-tune a fuzzy controller with four parameters in order to achieve the desired performance. According to overshoot again \( K_c^0(k) \), \( K_c^1(k) \), \( K_c^2(k) \), adjust until satisfaction. If the error range of looper’s height go to (v), else go to (ii).

(v) Maintain the previous fuzzy PID controller parameters does not change the value:

- if \( |e| > 0.75e_0 \), then \( \Delta u = \Delta u_{F-PID} \), and go to (vi), or
- if \( |e| > 0.25e_0 \), then \( \Delta u = \Delta u_{PID} \), and go to (vi).

(vi) Accept the \( \Delta u \) and terminate

4. Fuzzy controller design and control

4.1. Computer simulation results

In this paper MATLAB Environment, the actual parameters, looper's height control system of the continuous pickling plates and strips in the Yunnan Titanium Industrial Corporation is used, it approximates transfer function of controlled objects derived as following:

\[
G(s) = \frac{0.58}{0.048s + (0.036s + 1)} \tag{14}
\]

In fact, the continuous pickling plates and strips is unstable systems, at the same time, often accompanied by a variety of disturbances in the pickling process. The fuzzy controller is designed using Fuzzy Logic Toolbox. The simulation experiments are done to control the looper’s height using step signals by fuzzy controller by comparison with the conventional PID controller. The initial value, \( y_p = 0 \), and looper's height setting \( y_p = 1 \). With traditional PID design methods, control the parameter value as follows: proportional gain, \( K_p = 5.46 \), the integral time, \( T_i = 86 \), the derivative time, \( T_d = 4 \). Then calculates the parameters in equation (11), \( K_c^0(k) \), \( K_c^1(k) \), \( K_c^2(k) \). To make it equal to steady state in equation (6) fuzzy controller parameters, \( K_c^0(\infty) \), \( K_c^1(\infty) \), \( K_c^2(\infty) \), again combined (13), the fuzzy control of parameter values can be obtained for \( K_c = 1 \), \( K_d = 0.5975 \), \( K_p = 1.3509 \), \( K_pd = 24.015 \). Sampling time is 1 ms, and random noise with an amplitude for \( \delta = \pm 3.0 \) is added by accompanied at each sampling point in time the system. The closed-loop response results are shown as in Fig. 4-6 using PID control and fuzzy control simulation.

From Fig. 4 can be seen, conventional PID controller is unable to control the random noise, unstable systems. Fig. 5 shows that Fuzzy control algorithm for constantly adjusting the system error, fuzzy controller for the plates and strips continuous pickling of titanium looper's height with unstable system with random noise, and
error control of looper's height below 5%, to achieve better results. Fig. 6 shows that if the system is noise-free system, better performance can be arrived, and better control effect can be obtained.

![Figure 4. PID control for random noise and unstable process.](image)

![Figure 5. Fuzzy control for noise-free and unstable process.](image)

4.2. Results for industrial applications

During the project implementation of fuzzy controller is run, the continuity of the pickling titanium plates and strips is improved. Fig. 7 is the industrial application of the continuous pickling titanium plates and strips. The continuity of pickling (continuous pickling titanium plates and strips direct value is 120 million RMB) and the efficiency of the pickling (compared with in the deep grooves to be improved. The under or over pickling of the titanium plates and strips is avoided successfully (the first time of the pickling rate of up to 15%).
5. Conclusion

Fuzzy controller designed can significantly improve the dynamic performance of looper's height control. The process with random noise, unstable systems, conventional PID controller cannot do, while the fuzzy controller can do perfectly. Moreover, the design of fuzzy controller has not only precision and real-time control, but also with greater effectiveness and adaptability.

Figure 6. Fuzzy control for noise-free and unstable process.

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