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# Optimization and Design of Compound Fuzzy Control for Hydraulic Bending Roll System

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**Abstract:** The flatness control system is a long time-delay, on-linear, coupled multivariate system with variable parameters. Based on the system features, genetic algorithms which possesses parallel search ability synchronously optimize the fuzzy controller parameters based on combinative coding of membership functions, quantization factors and scale factor. This optimized operation can effectively avoid the difficulties of manual adjustment. Due to its membership functions' symmetrical feature which makes search space is in half. Then combine the optimized fuzzy controller with PID controller to achieve the fuzzy PID parallel control. At the same time it also effectively control the output pressure that comes from hydraulic bending roll-control system. A simulation test shows that the controller not only has high control precision but also has good stability as same as PID.

**Keywords:** flatness control, genetic algorithms, Fuzzy-PID parallel control

## 1. Introduction

With the increasing demand for improving the control quality and product accuracy in hot strip mill, the flatness and profile control have become an important issue in the steel industry. Hydraulic bending roller control system is one of the important approaches to strip flatness control. It has the advantages of quick response, rapid adjustment plate crown in the process of rolling. Hydraulic roll-bending force needs to be adjusted according to the actual ingot situation in real-time control. So rapid adjustment is essential in the hydraulic flatness control system and directly determines the accuracy and anti-interference capability. The steel enterprises mainly introduce control strategies of the traditional PID, but as such strip flatness is affected by roll-bending force, rolling force, the initial roll contour, roll wear and other complex factors. So flatness control system is a long time-delay, non-linear, coupled multivariate system with variable parameters. Conventional PID control capability is difficult to meet the requirements of high-precision control of flatness. Conventional fuzzy control algorithm can improve significantly dynamic response. However, control quality is not good in steady state [1]. To further improve the dynamic response and reduce the steady-state errors, this article optimize fuzzy controller's parameters, membership functions, quantization factors and the scale factors, with genetic algorithms-intelligent optimization algorithms. In addition a new method which combines fuzzy logic control with the traditional PID is used in the hydraulic bending roll system.

Fuzzy theory was firstly applied to the coolant zone control of the rolls by spraying cooling water for the shape control [2]. Since 1995, Jong-YeobJung et al. deeply research on flatness control progress of the general six roll mill. They explore feasibility about the use of fuzzy logic control and research the dynamic and static control properties of symmetric strip flatness. Later, They studied the control of arbitrary irregular strip shape and had made substantial progress[3),4)].

## 2. Hydraulic bending force flatness control system

Hydraulic bending force flatness control system mainly achieves performance through control of rolling deflection and thermal crown. Hydraulic cylinder produce hydraulic roll-bending force which act to work rollers or support rollers' neck to instantly changes roll effective deflection in hydraulic bending force control system. Thereby in control process of hydraulic bending roll, adjusting hydraulic roll-bending force can effectively regulate

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the profile of roll gap. So the bending roll force under specific conditions can be improved to change strip flatness. While this system is electro-hydraulic control system with high precision, quick response, etc. Therefore, the application is very extensive. Electro-hydraulic servo bending force control system consists of controller, V/I transformer, servo valve, hydraulic cylinder and pressure sensor [5),6)] as shown in **Fig. 1**.

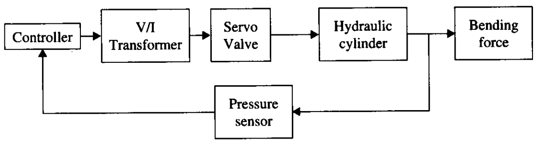


**Fig. 1** Electro-hydraulic servo bending force control system.

The manners of bending roll control have experienced process development from manual mode to the automatic mode. Manual methods, namely: selecting bending roll force value, the pre-set value, according to past experience before hot strip mill work. After the rolling process, according to condition of the wave shape correspond to decrease or increase bending roll force. This means simply rely on manual adjustment, the quality of flatness control is difficult to meet demand for high precision. To overcome the shortcomings of manual mode, control method that open-loop and closed-loop mode were applied. Open-loop control realizes strip flatness feedforward control based on rolling force. This method is that setting bending force value by the best mathematical models of bending roll or by the look-up table accumulated with experience. In the rolling process, bending roll force is adjusted in real-time control according to fluctuations of rolling force. Closed-loop control system is feedback control which based on flatness measurement equipment for the detection of the shape signal. Then deviation which shape signal compares with shape precision produce is regressed as polynomial which corresponds to the relevant shape regulatory machine's adjustable parameters[7)].

## 3. Genetic fuzzy logic controller

Fuzzy sets and fuzzy control concept were firstly proposed by L.A.Zadeh [8)]. Mamdani[9)] conducted the research on fuzzy control in 1974, based on the motive of Zadehs work on fuzzy algorithm and linguistic analysis. FLC is an expert system based on fuzzy rules, has the virtue of treating ambiguous or vague aspects of human perception and judgment, with which a non-fuzzy expert system normally cannot deal. Logic rules, membership functions and quantization and scale factors are key components of a fuzzy logic controller (FLC). Not only we need to construct good logic rules, but also establish reasonable membership functions, quantization factors and scale factors. Fuzzy membership function set is a very important aspect. It is the basis of quantitatively analyzes vague attributes of FLC. But the components are set subjectively may reduce the applicability of FLC and can't meet the global optimum of system. Quantization factors make the error and variable rate of error transform from basic domain to fuzzy domain and the scale factor is contrary to make the controller's output value transform from fuzzy sets to basic domain, while these factors are related to the distribution of the membership functions and the rule base. But three factors are difficult by manual adjustment[10)].

GA (genetic algorithms)[11)] is a search algorithm that simulates biology's genetic and evolution characteristic in nature environment. Simultaneously GA has an excellent adaptive probability in the process of global optimization and has been proven suitable for solving both composite optimization and parameter optimization problems. The GA process chart is shown in **Fig. 2**. The algorithms have become a standard for designing fuzzy logic controllers. Employing GA to construct a FLC system with learning process from examples, not only can avoid the bias caused by subjective settings of logic rules and membership functions but also can greatly enhance the control performance. This paper proposes that using genetic algorithm optimize membership functions' parameters, quantization factors and scale factor for fuzzy logic controller without subjectively presetting these parameters. To overcome the shortcoming that parameters selected are based on experience, while avoiding the trouble of manual adjustment. In addition, this controller's designing scheme are that constructing FLC and PID concurrent controller. The fuzzy logic controller is as same as conventional fuzzy controller in coupled fuzzy-PID concurrent control system; however, it does not replace the PID linear controller. PID linear controller and fuzzy controller calculate the process time of hydraulic bending roller system. Then the final controller output is decided by the calculation **Eq. 4**. The results show that the optimized and improved controller enhances the controlling precision and dynamic response speed of hydraulic bending roll control system.

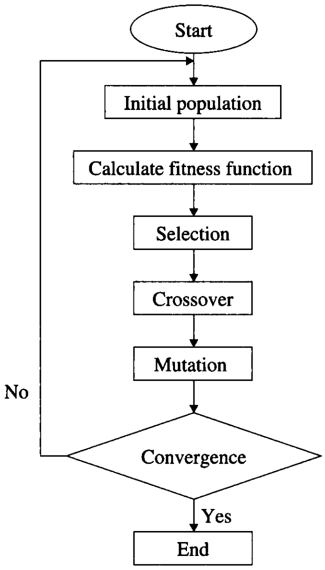


**Fig. 2** Process chart of genetic algorithms.

## 3.1 Encoding method for membership functions, quantization factors and scale factor

Chromosome encoding manners include real number coding, binary coding and combinative coding, and so on. This paper employs binary coding with strong search capability for selecting membership function parameters, quantization factors and scale factor. Every parameters optimized is composed of binary coding with the length of 10 bit. The input variables contain error $e$ and variable rate of error $e_c$, one output variable $u$. Take three variables as an example. Each variable has seven linguistic degrees (negative big (NB), negative (NM), negative small (NS), 0 (ZE), positive small (PS), positive medium (PM), positive big (PB)). To simplify the calculation, according to symmetrical features of fuzzy controller membership function, setting $\alpha_i, \beta_i, \gamma_i (i = 1, 2, 3)$ separately stand for the right center of three linguistic variable's membership function, which can completely denote the shape and position of membership function (as shown in **Fig. 3**).The number of every membership function parameters optimized is three. Then the number of membership function parameters of three linguistic variables is nine. Additional constraints are imposed:

$0 \le \alpha_1, \beta_1 \le 3, \quad 2 \le \alpha_2, \beta_2 \le 5,$
$4 \le \alpha_3, \beta_3 \le 7, \quad 0 \le \gamma_1 \le 3$
$2.5 \le \gamma_2 \le 5.5 \quad 5 \le \gamma_3 \le 8$

In addition, the number of quantization factors and scale factor is three. So 12 parameters will be optimized and the total length of chromosome chain is 120 bit.

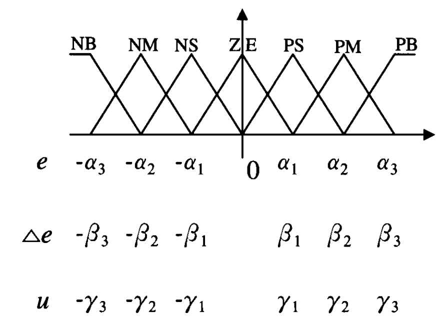


**Fig. 3** The membership function of variables.

## 3.2 Initial population

The GA starts from a population of chromosomes as a set of initial designs. The initial population is chosen randomly. The each bit of chromosomes is set randomly 0 or 1. Population size (the total number of chromosomes in the population) is very important in order to select the global optimum solution. Population size is set as 80 in this paper.

## 3.3 Selection fitness function

The GA uses a fitness function value that is the criterion of selecting populations to evaluate the merits of populations. According as the characteristic of dynamic response in control system, this paper sets ITAE performance index as the fitness function. ITAE value means higher degrees of the population adapt to the living environment[12].

$$ITAE = \int_0^\infty t\,|e(t)|dt \qquad (1)$$

If we only use ITAE as a performance index, the steady-state performance cannot be promised. Therefore we modify ITAE as:

$$ITAE = \int_0^\infty (w_1 t\,|e(t)| + w_2 u^2(t))dt \qquad (2)$$

u(t) is output value of controller.

### 3.4 Genetic operation

Genetic operation includes that both crossover and mutation. The crossover operation simulates the reproduction process of biological evolution. If a random number generated between 0 and 1 in program is less than the populations' crossover probability. Then select the parents for crossover generate two offspring. In order to maintain variability of population, mutation operation is also performed on certain individuals. Mutation operation is performed on a bit-by bit basis, which makes each bit change. The motive of variation is that maintain the diversity of individuals in groups and overcome limitation that developing local optimal solutions. If the random number between 0 and 1 is less than the probability of mutation, then the bit under consideration will be switched. This paper sets crossover probability $P_c$ as 0.7 and mutation probability $P_m$ as

$$P_m = 0.1 - i \times 0.01/80(\mathrm{i} = 1, 2 \cdots 80) \tag{3}$$

$P_m$ introduce the method of adaptive mutation probability.

Through the process of above operation, fuzzy controller's input and output variable's membership functions are optimized by the genetic algorithm . as shown in **Fig. 4,5**.

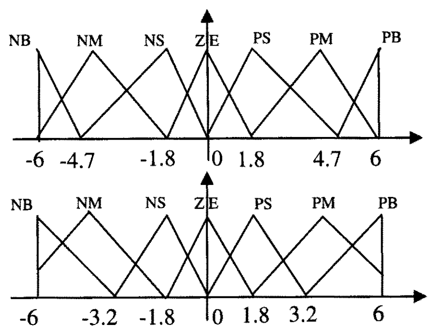


**Fig. 4** The input variables' membership function.

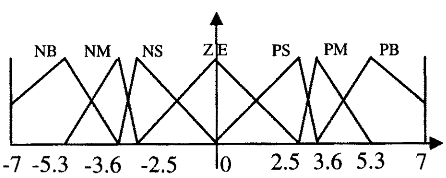


**Fig. 5** The output variable's membership function.

### 3.5 Design of Fuzzy-PID parallel controller

The control principle of Fuzzy-PID parallel controller optimized by GA as illustrated in **Fig. 6**. This paper introduces the way of parallel control, which mixes fuzzy logic controller optimized with GA and PID controller. Simultaneously the parallel control apply to hydraulic bending roller system. Both controllers' outputs commonly control the controlled object. Because the classic fuzzy logic controller has the outstanding dynamic performance characteristics and the PID has the advantage of the accurate steady-state performance. Fuzzy-PID parallel controller makes use of the virtue of the classic fuzzy and PID completely. The total output formula of controller as follow:

$$u = (1 - \alpha)u_1 + \alpha u_2 \tag{4}$$

$u_1$and $u_2$ stand for output of fuzzy controller and PID respectively. $\alpha$ is parallel factor of the fuzzy-PID controller. In accordance with the different time of control process, the effects of fuzzy logic controller and PID are also different. During entire control process, the $\alpha$ value is determined by the time (**Table 1**). Different process time shows different control weights of fuzzy controller and PID. Because the measured data are transferred to the fuzzy control algorithm and PID linear controller at the same time, they calculate output values at same iteration without time-delay. When the bending roll control meets quick response characteristic as soon as possible, the coordination factor in **Eq. 4** is close to 0 and then the final bending forces are mainly decided by the fuzzy control algorithm. If the flatness error is close to the desired data, the control system should pay more attention to avoid overshoot and guarantee steady control accuracy, so the coordination factor in **Eq. 4** is close to 1, PID linear control mainly decides the bending force. This design of controller effectively overcome disturbance that the fuzzy and PID switch and make response curve smoother.

In this study, fuzzy control rules for hydraulic bending roller control system were introduced to determine output of FLC based on the values of $e$ and $e_c$ , as shown in **Table 2**.

During the simulation process in MATLAB, Mamdani's minimum operation method and center of area method were used for fuzzy inference and defuzzification.

**Table 1** The value of parallel factor.

| Time(t/ms) | $\alpha$ |
|---|---|
| t≤5 | 0 |
| 5<t≤20 | 0.1 |
| 20<t≤50 | 0.5 |
| 50<t≤70 | 0.8 |
| t>70 | 1 |

**Table 2** Fuzzy control rules of FLC.

| $u$ | $e$ | | | | | | |
|---|---|---|---|---|---|---|---|
| $e_c$ | NB | NM | NS | O | PS | PM | PB |
| NB | NB | NB | NB | NB | NM | NM | NS |
| NM | NB | NB | NB | NM | NS | O | O |
| NS | NB | NB | NM | NS | O | O | O |
| O | NB | NM | NS | O | PS | PM | PB |
| PS | O | O | O | PS | PS | PB | PB |
| PM | O | O | PS | PM | PM | PB | PB |
| PB | PS | PM | PB | PB | PB | PB | PB |

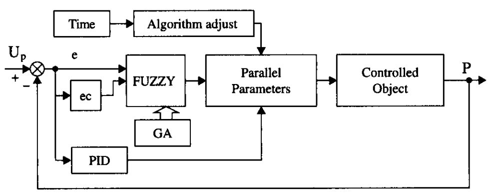


**Fig. 6** Fuzzy logic parallel controller optimized by GA.

## 4. System Simulation

According to the **reference [6]**, the model about electro-hydraulic servo pressure control system(mentioned as **Fig. 7**), dynamic characteristic of the system was analyzed in both frequency field and time field. While some suggestions were given to improve this system.

Fuzzy PID controller optimized by GA and the controlled object are simulated in MATLAB program. The input value is Step signal. The simulation figure of PID control and fuzzy-PID parallel control is showed as **Fig. 8**.

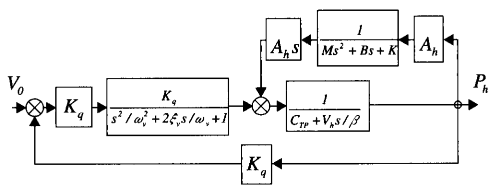


**Fig. 7** Design of hydraulic servo control system.

**Fig. 8** shows the simulation results by using fuzzy PID parallel control system and the comparison with data controlled by PID linear system. In the

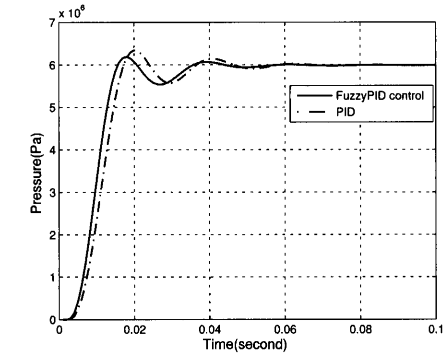


**Fig. 8** Comparison of fuzzy-PID control and conventional PID linear control system.

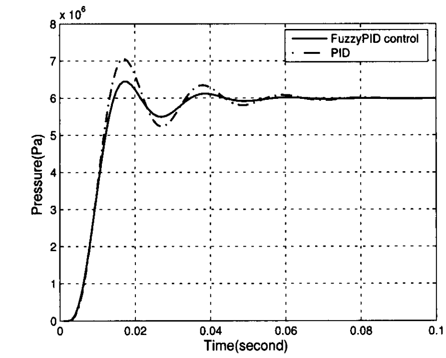


**Fig. 9** Comparison of fuzzy-PID control and conventional PID linear control system when change load's elastic rigidity.

figure, the rise time controlled by parallel controller is about 16ms, overshoot is about 3%. The dynamic performance parameters by using fuzzy control algorithm is better than that by conventional PID. Fuzzy control algorithm is more efficient than PID linear controller. In the steady state error, after 70ms the control process completely is controlled by PID, so the maximum error by the fuzzy PID control algorithm is as same as PID. So the total control process fully utilizes the merit of both controllers. **Figure 9** shows, when load's elastic rigidity K increase to 2 times of the original value, the controlled object changes, then test coupled controller and PID's anti-interference capability and control accuracy. Fuzzy-PID controller's control curve show that the overshoot is about 7 %and steady time is about 60ms. However, PID control overshoot produced more than 17 % and steady time is about 75ms. Meanwhile Fuzzy-PID controller has certain steady-state accuracy as same as PID; Through figures showed that fuzzy PID parallel controller optimized by GA not only retains the merits of the PID which had good static traits but also had other virtues which had high precision and fast response of fuzzy control. On the other hand its adaptability is stronger.

## 5. Conclusion

The flatness control system is a long time-delay, non-linear, coupled multivariable system with variable parameters. Based on the system features, Genetic algorithms use its overall range search capability to optimize the controls parameter of fuzzy controller. This method can avoid the difficulties of manual adjustment and enhance the control precision and dynamic response speed of hydraulic bending roll control system. Two fuzzy flatness control algorithms in hot strip mill were developed, conventional fuzzy control algorithm entirely replacing PID linear control system can improve significantly dynamic response. However, control quality is not good in steady state. The fuzzy-PID parallel controller for hydraulic bending roller control system effectively overcomes the shortcomings of traditional fuzzy control and PID control. The controller has the excellent quick response and good stability at steady state with PID linear controller.

## 6. Acknowledgements

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