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Optimal IMC-PID Controller Incorporating Predictive Functional Control Structure and Disturbance Observer

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***Abstract*: In this paper, a modified internal model control based PID (IMC-PID) control strategy incorporating the structure of predictive functional control (PFC) together with disturbance observer (DOB) is suggested. First, the optimal IMC-PID controller is calculated using particle swarm optimization (PSO) algorithm. Furthermore, combination of PFC and DOB with IMC-PID controller to compensate for the affections of time delay and disturbance not only enhances disturbance rejection ability but also enables the role of predictive control. At that time, the filter time constant of DOB is also determined by PSO algorithm. The predictive output is generated from the structure of PFC and the disturbance estimation is compensated by DOB to the manipulated variable calculated from IMC-PID control. Simulation results on the first order plus dead time (FOPDT) process illustrate the advantages of the proposed control system.**

***Keywords*: Predictive functional control, IMC-PID controller, PSO, Disturbance observer, Time delay.**

1. Introduction

In fact, there are actually time delays in most industrial processes. When common feedback control is applied to a process with time delay, the controller will continuously generate control actions based on the error of controlled variable before time delay, so overshoot may occur or the transient time may be prolonged, and in severe cases the system may oscillate. Time delay produces detrimental affections on the stability and performance of control system and control is generally more difficult unless the delay is compensated [1], [2]. Therefore, controllers with delay compensation should be applied to these processes.

There are several effective control methods for time-delay plants.

IMC has remarkable effect on improving control performance of systems having large time delays [3].

The delay compensation method studied by Smith is very effective in handling time delay and this method has been widely applied in time-delay processes [4], [5].

In [6], an improved parallel cascade control structure combined with Smith predictor for unstable plants having large time delay is studied. This control system has a secondary disturbance rejection controller, a primary stabilizing controller and a primary set-point tracking controller.

A modified Smith predictor is proposed for controlling unstable second order plus time delay processes and is tested focus on the robust disturbance rejection performance [7].

In [8], an improved PI controller design method based on a Smith-like predictor for high order systems.

In [9], the method incorporating fuzzy PID controller and Smith predictor is used to control the temperature of oil supplementing unit. And, a robust control method for time-delay plant using PFC method is described in [10].

In [11], PFC approach is combined with PI or PID controller to enhance the control performance for processes with time delay.

A new PID control system based on extended non-minimal state space predictive functional control is suggested for the control of the chamber pressure in an industrial furnace, which is expressed as a typical MIMO plant [12].

In [13], an improved optimal PI controller combined with predictive functional control is studied.

Using the effectiveness of predictive functional control, a novel PI-PD controller incorporating PFC optimization is proposed [14]. This method not only keeps the advantage of PFC, that is suitable for the process with time delay, but also has the framework of original PI-PD controller.

On the other hand, it is very important to consider the influence of disturbance in controller design. In general, there are two kinds of disturbances, external and internal disturbances.

These disturbances may have negative impact on product quality and closed-loop stability. A lot of superior control strategies, involving MPC, simply remove disturbances through the feedback part and do not reflect them directly in controller design [15]. In the processes where considerable disturbances exist, these control algorithms maybe cause several shortcomings. For example, the set-point tracking may be slower in the feedback control system or the vibrations of the controlled variables may be too severe to ensure the stability of the feedback control system. To eliminate the affection of disturbances, measurements are necessary, which may be very difficult or even impossible. Thus, estimating disturbance by using DOB, which is well-known as an effective technique to

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estimate the disturbance, is a feasible way [16].

In [17], a robust control system based on DOB is presented, and in [18], a MPC algorithm based on DOB is proposed to effectively satisfy the problems of stability of battery system.

In [19], chaos algorithm based LQR control method combined with DOB is studied to optimize the control system.

In [20], a disturbance observer-based sliding control system is suggested to enhance the control effect.

A novel disturbance observer based compensator is proposed and tested for the DC-drive actuators [21]. The application result of this method shows good effectiveness in compensating disturbances.

Meanwhile, people are studying new intelligent algorithms imitating biological and natural phenomena, or continuously improving algorithms to solve a lot of complex requirements in the industrial fields more effectively.

Several kinds of intelligent strategies have been widely introduced for the industrial domain (e.g., pattern recognition, production scheduling, system control, artificial intelligence, etc.). These algorithms are considered as an important part of science, and remarkable successes have been achieved by intelligence optimization strategies.

Appling these intelligent methods in solving several optimization problems has a lot of advantages because of their simple principles, brief applications and extension.

There are many intelligent optimization algorithms, for example, PSO, GA, GWO, ABC, ACO, etc.

In particular, PSO algorithm was suggested in 1995 and has been widely used in the parts of multi-objective optimization, neural network learning, function optimization and fuzzy control systems, etc. This optimization approach has several advantages such as low computational cost, fast convergence, and small number of parameters. However, in spite of these advantages, it has drawbacks on the other side, for example, global convergence is hard to be guaranteed.

In [22], based on the PSO algorithm, a novel evolutionary optimization model which combines the flocking behaviour of a spider is proposed.

In [23], the optimization of the core parameters of support vector machine (SVM) using PSO algorithm is presented.

A new parameter tuning method, which is called PSO with Time-Varying Acceleration Coefficients (PSO-TVAC) is presented [24]. This algorithm has a strong ability to control both global and local search for every iteration process. According to this advantage, it can considerably increase the probability of searching the global optimal value.

In [25], an improved particle swarm optimization algorithm is proposed to identify the parameters of dynamic models according to offline and online method.

In this paper, we design the optimal IMC-PID controller by PSO and combine PFC structure and DOB to effectively compensate the affections of time delay and disturbance existing in the process.

This paper is organized as follows.

In Section 2, the optimal IMC-PID controller design method using PSO is described.

Section 3 describes the controller design method combining PFC structure and DOB with optimal IMC-PID controller.

Section 4 presents numerical simulations and validates the effectiveness through comparative analysis. Section 5 presents conclusions.

2. Optimal IMC-PID Controller Design by PSO

In real industrial processes, it is difficult to obtain the mathematical models of plants accurately, since the input-output relation is usually nonlinear and time-varying, rather than linear. However, in the region that can be considered as linear relation, the step response method is able to be employed to get linear models that reflect the main characteristics of the processes.

We proceed the controller design for the FOPDT model:

$$G(s)=\frac{Ke^{-\tau s}}{Ts+1} \tag{1}$$

In Eq. (1), K is gain, T is time constant of process, and τ is time delay.

According to Pade approximation about $e^{-\tau s}$, the internal model of the process described by Eq. (1) can be written as following.

$$G_p(s)=\frac{K(-0.5\tau s+1)}{(Ts+1)(0.5\tau s+1)} \tag{2}$$

where, $G_p(s)$ is the internal model.

Eq. (2) consists of two items, that is,

$G_{p-}(s)=\frac{K}{(Ts+1)(0.5\tau s+1)}$, which is stable one, and $G_{p+}(s)=-0.5\tau s+1$, which is unstable one.

Therefore, the IMC controller $q(s)$ can be written as following.

$$q(s)=\frac{1}{G_{p-}(s)}F(s) \tag{3}$$

where, $F(s)$ is the filter, the transfer function of which is expressed as following.

$$F(s)=\frac{1}{\lambda s+1} \tag{4}$$

Thus, according to the principle of internal model control, the transfer function of feedback controller can be described as follows.

$$\begin{aligned}G_c(s)&=\frac{q(s)}{1-q(s)G_p(s)}=\frac{(Ts+1)(0.5\tau s+1)}{K(\lambda+0.5\tau)s}=\\&=\frac{T+0.5\tau}{K(\lambda+0.5\tau)}+\frac{1}{K(\lambda+0.5\tau)}\cdot\frac{1}{s}+\frac{0.5T\tau}{K(\lambda+0.5\tau)}\cdot s\end{aligned} \tag{5}$$

From Eq. (5), IMC-based PID parameters can be calculated as follows.

$$K_p = \frac{T+0.5\tau}{K(\lambda+0.5\tau)},\ T_i = T+0.5\tau,\ T_d = \frac{T\tau}{2T+\tau} \tag{6}$$

In Eq. (6), the most important parameter λ represents time constant of filter, and it is determined bigger than 0.8τ. In other words, there is no obvious way to determine λ. A small value of λ improves the response. But, the robustness is deteriorated. Thus, we determine optimal λ by employing PSO algorithm. By doing so, we ensure minimal IAE (integral of absolute error) and proper M_s (maximum sensitivity). IAE and M_s (normally 1.2~2) are defined as the following, respectively.

$$IAE = \int_0^\infty |e(t)|dt \tag{7}$$

$$M_s = \max_\omega |S(j\omega)| = \max_\omega \left| \frac{1}{1+G_c(j\omega)G(j\omega)} \right| = \max_\omega |1-T(j\omega)| \tag{8}$$

Where, M_s can be defined as the inverse of the nearest length from $(-1, j0)$ point to frequency characteristics of the closed-loop system. A larger value of M_s allows the response speed to be faster and a smaller value makes the robustness better.

PSO is well suited to solve such optimization problems. The reason why this algorithm is widely used is that its computation is very simple and optimization objective can be achieved successfully. The speed and position of each particle are updated according to the following equations:

$$v_i^{k+1} = wv_i^k + c_1\zeta_1(pbest_i - x_i^k) + c_2\zeta_2(Gbest - x_i^k) \tag{9}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{10}$$

In Eq. (9) and Eq. (10), v_i^k and x_i^k represent the speed and the position of the particle i at k time instant, respectively. $pbest_i$ and $Gbest$ represent the best solutions of the particle i and the particle swarm. c_1 and c_2 denote acceleration coefficients. These values are determined by the user to 2.0 according to past experience. And the random numbers ζ_1 and ζ_1 are chosen in the range of $[0,1]$. w is called the inertia coefficient, which is given as following.

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{k_{\max}} k \tag{11}$$

In Eq. (11), $k_{\max}$ and k denote the greatest and the present generation numbers. By PSO operation, the optimal λ can be determined, then the optimal K_p, T_i and T_d can be obtained according to Eq. (6).

3. Coupling with Compensating Structures

A. Combining PFC Structure

Predictive functional control has been introduced in the field of mechatronics, metal and chemical processes, and has achieved great successes [26]. It has smaller computational load than the standard MPC, because online optimization is not necessary. In particular, this predictive control algorithm is suitable for time-delay processes, since it can compensate the affection of time delay.

The IMC-PID control system coupled with PFC structure is shown in Fig. 1.

Here, the PFC structure is mixed in the feedback loop and IMC-PID controller optimized by PSO let the plant to follow set-value.

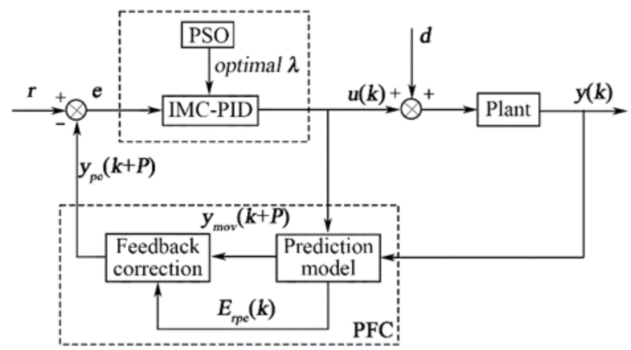

Fig. 1. IMC-PID control system with PFC structure

In this controller, the role of PFC is only to predict the output value. the predictive model is also referred to as FOPDT model.

$$G(s) = \frac{K_m e^{-\tau_m s}}{T_m s + 1} \tag{12}$$

The discrete model of the above equation can be written as the following.

$$y_m(k+1) = b_m y_m(k) + K_m(1-b_m)u(k-L) \tag{13}$$

In Eq. (13), $b_m = e^{(-T_S/T_m)}$, and L is calculated by τ_m / T_s. T_s denotes sampling time.

The control action of PFC algorithm consists of basis functions like step function, which is used in this approach.

$$u(k+j) = u(k),\ j = 1,2,\cdots \tag{14}$$

According to PFC, the predictive output can be expressed by present data together with future control action. If we do not consider time delay, the *P*-step prediction can be obtained as following.

$$y_{mov}(k+1) = b_m y_{mov}(k) + K_m(1-b_m)u(k) \tag{15}$$

$$y_{mov}(k+p) = b_m^P y_{mov}(k) + K_m(1-b_m^P)u(k) \tag{16}$$

In Eq. (16), $y_{mov}(k+P)$ represents output value of the model at time $(k+P)$.

However, if we should consider time delay, predictive output equation has to be modified as follows.

$$y_{rov}(k) = y(k) + y_{mov}(k) - y_{mov}(k-L) \tag{17}$$

In Eq. (17), $y(k)$ and $y_{rov}(k)$ represent the actual and revised value of output in the plant, respectively. Then, error between them is written as following.

$$E_{rpe}(k) = y_{rov}(k) - y_{mov}(k) \tag{18}$$

In order to reduce the affections of disturbance and modeling error, the following feedback correction is necessary for the predicted value calculated by Eq. (16).

$$y_{pc}(k+P) = y_{mov}(k+P) + E_{rpe}(k) \tag{19}$$

$$e = r - y_{pc}(k+P) \tag{20}$$

where, $y_{pc}(k+P)$ and r denote the corrected predicted output and set-point, respectively.

B. Combining DOB

To suppress the influence of disturbance more effectively, we combine DOB with the above controller. The overall control system diagram is shown in Fig. 2.

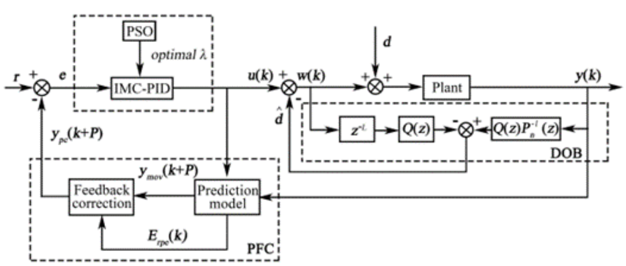

Fig. 2. Proposed control system

As shown in Fig. 2, DOB consists of two components P_n and Q-filter, which should be determined by user. P_n is the nominal transfer function of the plant except for delay, which can be obtained through identification such as step response method. In Fig. 2, $Q(z)$ is the discrete type of low-pass filter.

In DOB, the most important problem is to determine filter $Q(s)$. The filter design consists of two parts: the type of filter and the time constant of the filter.

The relative order of the Q-filter must be equal or greater than the relative order of the nominal transfer function. And, from the physical realization point of view, the order of the filter must be as low as possible, so it is actually assigned to be equal to the relative order of the nominal transfer function.

About the first order plant, the lowest order filter is as following [27].

$$Q(s) = \frac{1}{\sigma s + 1} \tag{21}$$

Good control effect can be achieved by carefully selecting the Q-filter time constant σ. In control system, the magnitude of reflects a tradeoff between the required dynamic range and the measured noise. The larger σ is, the smaller the bandwidth of $Q(s)$ is, and the less robust performance of the closed-loop system is. We use PSO algorithm to obtain the Q-filter time constant σ, where we also use the IAE index as section 2.

$$G(s) = \frac{e^{-300s}}{350s+1} \tag{22}$$

4. Simulation and Discussions

We test the effectiveness of the proposed method on the plant with the following transfer function.

At first, a comparative test with three arbitrarily chosen cases of λ is conducted to analyze effectiveness of the IMC-PID controller with optimal λ by PSO algorithm. T_s is set to 30 to obtain the discrete model. Then, b_m is equal to 0.92, and L is equal to 10. And the PSO parameters are set as follows. That is, particle number is 20, generation number is 10, c_1 and c_2 are equal to 2, $w_{\max}$ is 0.9, $w_{\min}$ is 0.4. Meanwhile, λ is chosen between 0.8τ and 5τ. The set-value is set to 1. There is the input disturbance at 250s. The simulation results can be seen from Fig. 3 and Table 1.

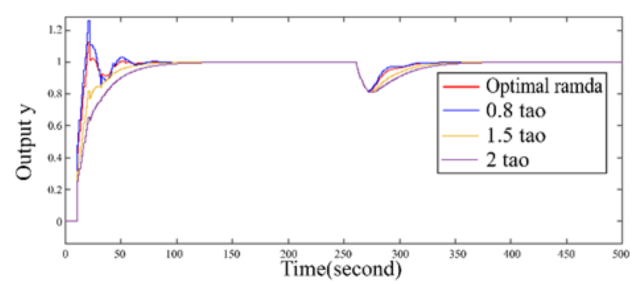

Fig. 3. Comparison curves of several cases

Table 1
Controller parameters

	λ	K_P	T_i	T_d	**IAE**
Case 1	$\lambda = 0.8\tau$	1.282	500	105	19.73
Case 2	$\lambda = 1.5\tau$	0.833	500	105	25.99
Case 3	$\lambda = 2\tau$	0.667	500	105	32.49
Optimal λ	$\lambda = 0.958\tau$	1.143	500	105	19.56

It can be seen that the smaller the value of λ , the faster the response, but the more the oscillation occurs. These oscillations may have detrimental affections on actuators. And, in the case of the optimal filter time constant, IAE value is the smallest. At that time, the value of M_s is 1.522.

In the simulation, a performance comparison between the cases of combined and uncombined with PFC structure is made for the optimal IMC-PID controller. First, we analyze how the response of IMC-PID control system changes if there is time delay in the plant. The results are shown in Fig. 4.

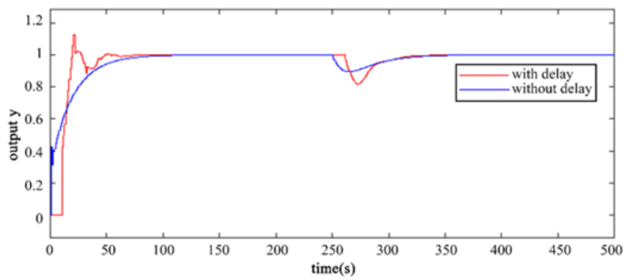

Fig. 4. Closed-loop responses of plants with and without time delay

As you can see, the influence of the time delay not only causes oscillations in the response curve, but also the disturbance response characteristic is not good. Next, for the real plant with time delay, the control effect of the IMC-PID controller combined with PFC structure is shown in Fig. 5.

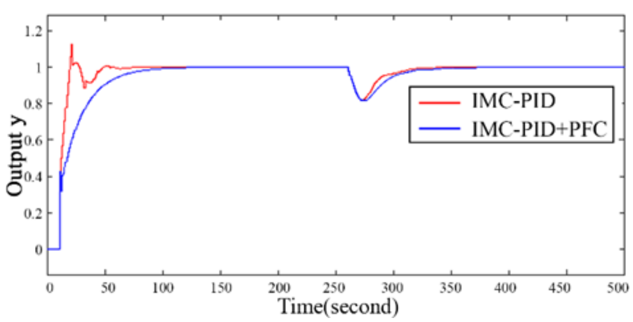

Fig. 5. Closed-loop responses of controllers combined and uncombined with PFC structure

It can be seen that the disturbance rejection performance is rather poor compared to IMC-PID controller, although the oscillations caused by time delay are effectively eliminated.

Subsequently, we perform an efficiency analysis for the cases of combined and uncombined with DOB. The value of the Q-filter time constant of DOB is determined to 90.7 by PSO algorithm.

The simulation results are shown in Fig. 6 and Fig. 7.

It can be seen that the control system combined with DOB significantly improves the disturbance rejection effect.

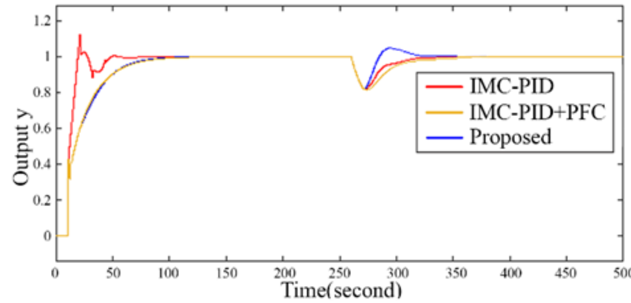

Fig. 6. Comparison curves with the proposed method

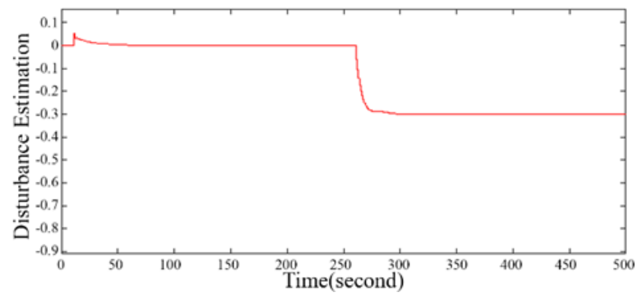

Fig. 7. Disturbance estimation curve

5. Conclusion

An improved IMC-PID controller incorporating PFC structure and DOB is presented. The optimal IMC filter time constant, that is used in calculation of PID parameters, is determined by PSO algorithm to keep the smallest IAE and appropriate M_s indexes. The PFC structure and DOB are combined with this optimal IMC-PID control system to compensate for the affections of time delay and input disturbance. The filter time constant of DOB is optimally determined using PSO algorithm. Simulation results show that the proposed controller has the ability to effectively compensate for the affections of time delay and disturbance.

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