International Journal of Control and Automation
Vol. 9, No. 10 (2016), pp.247-256
http//dx.doi.org/10.14257/ijca.2016.9.10.24

PID Predictive Control of Automobile Engine Air-Fuel Rati Based on the Unscented Kalman Filter

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Abstract

In order to overcome the disadvantage that single-degree-of-freedom PID controller cannot integrate the optimal target tracking performance and anti-interference function, this article puts forward a design of two-degree-of-freedom IMC-PID controller for the time-delay control system according to the Internal Model Control (IMC) principle. It also puts forward a parameter setting method for the two-degree-of-freedom controller based on the maximum sensitivity. First of all, it deduces the relationship between one of the filter parameters with the maximum sensitivity, and determine this parameter according to the maximum sensitivity index, which gives the system strong robustness; then it revises another filter parameter according to the dynamic performance of the system, which gives the system a strong target tracking characteristic. Meanwhile, it conducts the robust stability analysis on the process model mismatch condition, and obtains the conditions for system stability. According to the simulation results, the time-delay control system which is designed based on two-degree-of-freedom IMC-PID controller has good target tracking characteristic, anti-interference performance and robustness, which proves that the parameter setting method which is based on the maximum sensitivity is effective. The negative impact of time delay on the system can be effectively overcome by using the method put forward here.

***Keywords**: Two-degree-of-freedom; IMC-PID; Max. sensitivity; Filter parameter; Robustness*

1. Introduction

Although there are various kinds of advanced control algorithms, PID controller is still widely applied in industrial field because of its simple structure and reliable performance[1-3].In recent years, a variety of excellent PID controller parameter setting methods are combined with more advanced control algorithms, which gives PID controller more remarkable control effect in the industrial control[4-7]. Among them, Reference [4] puts forward a parameter setting method that based on magnitude and phase margins (magnitude margin and phase margin), and proves its effectiveness through simulation examples. Reference [5] and [6] applies the parameter setting method that based on magnitude and phase margins to the system whose control target is first-order unstable and lingering target, and obtains good control effects. As opposed to magnitude margin and phase margin, the maximum sensitivity can better reflect the robustness of the system; therefore, Reference [7] puts forward a PID parameter setting method that based on the maximum sensitivity, and points out that this method is more effective than those based on magnitude and phase margins. In addition, in view of the uncertainty of time-delay system parameters, Reference [8] puts forward a robust PID controller design

ISSN: 2005-4297 IJCA

method, which can quickly obtain the parameter sets of all robust PID controllers, so that the design efficiency of PID controller during industrial control process is improved. Besides, there are many scholars have combined the adaptive control, fuzzy control and neural network control with PID control, and effectively improve the performance of the control system [9-12], but such kind of control algorithms need too high computational complexity which cannot be reached by the SCMs that are commonly used for industrial purposes and have low processing speeds, therefore, such kinds of control algorithms are still seldom used in practical systems. In order to make the PID control parameters setting simpler and more convenient, Reference [13-15] combines IMC with PID control, and designs an IMC-PID controller which has a simple structure but integrates the advantages of both IMC and PID, and the parameter setting becomes more convenient and the controller has stronger robustness. The above-mentioned researches mostly focuses on single-degree-of-freedom PID controller which has only one set of control parameters and usually cannot integrate the optimal target tracking characteristic and anti-interference function[16]; in order to overcome this disadvantage, the design concept of a two-degree-of-freedom PID controller was put forward and proved effective by means of experimental verifications[17-18]; but Reference [17] does not make further research on the controller parameter setting and Reference [18] only puts forward a design method which is still difficult to implement. Therefore, the research of a simple two-degree-of-freedom IMC-PID parameter setting method has certain theoretical and practical significance. This article puts forward a two-degree-of-freedom IMC-PID parameter setting method which is based on the maximum sensitivity, and this method can avoid the blindness in parameter setting, making it simple and convenient. At last, it conducts a simulation research on the time-delay process model commonly used for industrial purposes by using the method put forward here.

2. Design of Two-Degree-of-Freedom IMC-PID Controller

The so-called two-degree-of-freedom PID controller is not composed by two PID controllers, but it has two sets of adjustable parameters. Based on the idea of inner model control, plus the two-degree-of-freedom PID controller, thus how a two-degree-of-freedom IMC-PID controller is designed, and the number of adjustable parameters are reduced to two. The system designed according to two-degree-of-freedom IMC-PID controller is as shown in Figure 1[17].

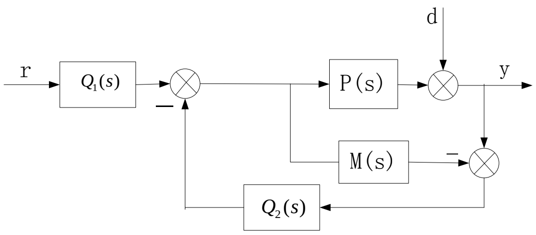


Figure 1. Structure Diagram of Two-Degree-of-Freedom IMC-PID Controller System

In Figure 1, r is input by the system; y is system output; d is the interference signal; *P(s)* is the actual mathematical model in the process of being controlled; *M(s)* is the nominal model in the process of being controlled; *Q1(s)* and *Q2(s)* make up the two-degree-of-freedom IMC-PID controller, in which *Q1(s)* can be used to adjust the target tracking characteristic of the setting system and *Q2(s)* can be used to adjust the robustness of the setting system. It can be obtained from Figure 1:

$$Y(s)=\frac{P(s)Q_1(s)}{1+Q_2(s)[P(s)-M(s)]}R(s)+\frac{1-M(s)Q_2(s)}{1+Q_2(s)[P(s)-M(s)]}D(s) \tag{1}$$

When the model is matched, *i.e. M(s)=P(s)*, it will be

$$Y(s)=P(s)Q_1(s)R(s)+[1-M(s)Q_2(s)]D(s) \tag{2}$$

It can be seen from the analysis of Formula (2), the system can have strong target tracking characteristic and anti-interference performance at the same time by adjusting *Q1(s)* and *Q2(s)*.

The design of Q1(s) and Q2(s) of two-degree-of-freedom IMC-PID controller is generally divided into two steps: Breakdown of target model and robustness design of model error.

Step 1, breakdown of target model. M(s) can be divided into:

$$M(s)=M_+(s)M_-(s) \tag{3}$$

Where M-(s) is the minimum phased section and M+(s) is the all-pass section.

Step 2, Robustness design of model error. In order to increase the robustness of the system and reduce negative impact of model error on the system, a low-pass filter can be added in the controller.

After completing the above two steps, a two-degree-of-freedom IMC-PID controller can be obtained as follows:

$$\begin{cases} Q_1(s)=M_-^{-1}(s)f_1(s) \\ Q_2(s)=M_-^{-1}(s)f_2(s) \end{cases} \tag{4}$$

where f1(s) and f2(s) are simple low-pass filter, they are

$$\begin{cases} f_1(s)=\dfrac{1}{\lambda_1 s+1} \\ f_2(s)=\dfrac{1}{\lambda_2 s+1} \end{cases} \tag{5}$$

where λ1 and λ2 are filter time constant and λ1>λ2. Figure 1 can be equivalently transformed into the setting value filter type two-degree-of-freedom control system shown in Figure 2.

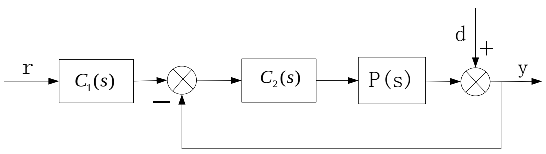


Figure 2. Structure Diagram of Setting Value Filter Type Two-Degree-of-Freedom Control System

Where C1(s) is the setting value filter and C2(s) is the controller. It can be obtained from Figure 2:

$$Y(s)=\frac{C_1(s)C_2(s)P(s)}{1+C_2(s)P(s)}R(s)+\frac{1}{1+C_2(s)P(s)}D(s) \tag{6}$$

It can be obtained from the comparison of Formula (5) and Formula (6):

$$\begin{cases} C_1(s)=\dfrac{Q_1(s)}{Q_2(s)} \\ C_2(s)=\dfrac{Q_2(s)}{1-M(s)Q_2(s)} \end{cases} \tag{7}$$

Obviously, C1(s) and C2(s) can be obtained through the design of Q1(s) and Q2(s), plus simple computation. The classic process model commonly used in the industrial fields can be expressed as inertial link and pure delay link, and its transfer function is

$$P(s)=\frac{K_m e^{-L_m s}}{\prod_{i=1}^{i=n}(T_{mi}s+1)}, T_i>0 \tag{8}$$

where Km is the gain coefficient; Lm is the delay time; Tmi is the time constant of No.i inertial; and n is the order of the system. The first-order Taylor is used to expand the approximate $e^{-L_m s}=1-L_m s$, and plus Formula (4), (5), (7) and (8), it can be obtained:

$$\begin{cases} C_1(s)=\dfrac{\lambda_2 s+1}{\lambda_1 s+1} \\ C_2(s)=\dfrac{\prod_{i=1}^{i=n}(T_{mi}s+1)}{K_m(\lambda_2+L_m)s} \end{cases} \tag{9}$$

Substitute Formula 9 into (6) and apply Taylor approximation to the delay link in the denominator, it can be obtained:

$$Y(s)=\frac{e^{-L_m s}}{(\lambda_1 s+1)}R(s)+\frac{(\lambda_2 s+L_m)s}{(\lambda_2 s+1)}D(s) \tag{10}$$

It can be seen from Formula (10) that by using the two-degree-of-freedom IMC-PID control design system, the closed-loop transfer function of the system has nothing to do with the inertial link, which greatly simplifies the system analysis, and the response speed and anti-interference performance of the system can be obtained by adjusting λ1 and λ2, respectively, which overcomes the disadvantage that the system has to make a compromise in parameter selection between meeting the requirements of response speed and anti-interference performance.

3. Parameter Setting

Definition 1: The sensitivity reflects the dependence of system characteristics on independent links of the system; G0 and α0 are the system response and link characteristics in initial design, and ΔG and Δα are the difference between initial system characteristic G and link characteristic α with their actual values, then the sensitivity function can be defined as

$$S_\alpha^G(s)=\frac{\Delta G / G}{\Delta\alpha / \alpha} \tag{11}$$

where G= G0+ ΔG and α= αΔ+ α0.

In terms of Figure 1, when d= 0, the closed-loop transfer function of the system is

$$G(s)=\frac{C_1(s)C_2(s)P(s)}{1+C_2(s)P(s)} \tag{12}$$

According to the definition 1, the sensitivity function of the closed-loop transfer function to control target parameters change is:

$$S_P^G(s)=\frac{1}{1+C_2(s)P(s)} \tag{13}$$

The maximum magnitude of the sensitivity function is defined as the maximum sensitivity, *i.e*.

$$M_s=\max_{0\le w<\infty}\left|\frac{1}{1+C_2(jw)P(jw)}\right| \tag{14}$$

The maximum sensitivity indicates the inverse of the closest distance from the Nyquist curve of open-loop transfer function C2(s)P(s) to the stable critical point (-1, 0), and its geometric meaning is as shown in Figure 3.

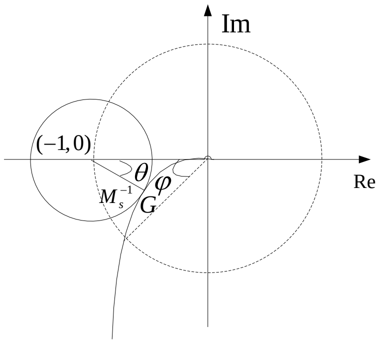


Figure 3. Geometric Meaning of the Maximum Sensitivity

In Figure 3, point G is the tangent point of Nyquist curve with the circle whose center is (-1, 0) and radius is Ms-1. The magnitude margin and phase margin of the system are set to Am and φm, then the relationships between the maximum sensitivity and Am and φm is[7]

$$\begin{cases} A_m > \dfrac{M_s}{M_s - 1} \\ \varphi_m > 2\arcsin\dfrac{1}{2M_s} \end{cases} \tag{15}$$

It can be seen from Formula (15) that the maximum sensitivity can reflect the magnitude margin and phase margin at the same time, and the smaller the maximum margin is, the bigger the magnitude and phase margin will be, *i.e.* the better the system stability will be. It can be obtained from Formula (8) and (9)

$$C_2(s)P(s) = \frac{e^{-L_m s}}{(\lambda_2 + L_m)s} \tag{16}$$

By means of the methods in Reference [14], the relationship between the maximum sensitivity Ms and filter parameter λ2 is

$$\lambda_2 = \frac{1.508 - 0.451M_s}{1.451M_s - 1.508} L_m \tag{17}$$

Based on Formula (17), the filter parameter λ2 in two-degree-of-freedom IMC-PID controller can be determined according to the maximum sensitivity index. Then correct the other filter parameter λ1 according to the dynamic response curve of the system, and when the system overshooting is larger, λ1 can be increased appropriately to suppress the overshooting; when the system overshooting is smaller but the system setting time is longer, λ1 should be decreased appropriately, which can help accelerate the system response speed. Through the correction of λ1, the system can have a good target tracking characteristic.

4. Robust Stability Analysis of Model Mismatch

In actual industrial applications, the process model parameters in the system are not always identical in different moments and environments. Therefore, the analysis of the system robust stability when process target parameters change has a certain theoretical guiding significance for controller design. Main parameters of process target mainly include target gain coefficient Km, delay time coefficient Lm and inertial time constant Tmi. Below are the separate analysis of system robust stability of three parameters under the mismatch conditions.

Theorem 1: If there is any gain mismatch between process model and nominal model and process model gain K= ΔK· Km, where ΔK> 0, the condition for system remaining stable is

$$0 < \Delta K < 1 + \frac{\lambda_2}{L_m} \tag{18}$$

Theorem 2: If there is any delay time constant mismatch between process model and nominal model and the process model delay time constant L=ΔL· Lm, where ΔL> 0, the condition for the system remaining stable is

$$0 < \Delta L < 1 + \frac{\lambda_2}{L} \tag{19}$$

Theorem 3: If there is any inertial time constant mismatch between process model and nominal model and the inertial time constant in No. i inertial link of process model T=ΔT· Tmi, where ΔT> 0, the condition for the system remaining stable is

$$\Delta T > 1 - \frac{\lambda_2}{\lambda_2 + L_m} \tag{20}$$

It proves that: for Theorem 1:

The characteristic formula when the system is under model gain mismatch is

$$D(s) = 1 + C_2(s)P(s) = 1 + \frac{\Delta K e^{-L_m s}}{(\lambda_2 + L_m)s} = 0 \tag{21}$$

The first-order Taylor approximation is used for the time delay link, then

$$(\lambda_2 + L_m - \Delta K \cdot L_m)s + \Delta K = 0 \tag{22}$$

In order to keep the system stable, it can be obtained based on the Routh stability criterion that

$$\begin{cases} \Delta K > 0 \\ \Delta K < 1 + \dfrac{\lambda_2}{L_m} \end{cases} \tag{23}$$

Therefore, the stability conditions described in Theorem 1 are valid.

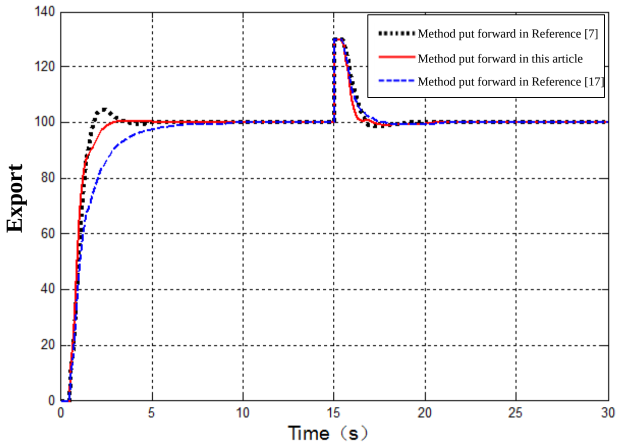
Similarly, the stability conditions in Theorem 2 and Theorem 3 can be proved valid. The stability conditions of Theorem 1, 2, and 3 show that, the greater the value of λ2 is, the larger the value ranges of ΔK, ΔL and ΔT (the model mismatch coefficients in corresponding stability conditions) will be, (which means) the larger the extent of model mismatch allowed for system remaining stable will be, namely, the stronger the robustness of the system will be.

5. Simulation Test

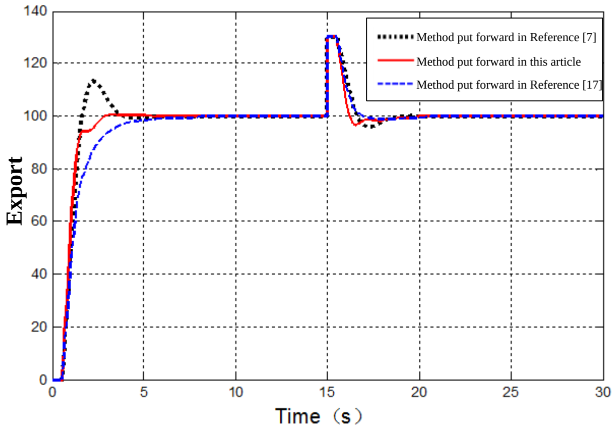
In order to verify the effectiveness of the method put forward in this article, simulation tests were carried out on a furnace temperature control system and the oil pressure control system of a high pressure oil pump, respectively. The method proposed in this section is compared with the methods put forward in Reference [7] and Reference [17], and the maximum sensitivity index in Reference [7] is selected to be Ms=1.6 and filter parameters in Reference [17] are selected to be λ2=1 andλ1=1.5, respectively. In the oil pressure control system of the oil pump, the controlled target can approximate to the series connection of first-order inertia link and pure delay, and it is a first-order process of time delay (FOPTD), with tis transfer function as follows:

$$P(s) = \frac{e^{-0.5s}}{s+1}$$

The simulation results are as shown in Figure 4. Figure 4(a) and 4(b) show the step response curves of process model match and process model mismatch by 10% for all parameters, respectively, and an interference with a magnitude of 30 is added into the system when t=15s.



(a) Model match (FOPTD)



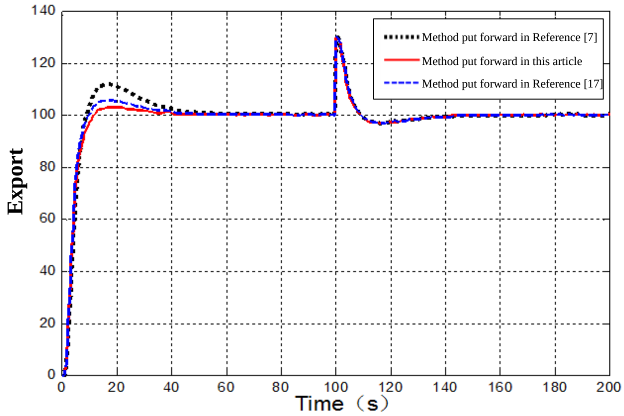
(b) Model mismatch (FOPTD)

Figure 4. Simulation Result of the Oil Pressure Control System of High Pressure Oil Pump

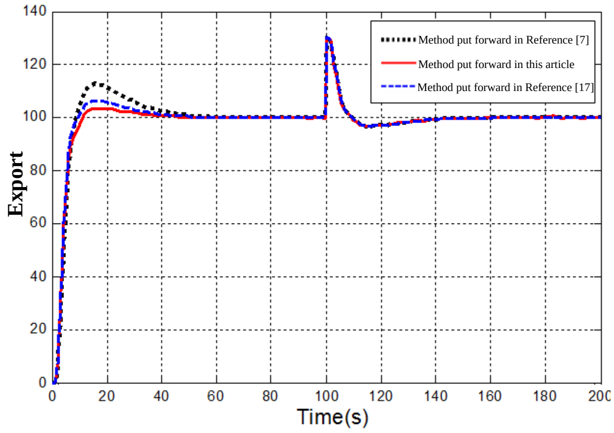
In the furnace temperature control system, the controlled target can approximate to the series connection of second-order inertia link and pure delay, and it is a second-order process of time delay (SOPTD), with tis transfer function as follows:

$$P(s) = \frac{e^{-s}}{(10s+1)(5s+1)}$$

The simulation results are as shown in Figure 5. Figure 5(a) and 5(b) show the step response curves of process model match and process model mismatch by 10% for all parameters, respectively, and an interference with a magnitude of 30 is added into the system when t=100s.



(a) Model match (SOPTD)



(b) Model mismatch (SOPTD)

Figure 5. Simulation Result of Furnace Temperature Control System

The simulation results show that, when the system is designed based on the two-degree-of-freedom IMC-PID controller and the controller parameter setting are completed by using the maximum sensitivity, its control effect is obviously better than the single-degree-of-freedom PID control which is based on the maximum sensitivity parameter setting described in Reference [7]. Compared with the two-degree-of-freedom PID controller IMC setting method described in Reference [17], although the method described in Reference [17] has strong anti-interference performance when SOPTD process model mismatches, the method put forward in this article has better rapidity, and in the rest conditions, the systems designed based on the method put forward in this article have better control performances; therefore, the method put forward in this article is better than that of Reference [17] on the whole.

6. Conclusion

Based on the advantages of internal model control and two-degree-of-freedom control, this article designs a two-degree-of-freedom IMC-PID controller. And puts forward a parameter setting method which is based on the maximum sensitivity, and the setting method is simple and effective, avoiding the blindness of parameter selection in common two-degree-of-freedom PID controller. Meanwhile, this article studies the robustness of the system when process model mismatches and obtained the preconditions for system stability, then it provides the theoretical proof, which has a certain theoretical guiding significance for controller design. The two-degree-of-freedom IMC-PID control is used to design the oil pressure control system of an oil pump and the furnace temperature control system, and the method put forward in this article is used to complete the controller parameters setting; the simulation result shows that the systems have good target tracking characteristic, anti-interference performance and robustness, which proves that the method put forward in this article can overcome the negative impact of time delay on the system, and meanwhile, it verifies the effectiveness of this parameter setting method. Parameter λ2 can be set in a fast and convenient manner by using the parameter setting method put forward in this article, but parameter λ2 still needs to be determined according to the system response, and its setting process is still complicated; in order to solve this disadvantage and further study and development on new parameter setting method based on the maximum sensitivity method can be made, so that the setting of λ1 will become more convenient and simpler.

Acknowledgement

This research was financially supported by the Funds of: the National Natural Science Foundation of China (No.51305251)

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