A universal tuning method of large dead-time system

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Abstract

The current approach of the PID controller design and tuning for the large dead-time system are almost based on the first-order time delay model, such as all PID algorithms and Ziegler function in MATLAB. And these algorithms generally only apply to the following system $0.1 \le \tau / T \le 2$. Therefore, the application effect of these algorithms in large dead-time system are not ideal. Based on the second-order system, this paper proposed a universal tuning method of PID controller for large dead-time process. By the introduction of the controller pre-coefficient K_f, this method makes the large dead-time system PID controller design and tuning simplistic. The fitting formula of controller pre-coefficient K_f was given in this paper. The method is simple, versatile, suitable for the object of $(\tau / T) \to +\infty$ and second-order, higher-order system, overcomes the limitations of traditional PID control algorithm in large dead-time system applications. The simulation results show that the method is correct, effective and has practical value.

Keywords: dead-time system, PID controller, parameter tuning, second-order system, pre-coefficient

1 Introduction

PID controller design and tuning for large dead-time system are recognized problem in control community. With the pure delay time τ increases, the control of dead-time system will become increasingly difficult [1, 9]. Due to the existence of pure time delay, the control system tends to instability, it is difficult to obtain good quality.

Now, using the powerful MATLAB language for PID controller design and tuning is very advanced and effective method. However, all PID algorithms in MATLAB are based on the first order time delay model. That is:

$$G(s) = \frac{k}{Ts+1} e^{-\tau s} . \quad (1)$$

If the first-order time delay model is more precise, the control effect of PID will be close to the control of the first-order time delay model. These algorithms are generally only applied to the following system $0.1 \le \tau / T \le 2$. These algorithms in MATLAB are not suitable for the controller design for large time delay system. Therefore, these algorithms have certain limitations on the scope of application [1, 2]. The well-known Ziegler-Nichols tuning formula mentioned in literature [3-4] is based on the first-order inertia and delay object. The tuning effect for large delay process using the famous Ziegler-Nichols tuning formula is far from ideal. Similarly, the design of the Ziegler function in MATLAB is also based on the first order time delay model [1, 2]. In literature [5], the PI controller tuning for large dead-time process is also based on the first order time delay model. Nearly a hundred tuning methods and rules of PID controller for large dead-time process are showed in literature [6-7], but these tuning methods and rules are all based on the first order time delay model.

Therefore, whether the MATLAB or the Ziegler-Nichols tuning formula, now, all the PID controller-tuning methods of large dead-time process are based on the first-order time delay model, have certain limitations on the scope of application, and are powerless for large delay system.

The second-order system is the most representative system in the control. Generally, the controller for the second-order system is versatile [8]. Based on the second-order system, a simple and effective PID parameter tuning methods of large dead-time process was proposed. The method is simple, versatile and suitable for the object of $(\tau / T) \to +\infty$. This method solved the large delay control system design and tuning problem, which has been in existence. The simulation results show that the method is correct, effective and has practical value.

2 Control system design and tuning

There is a stable time-invariant second-order dead-time system:

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$$G(s) = ke^{-\tau s} / (as^2 + bs + 1) = e^{-\tau s} G_1(s) , \quad (2)$$

where τ is the lag time, $e^{-\tau s}$ is the time lags, and

$$e^{-\tau s} = 1 - \tau s + (\tau s)^2 / 2! - (\tau s)^3 / 3! + \ldots . \quad (3)$$

In fact, $e^{-\tau s}$ is a non-minimum phase factor, equivalent to the controlled object has an infinite number of unstable zeros:

$$G_1(s) = k / (as^2 + bs + 1) . \quad (4)$$

The designed control system is shown in Figure 1.

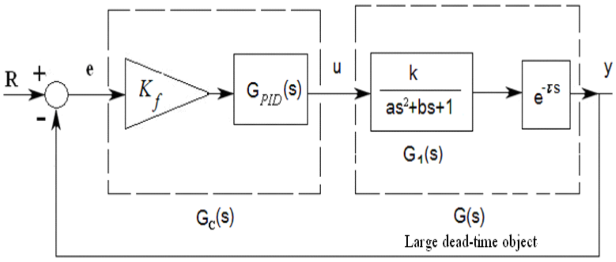


FIGURE 1 The PID control system of large dead-time process

Let

$$G_c(s) = G_{PID}(s) K_f . \quad (5)$$

The control system design methods can be divided into two steps.

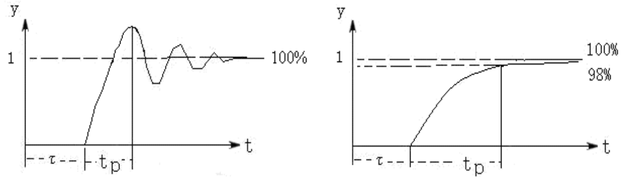
Step 1: Design of PID controller

It is difficult to design the PID controller according to the equation 2 (second-order dead-time system). But it is easy to design the PID controller according to the equation 4 (stable time-invariant second-order system). According to the equation 4, by optimizing, the designed controller is:

$$G_{PID}(s) = [K_p + K_i / s + K_d s / (T_d s + 1)] . \quad (6)$$

There are many kinds of optimization methods can design the PID controller now. In order to avoid pure differential operation, we are often using the first-order lags to approximate pure differential link [1].

The PID controller parameters designed according to the equation 4(the object which not contain a pure time delay) is very easy tuning. We are trying to achieve the purpose of tuning the PID controller parameters by adjusting the controller pre-coefficient K_f when $e^{-\tau s}$ is added to the control system.



A: $\xi < 0.76$ **B:** $\xi \geq 0.76$

FIGURE 2 The step response of second-order dead-time system

Step 2: set and adjust the controller pre-coefficient

In Figure 2, A and B is the step response of the system shown in equation 2 in the case of damping $\xi < 0.76$ or $\xi \geq 0.76$. In Figure 2 A, t_p is the time of the step response overshoot to the first peak. In Figure 2 B, t_p is the time of the step response to achieve 98% steady-state value,

$K_f = f(\tau / t_p) = f(h)$, $h = \tau / t_p$. K_f is a monotonically decreasing function about h. $0 < K_f \leq 1$, (if $\tau = 0$ then $K_f = 1$). Engineering practice shows that K_f must be reduced in order to ensure the stability and quality of the control system when the coefficient $h = \tau / t_p$ increases.

The closed-loop system output step response designed based on the equation 4(the object which not contain a pure time delay) is shown in figure 3A. Therefore, you can always find a value of K_f in the same PID parameters to make the following result holds. That is, the closed-loop system output step response of equation 2 (the object which contain a pure time delay) is the result of the closed-loop system output step response of equation 4 (the object which not contain a pure time delay) to the right pan τ. The closed-loop system output step response of the equation 2 is shown in Figure 3B.

Under the same PID parameters, each h is accordingly able to find the K_f, making no time delay object closed-loop output pan right τ to get the time delay object closed-loop output, which containing $e^{-\tau s}$.

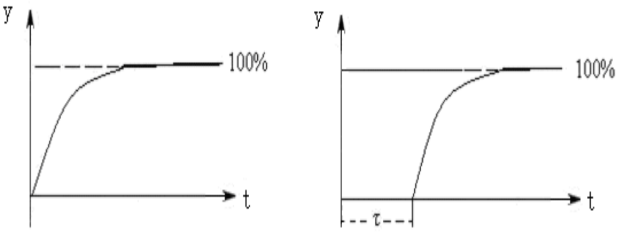
$K_f = f(\tau / t_p)$, K_f can be obtained by curve fitting method.

$$K_f = f(h) = c_0 + c_1 h + c_2 h^2 + c_3 h^3 + c_4 h^4 + \cdots , \quad (7)$$

or

$$K_f = f(h) = e^{-(c_0 + c_1 h + c_2 h^2 + c_3 h^3 + c_4 h^4 + \cdots)} . \quad (8)$$

The nonlinear of computing K_f can compensate the impact of non-minimum phase factor $e^{-\tau s}$ in equation 2.



A: No $e^{-\tau s}$ **B:** Containing $e^{-\tau s}$

FIGURE 3 The step response of second-order closed loop system

3 Simulation study

The control system shown in Figure 1 was simulated as follows.

3.1 SIMULATION EXAMPLE 1

Input R is the step signal. The second-order time delay controlled object is shown in equation 2. Object parameters are [k a b τ]. Simulation step is $t_s = 0.01s$.

1) Let [k a b τ] = [1.6 0.21 0.37 0]; PID parameters is [K_p K_i K_d T_d] = [0.45 1.5 0.27 0.077]; $K_f = 1$. The simulation results are shown in Figure 4. In Figure 4, the dotted line is the open-loop step response of controlled object; the solid line is the closed-loop output step response of controlled object (following the same).

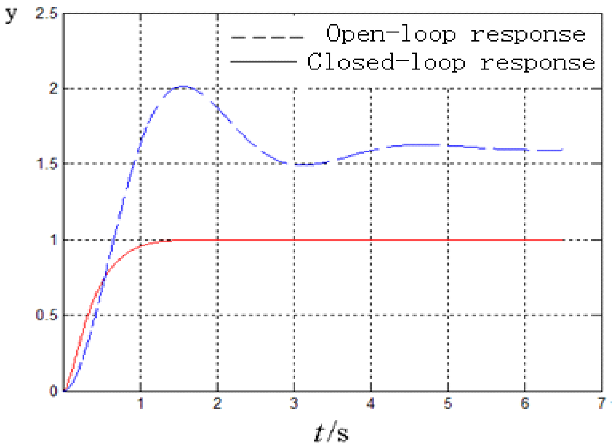


FIGURE 4 The simulation of example 1 ($\tau = 0$)

2) Let [k a b τ] = [1.6 0.21 0.37 0.4]; In the same PID parameters, $K_f = 0.36$. The simulation results are shown in Figure 5. It can be seen, Figure 5 is the results of Figure 4 pan right 0.4s.

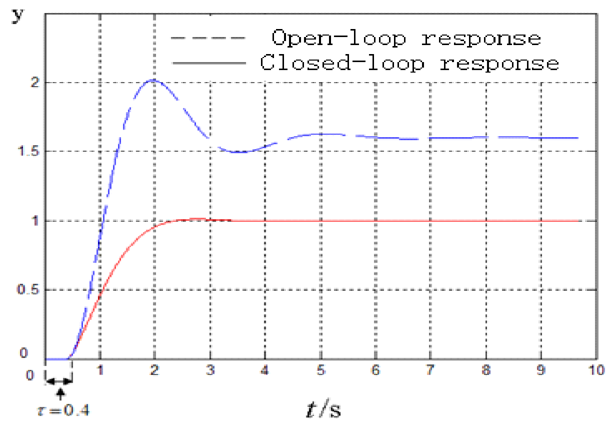


FIGURE 5 The simulation of example 1 ($\tau = 0.4$)

3.2 SIMULATION EXAMPLE 2

Input R is the step signal. The controlled object is $G(s) = ke^{-\tau s}/(Ts+1)$, the parameters is [k T τ], Simulation step is t_s=0.2s .

1) Let [k T τ] = [1.3 100 0], PI parameters are [K_p K_i] = [1.37363 0.0137363]; K_f =1; The simulation results are shown in Figure 6. In Figure 6, the dotted line is the open-loop step response of controlled object; the solid line is the closed-loop output step response of controlled object (following the same).

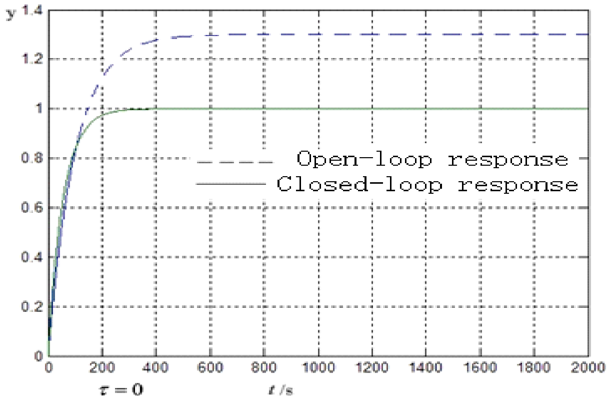


FIGURE 6 The simulation of example 2 ($\tau = 0$)

2) Let [k T τ] = [1.3 100 100]; In the same PI parameters, K_f =0.22, the ratio of delay time τ and the time constant T is $\tau/T = 1$; The simulation results are shown in Figure 7. It can be seen, Figure 7 is the results of Figure 6 pan right 100s.
3) Let [k T τ] = [1.3 100 400]; In the same PI parameters, K_f =0.06, $\tau/T = 4$; The simulation results are shown in Figure 8. It can be seen, Figure 8 is the results of Figure 6 pan right 400s.

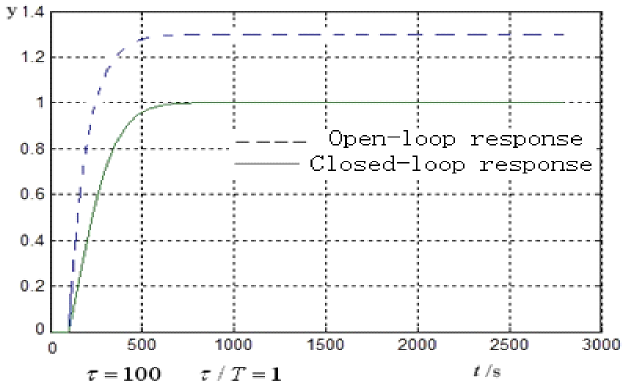


FIGURE 7 The simulation of example 2 ($\tau = 100$)

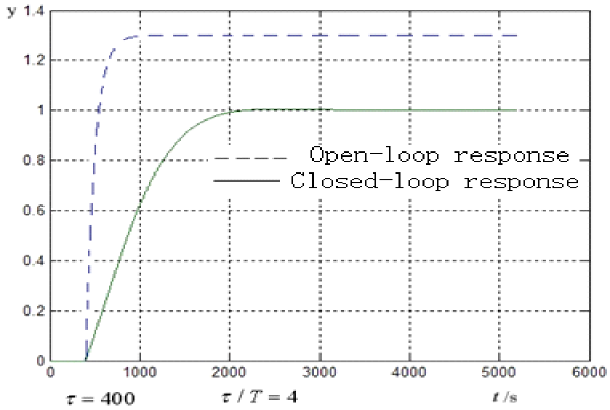


FIGURE 8 The simulation of example 2 ($\tau = 400$)

4) Let [k T τ]= [1.3 100 600]; In the same PI parameters, K_f =0.04, $\tau / T = 6$; The simulation results are shown in Figure 9. It can be seen, Figure 9 is the results of Figure 6 pan right 600s.

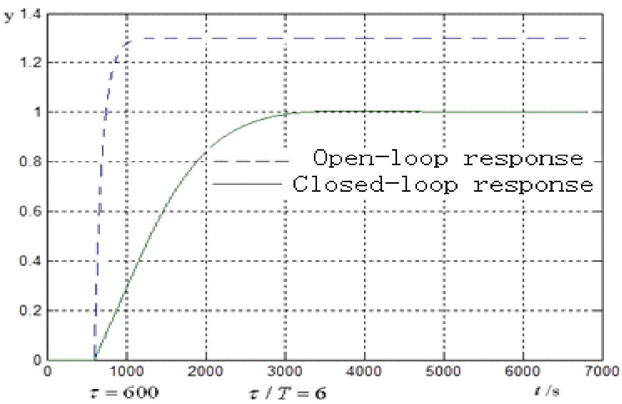


FIGURE 9 The simulation of example 2 ($\tau = 600$)

3.3 SIMULATION EXAMPLE 3

The higher-order object is $\frac{1.202}{(1+27.1s)^7}$ the higher-order object was reduced to the first-order delay system $\frac{1.202}{71.7s+1}e^{-118s}$.

Let τ =0, [K_p K_i]=[1.399 0.03]; K_f =1; In the same PI parameters, let τ =118, K_f =0.16; The simulation results are shown in Figures 10 and 11. It can be seen, Figure 11 is the results of Figure 10 pan right 118s.

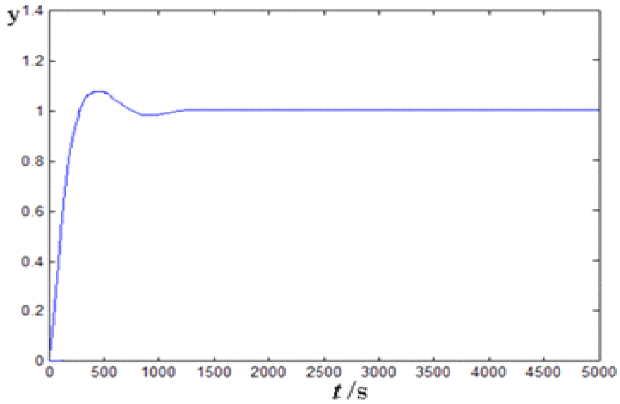


FIGURE 10 The simulation of example 3 ($\tau = 0$ 75% load)

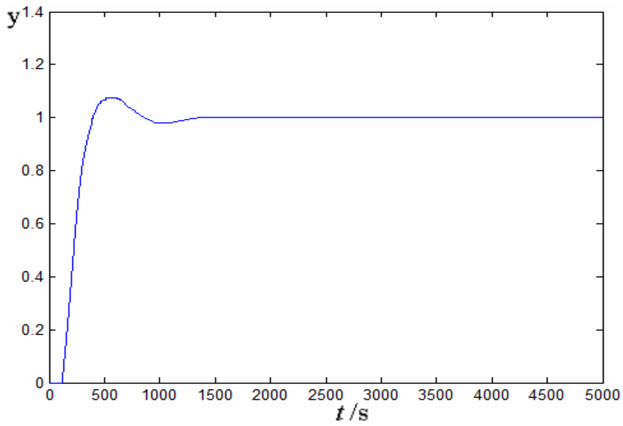


FIGURE 11 The simulation of example 3 ($\tau = 118$ 75% load)

It can be seen from the above simulation results that PID controller parameters can remain unchanged when large delay links $e^{-\tau s}$ is added to the control system, only need to adjust the system pre-coefficient can be overcame the impact of dead-time and achieved the desired control effect.

The applications of the tuning method in second-order delay system and first-order delay system are shown as Example 1 and Example 2. It can be seen from example 2 that the method proposed in this paper is suitable for large time delay object, i.e. the object of (τ / T)→+∞, and effectively overcomes the limitations of traditional design and tuning method in the application of large dead-time system. The applications of the tuning method in higher-order system, which can be reduced to first-order system are shown as Example 3.

5 Conclusions

The tuning method about large delay system in this paper has the following characteristics:

1) Simple and less adjustable parameters. When the controller design based on without delay stable system is completed, only need to adjust a parameter K_f can overcome the impact of the time delay. Adjusting a parameter K_f, which is equivalent to changing the PID controller four parameters [K_p K_i K_d T_d]. So, makes the PID controller tuning method simplicity, practical and effective.
2) Has a strong commonality. The tuning method is suitable for not only the first-order delay system but also the second-order delay system(overshoot and no overshoot)and the higher-order delay system which can be reduce to the first-order or second-order system.
3) Wide range of applications. This method is suitable for the object of (τ/T)→+∞, $K_f \to 0$; This is an improvement over the traditional design method. In the traditional method, the value of τ/T is limited to a lesser extent. It may be more effective if the method used in open-loop stepper control.

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