An improved 2-degree-of-freedom internal model proportional–integral–derivative controller design for stable time-delay processes

Sheng Wu, Ziwei Li and Ridong Zhang

Abstract
In this article, an enhanced 2-degree-of-freedom internal model control strategy for typical industrial processes with time-delay is developed. For the proposed controller, it is composed of an inner loop feedback controller which is designed based on the internal model control theory and a weighted set-point tracking controller. Note that the adjustment of set-point tracking performance and disturbance rejection characteristics can be decoupled by employing the developed strategy, which indicates that more degrees of freedom are obtained for the proposed controller design; thus, better ensemble performance and stronger robustness are anticipated by regulating these two controllers separately, which may not be achieved in the conventional internal model control method. Case studies on two kinds of stable processes with time-delay verify the effectiveness of the proposed scheme finally.

Keywords
2-Degree-of-freedom, set-point tracking, disturbance rejection, internal model control

Introduction
Because of the simple structure, convenient parameter setting and good stability, proportional–integral–derivative (PID) controller has been widely used in industrial processes.\(^1\)\(^-\)\(^3\) In the past decades, there are lots of progresses on the theory and application of various advanced control technologies, which also promotes the development of PID controllers to some extent.\(^4\)\(^,\)\(^5\) As to the PID controller, its control parameters affect the corresponding closed-loop response greatly; therefore, the relevant tuning approaches are vital.\(^6\) Note that many advanced control algorithms are proposed to combine with the PID design strategies, which provides new vitality for the PID control technology and the relevant tuning methods.

As to the linear systems without time-delay, traditional PID control possesses good control performance.\(^7\) However, time-delay is inevitable in practical engineering applications. Meanwhile, the model uncertainty is another considerable factor in control system, so that the robustness of the system needs to be considered in the controller design.\(^8\)\(^-\)\(^11\) For the time-delay in control systems, internal model control (IMC) strategy is an effective method, and the IMC-PID schemes in which the IMC approach is employed to tune PID control parameters have been investigated by many researchers.\(^9\)\(^-\)\(^11\) In previous studies,\(^12\)\(^-\)\(^15\) the design and setting method of the IMC-PID control were addressed, which solve the problem of time-delay well. In Shamsuzzoha and Lee,\(^16\) the IMC-PID controller was designed to improve the disturbance rejection ability of the time-delay processes. The design principle is simple and the parameter setting is also straightforward and clear, but the derived IMC-PID control has only one parameter that needs to be set; thus, the degree of freedom for the relevant controller design may be limited. As to the method in Liu et al.,\(^17\) the corresponding setting is relatively simple, but good set-point tracking performance and disturbance rejection characteristics are hardly to be obtained simultaneously, because the two characteristics need to be traded off in the relevant controller design. In Tan et al.,\(^18\) an improved internal model structure design method with three compensators

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was developed. The structure of the IMC can be separately designed for set-point tracking and interference suppression, but the controller needs to be designed three times and the structure is complex. In Alfaro et al., an analytical control method using the IMC theory was presented, and the relevant tuning formula is simple. Nevertheless, the IMC filter adopts the form of lead lag, which may result in excessive overshoots in the set-point tracking responses. An enhanced method of the IMC-PID controller was developed for various processes in Wang et al. For the stable process, the virtual filter based on the zero-pole transformation was considered. A lead lag compensator was designed for the first-order additive integral and second-order plus time-delay (SOPTD) unstable processes. However, it is not suitable for the case where the ratio of the process time constant and the delay time constant is relatively large, because the corresponding set-point tracking performance may not be satisfactory. The introduction of the 2-degree-of-freedom (2-DOF) controller enables the control system to achieve good tracking performance and anti-interference performance simultaneously. A 2-DOF control structure was studied for a class of integral time-delay processes in Astrom et al., where the advantage is that the set-point tracking response and external interference suppression characteristics of the system are decoupled and can be optimized separately, but the controller is too complex and has no intuitive physical meaning. In Matausek and Micic, the method in Astrom et al. was further improved and the relevant compensator was simplified to a constant. This makes the controller simple, but its interference suppression performance is poor. A 2-DOF control method with a set-point filter was addressed in Wang and Cai, which enhances the performance of interference suppression, but the response speed of the set-point command is slow. In Lu et al., a dual 2-DOF control method with good interference suppression characteristics and faster set-point tracking was investigated, but it has four controllers that need to be designed, which makes its structure more complex. The 2-DOF-PID controllers in previous studies has five or six parameters that need to be set. The method presented in Zhang and Sun modified this method and gave the minimum order form of the compensator. The controller has only two parameters, but the structure of the controller is redundant. What’s more, in Yan and Yao, fuzzy logic was applied to the 2-DOF-IMC method and used to modify the parameters of the filter in the IMC controller to improve control performance. A 2-DOF-PID control algorithm was implemented in Wei and Quan. The controller parameters are automatically adjusted by weight self-learning, such that the set-point tracking performance and anti-interference performance of the system are optimized at the same time, but the weight coefficient needs to be corrected. Besides, there are also many other representative results about 2-DOF control strategy. These 2-DOF control methods based on intelligent control theory can overcome the influence of parameter variation and uncertainty in the control system, but the relevant control algorithms are generally more complicated.

In order to solve the above problems, this paper proposes a novel 2-DOF-IMC-PID controller design and the corresponding tuning method. In the control scheme, the IMC theory and an effective time-delay approximation method are employed, and the obtained control structure is simple. The set-point tracking and disturbance rejection are decoupled and tuned by different controllers separately; thus, more degrees of freedom are achieved for the proposed controller design. By employing the developed scheme, enhanced ensemble control performance and stronger robustness are expected. Besides, there are only two parameters that need to be set for the proposed method, and its tuning approach is also simple and targeted. The developed control strategy is tested on the first-order plus time-delay (FOPTD) and second order plus time-delay (SOPTD) processes, respectively, and the simulation results show that good set-point tracking performance and interference suppression characteristics are both achieved.

This paper is organized as follows: a brief introduction to the internal model extension structure and the approximation of the time-delay is addressed in section “IMC control structure.” In section “Design of 2-DOF-IMC structure,” the design method for the 2-DOF-IMC structure is presented, and section “Tuning method for stable processes” describes the tuning of the corresponding PID controllers for FOPTD and SOPTD processes. In section “Simulation,” the effectiveness of the proposed method is illustrated by simulations and comparisons, and conclusion is given in section “Conclusion.”

**IMC control structure**

The traditional IMC structure is shown in Figure 1. Here, $G(s)$ and $M(s)$ represent the controlled process and the process model, and $G_{IMC}(s)$ denotes the IMC controller. $r$, $y$ and $d$ are reference value, process output and the interference signal, respectively.

The closed-loop transfer function of the system output can be derived from Figure 1

![Figure 1. Block diagram of IMC.](image-url)
As to the transfer function in equation (1), the following formula will hold if the relevant process model is accurate, that is, \( G(s) = M(s) \)

\[
y = \frac{G_{IMC}(s)G(s)}{1 + G_{IMC}(s)[G(s) - M(s)]}f + \frac{1 - G_{IMC}(s)M(s)}{1 + G_{IMC}(s)[G(s) - M(s)]}d
\]

(1)

It can be known that the set-point tracking characteristics and the disturbance rejection characteristics of the controlled system are closely related to \( G_{IMC}(s) \). When the process model is accurate and there is no external interference, that is, \( d = 0 \), the system output will be equal to the reference value if we choose \( G_{IMC}(s) = G^{-1}(s) \). At this time, the whole system is equivalent to an open-loop control system. In practice, the performance of the controlled system is affected by various uncertainties. For the IMC controller, it is also a challenge to guarantee the desired performance under kinds of conditions. Some reasons are as follows:

(a) If the process model has a right half plane zero, the controller \( G_{IMC}(s) = M^{-1}(s) \) will have a right half plane pole.
(b) For a process with time-delay, the controller \( G_{IMC}(s) = M^{-1}(s) \) may not be implemented.
(c) In the case of model/plant mismatch, the controller \( G_{IMC}(s) = M^{-1}(s) \) will not be suitable, because it may lead to the fact that the manipulated variables are under infinitesimal high-frequency interference, and it is physically impossible.
(d) If plant and model is mismatched, the controller \( G_{IMC}(s) = M^{-1}(s) \) will not have double (open-loop and closed-loop) stability. Meanwhile, the whole closed-loop system will be unstable.

In order to solve the aforementioned problems, \( M(s) \) is decomposed into two parts to realize the IMC design, and the corresponding design process is given as below.\textsuperscript{33,34}

First, the process model is decomposed into two parts

\[
M(s) = M_+(s)M_-(s)
\]

(3)

where \( M_+(s) \) and \( M_-(s) \) are the irreversible part and the reversible part of the process model, respectively.

Here, we select \( G_{IMC}(s) \) as the reciprocal of the reversible part

\[
G_{IMC}(s) = M_+^{-1}(s)
\]

(4)

To make the IMC achievable, a low pass filter is considered to stabilize the controller, and the relevant filter is designed as

\[
f(s) = \frac{1}{(\lambda s + 1)^\alpha}
\]

(5)

where \( \lambda \) is a tuning parameter, and \( \alpha \) is selected to facilitate the controller design.

Then, the IMC controller can be further described as

\[
G_{IMC}(s) = M_+^{-1}(s)\frac{1}{(\lambda s + 1)^\alpha}
\]

(6)

As to the treatment of the time-delay term in the process model, we usually choose Taylor series expansion or Padé approximation. The following approximation method is selected in this paper

\[
e^{-\theta s} \approx \frac{1}{1 + \theta s + \frac{1}{2} \theta^2 s^2}
\]

(7)

For the IMC structure in Figure 1, it can be transformed into the following classic feedback control structure as shown in Figure 2.

Finally, we can obtain the controller \( C(s) \) based on the equivalence relationship

\[
C(s) = \frac{G_{IMC}(s)}{1 - M(s)G_{IMC}(s)}
\]

(8)

**Design of 2-DOF-IMC structure**

In Figure 3, the structure of the 2-DOF-IMC is shown. Here, \( Q_1(s) \) and \( Q_2(s) \) constitute the 2-DOF-IMC controller.

The relationship between the system output and the disturbance can be acquired easily from Figure 3.
For the closed-loop system in Figure 3, the relevant complementary sensitivity function is

\[
T(s) = \frac{G(s)Q_2(s)}{1 + G(s)Q_2(s)}
\]  

(10)

then, the controller \(Q_2(s)\) can be gained from the above equation

\[
Q_2(s) = \frac{1}{G(s)} \frac{T(s)}{1 - T(s)}
\]  

(11)

Furthermore, the relationship formula in equation (9) can be rewritten as

\[
\frac{y}{d} = [1 - T(s)]G_d(s)
\]  

(12)

Refer to Rivera et al.,\(^35\) we select the formula of complementary sensitivity as follows

\[
T(s) = G^+(s)h(s)
\]  

(13)

where

\[
h(s) = \frac{1}{\lambda_s + 1}
\]

then, we can obtain the controller \(Q_2(s)\) as

\[
Q_2(s) = \frac{1}{G^-(s)} \frac{h(s)}{1 - G^+(s)h(s)}
\]  

(14)

Similarly, the 2-DOF-IMC structure in Figure 3 can be simplified into the conventional 2-DOF control structure shown in Figure 4. Here, \(C_1(s)\) and \(C_2(s)\) form the 2-DOF controller.

On the basis of the equivalence relationship, the following formulas hold

\[
C_1(s) = Q_2(s)

C_2(s) = \frac{Q_1(s)}{Q_2(s)} + G^+(s)f(s)
\]  

(15)

Furthermore, we can acquire

\[
C_1(s) = \frac{1}{G^-(s)[1 + \lambda_2s - G^+(s)]}

C_2(s) = \frac{\lambda_2s + 1}{\lambda_s + 1}
\]  

(16)

Through the designed two controllers, the set-point tracking and disturbance rejection are anticipated simultaneously for the controlled system. Meanwhile, more degrees of freedom are achieved for the presented scheme; thus, the robustness of the relevant system under various uncertainties will also be stronger.

**Tuning method for stable processes**

In the design of the 2-DOF-IMC controller, there are two adjustable parameters, that is, \(\lambda\) in the set-point filter and \(\lambda_2\) in the internal model feedback filter. Note that the system performance is influenced by the two parameters greatly. As to the two parameters, \(\lambda\) affects the set-point tracking performance of the system, and \(\lambda_2\) influences both the set-point tracking performance and the disturbance rejection characteristics. Here, we first adjust the value of \(\lambda_2\), and the value of \(\lambda\) is tuned subsequently to achieve the desired set-point tracking performance.

In order to reduce the mutual influence, the value of \(\lambda_2\) is chosen to be slightly smaller than that of \(\lambda\). The following formula in which a weighting factor is employed is introduced for the set-point controller \(C_2(s)\)

\[
C_2(s) = \frac{\mu\lambda s + 1}{\lambda s + 1}
\]  

(17)

where \(0 \leq \mu \leq 1\). Note that \(C_2(s)\) will be equal to a filter with no lead item if \(\mu = 0\), and \(C_2(s)\) is equivalent to a proportional gain of 1 if \(\mu = 1\).

**FOPTD processes**

The FOPTD process is representative in industrial system, and the following FOPTD model is considered:\(^36,37\)

\[
G(s) = \frac{Ke^{-\theta s}}{Ts + 1}
\]  

(18)

where \(K, T\) and \(\theta\) are the gain, time constant and the time-delay of the model, respectively.

Here, the IMC filter is designed as the following form for the 2-DOF control

\[
h(s) = \frac{1}{\lambda_s + 1}
\]  

(19)

According to the design method described above, the controller \(C_1(s)\) is obtained

\[
C_1(s) = \frac{1}{G^-(s)[1 + \lambda_2s - G^+(s)]}

= \frac{0.5T\theta^2s^3 + (T\theta + 0.5\theta^2)s^2 + (T + \theta)s + 1}{K[0.5\lambda_2\theta^2s^3 + (\lambda_2 + 0.5\theta^2)s^2 + (\lambda_2 + \theta)s]}
\]  

(20)
Furthermore, the controller \( C_1(s) \) can adopt the PID control structure if it is rewritten in the following form

\[
C_1(s) = \frac{T_1 + T_2}{K_\lambda} \left( 1 + \frac{1}{(T_1 + T_2)s} + \frac{T_1 T_2}{T_1 + T_2} s \right) + \frac{1}{1 + \frac{1}{T_1 + T_2} s} + \frac{1}{s}\left( \frac{T_1 T_2}{T_1 + T_2} s \right) + \frac{1}{s}\left( \frac{T_1 T_2}{T_1 + T_2} s \right) s^2 + \ldots
\]

(21)

Consider the following PID control structure

\[
C_{PID}(s) = K_p + \frac{T_i}{s} + T_d s
\]

(22)

where \( K_p, T_i \) and \( T_d \) are the proportional, the integral and the differential coefficients of the PID controller.

By synthesizing equations (20)–(22) and letting \( W(s) = (m(s)/n(s)) \), the following formulas are derived

\[
m(s) = 0.5T\theta^2s^3 + (T\theta + 0.5\theta^2)s^2 + (T + \theta)s + 1
\]

\[
n(s) = K[0.5\lambda_2\theta^2s^2 + (\lambda_2 + 0.5\theta^2)s + (\lambda_2 + \theta)]
\]

(23)

\[
K_p = W'(0)
\]

\[
T_i = W^{-1}(0)
\]

\[
T_d = \frac{W''(0)}{2}
\]

(24)

then, the PID control parameters can be obtained according to the Maclaurin series expansion sequence

\[
T_i = K(\lambda_2 + \theta)
\]

\[
K_p = \frac{0.5\theta^2 + T\theta + \lambda_2 T}{K(\lambda_2 + \theta)^2}
\]

\[
T_d = \frac{0.5\theta^4 + T\theta^3 + \lambda_2 T\theta^2 + \lambda_2 \theta T}{4K(\lambda_2 + \theta)^3}
\]

(25)


### SOPTD processes

Here, we consider the following SOPTD process model

\[
G(s) = \frac{K e^{-\theta s}}{(T_1 s + 1)(T_2 s + 1)}
\]

(26)

where \( K \) and \( \theta \) are the gain and the time-delay of the process model, and \( T_1 \) and \( T_2 \) are the time constants of the process model.

In order to obtain the corresponding PID control parameters, we can rewrite the controller \( C_1(s) \) into the form of a PID controller connected in series with an advanced-lag filter

\[
C_1(s) = C_{PID}(s) = K_p \left( 1 + \frac{1}{T_i s} + T_d s \right)
\]

(27)

Through further calculation and simplification, the following formula is acquired

\[
ds^3 + bs^2 + cs + 1
\]

\[
\frac{ds^3 + es^2 + ps + 1}{ds^3 + es^2 + ps + 1}
\]

Finally, the relevant control parameters are derived

\[
a = 0; b = 0.5\theta^2; c = \theta; d = 0
\]

\[
e = 0.5\lambda_2\theta^2; p = \frac{\lambda_2\theta + 0.5\theta^2}{\lambda_2 + \theta}
\]

(29)

\[
K_p = \frac{T_1 + T_2}{K_\lambda}; T_i = T_1 + T_2; T_d = \frac{T_1 T_2}{T_1 + T_2}
\]

(30)

### Simulation

In this section, a FOPTD process and a SOPTD process are introduced to verify the validity of the proposed approach. Meanwhile, the recently presented strategies are also employed as the comparison.

#### Example 1

Consider the FOPTD process in Wang et al.\textsuperscript{12}

\[
G(s) = \frac{e^{-s}}{0.2s + 1}
\]

(31)

From the process model in equation (31), it is obvious that \( K, T \) and \( \theta \) are 1, 0.2 and 1. Here, we consider \( \lambda_2 = 2 \min (\theta, T) = 0.4 \), then the relevant PID control parameters are \( K_p = 0.4, T_i = 1.4 \) and \( T_d = 0.07 \). Note that the set-point tracking performance and disturbance rejection characteristics can be regulated separately in the developed approach. In order to test the relationship between the selection of \( \mu \) and the set-point tracking performance, five values are chosen, and the corresponding responses are shown as follows (see Figure 5).
It can be easily seen that the ensemble set-point tracking performance is better when \( \mu = 0.7 \), and the corresponding responses are fast with no overshoot. Meanwhile, we can find that the selection of \( \mu \) doesn’t affect the disturbance rejection performance.

Here, we introduce the approaches in Lee et al. and Qing et al. to evaluate the effectiveness of the proposed strategy. For a fair comparison, the same maximum sensitivity is chosen for all methods. In order to test the disturbance rejection ability for these approaches, the disturbance with amplitude of \( -0.2 \) is added. Figure 6 shows the corresponding responses for the three methods under no model/plant mismatch. We can easily see that the responses of the proposed scheme show good set-point tracking performance with small overshoot and oscillations. At the same time, the recovery ability under disturbance is also superior. From an overall perspective, the ensemble control performance of the developed scheme is the best.

In order to test the validity of these approaches further, here three model/plant mismatched cases are generated through the Monte Carlo method. Here, the maximum degree of mismatch is chosen as \( \pm 20\% \), and the three cases are as follows:

Case 1: \( K = 1.2, \: T = 0.2, \: \theta = 1.2 \).
Case 2: \( K = 0.9582, \: T = 0.1673, \: \theta = 1.1824 \).
Case 3: \( K = 1.1782, \: T = 0.2267, \: \theta = 0.9703 \).

Figures 7–9 show the relevant responses for all the schemes under cases 1–3. In these figures, it is obvious that the set-point tracking performance and disturbance rejection characteristics are the best in the responses of the presented strategy. As to the other two methods, bigger overshoot and oscillations are shown in their responses. In a word, the proposed scheme provides improved ensemble control performance.

**Example 2.** Consider the following SOPTD process in Wang et al.\(^{12}\)

\[
G(s) = \frac{e^{-2s}}{(s + 1)(0.7s + 1)} \quad (32)
\]

Here, \( T_1 = 1, \: T_2 = 0.7, \: K = 1 \) and \( \theta = 0.2 \). We select \( \lambda_2 \) as 4, then the relevant control parameters are
\( K_p = 0.425, \ T_i = 1.7, \ T_d = 0.41, \ a = 0, \ b = 2, \ c = 2, \)
\( d = 0, \ e = 1.33 \) and \( p = 1.67 \). In this section, \( \mu = 0.7 \) is also chosen for the developed method. Meanwhile, the strategies in Lee et al. and Qing et al. are also utilized as the comparison. The responses for these schemes under model/plant match are displayed in Figure 10. It is obvious that the responses of the proposed scheme are these with the smallest overshoot and oscillations, which implies that enhanced ensemble control performance is achieved for the developed strategy.

Similarly, three model/plant mismatched cases are produced via the Monte Carlo method to evaluate the validity of the proposed method further. Here, the maximum degree of mismatch is also \( \pm 20\% \), and the three cases are as follows:

Case 4: \( K = 1.1625, \ T_1 = 0.6331, \ T_2 = 0.9302, \theta = 1.9403 \).
Case 5: \( K = 0.8324, \ T_1 = 0.8283, \ T_2 = 1.1125, \theta = 2.1303 \).
Case 6: \( K = 1.1903, \ T_1 = 0.8835, \ T_2 = 1.1802, \theta = 1.8106 \).

The relevant responses for these approaches under cases 4–6 are displayed in Figures 11–13. In all cases, the presented strategy provides the smoothest responses with the smallest overshoot and oscillations. For the other two methods, their responses are with bigger overshoots and more drastic oscillations. In a word, modified ensemble control performance is obtained for the proposed control strategy.

**Conclusion**

In this paper, an improved design method of 2-DOF-IMC-PID controller is presented for stable process with time-delay. In the new design approach, set-point tracking performance and disturbance rejection characteristics are expected simultaneously by adjusting different controllers separately, and the proposed controller is designed for the FOPTD process and the SOPTD process, respectively. For the control of the FOPTD process, the Maclaurin expansion sequence and the PID controller approximation method are employed for the inner loop feedback controller, and the set-point
tracking controller can be further tuned to achieve better tracking performance. In the design for the SOPTD process, the PID controller connected in series with an advanced-lag filter is utilized for the inner loop controller to enhance disturbance rejection characteristics. Finally, simulations on the FOPDT process and the SOPTD process demonstrate the validity of the proposed strategy.

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