Design of a Performance-Adaptive PID Controller Based on IMC Tuning Scheme*

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***Abstract*—PID control schemes have been widely used in most process control systems for a long time. However, it is a very important problem how to choose PID parameters. Because these parameters give a great in uence on the control performance. Especially, it is dif cult to tune these parameters for time-varying systems. In this paper, performance adaptive controller is proposed for such systems, which is based on the IMC tuning scheme. It is well known that the IMC tuning method includes a user-speci ed parameter. According to this scheme, the user-speci ed parameter can be adjusted based on control performance.**

I. INTRODUCTION

In process industry, the PID controller[1], [2], [3] has been widely used because PID controller is simple and control parameters are clear. Since the control performance is strongly in uenced by the PID parameters, it is very important to choose these parameters. However, desirable control performance is not capable of obtaining when characteristics of systems have been changed or the controlled systems have large time-delay.

On the other hand, the Internal Model Control (IMC) has been proposed for large time-delay systems. According to the literature [4], IMC is proposed in continuous time. Furthermore, in the method of the literature [5], [6], it is proposed in desecrate time. The schemes of the literature [4], [5], [6] can be used to adjust PID parameters. Moreover, the discrete-time IMC tuning scheme can be accommodated to the non - minimum phase systems and unknown time-delay systems. In particular, in the literature [5], self-tuning PID control scheme has been proposed in the discrete-time IMC tuning scheme, which corresponding to time-varying systems.

However, the sequential adjustment of control parameters is not practical from the viewpoint of reliability and computational cost. The idea of so-called "Tuning on Demand" has appeared, in which the control parameters will be changed only when it is deteriorated. In other words, performance-adaptive control[7], [8], [9], [10], [11] becomes more necessary, which integrates "control performance evaluation" and "control system design".

This paper presents a discrete-time IMC tuning scheme. The control performance is evaluated and the controller parameters is adjusted by the proposed scheme only when the evaluation is not desired. The scheme of adjusting control parameters is to tune the adjustable parameter in the controller (1-parameter tuning), so as to satisfy the desired control performance which has been set in advance. Furthermore, numerical simulations is performed in order to verify the effectiveness of the proposed scheme.

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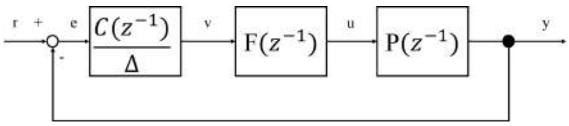

Fig. 1. Block diagram of the PID control system.

II. IMC TUNING OF PID PARAMETERS

A. System Description

The discrete-time system is described such as the equation:

$$A(z^{-1})y(t) = z^{-(d_m+1)}B(z^{-1})u(t) + \xi(t)/\Delta \quad (1)$$

$$\left.\begin{array}{l} A(z^{-1}) = 1 + a_1 z^{-1} \\ B(z^{-1}) = b_0 + b_1 z^{-1} + \cdots + b_m z^{-m} \end{array}\right\}. \quad (2)$$

In the (1) equation, $u(t)$ and $y(t)$ are the control input and system output respectively, ξ(t) shows the Gaussian white noise which has 0 mean and σ^2 variance. In addition, z^{-1} which implies $z^{-1}y(t)$=$y(t-1)$ is a backward operator. Δ denotes a difference operator which is de ned as $\Delta := 1 - z^{-1}$. Moreover, d_m shows the minimum estimate of the time-delay of controlled system. For example, d_m is set as 3 if controlled system has 3-5 step time-delay. In addition, m denotes the order of $B(z^{-1})$. If time-delay is ambiguous or unknown, elements of the low-order $B(z^{-1})$ is close to 0.

B. IMC Tuning

The calculation of PID parameters based on IMC tuning method is brie y explained. Fig. 1 shows the block diagram of the PID system. In Fig. 1, $C(z^{-1})/\Delta, F(z^{-1})$ and $P(z^{-1})$ are PID controller, rst-order lter and system can be expressed as:

$$C(z^{-1}) = k_c\left(\Delta + \frac{T_s}{T_I} + \frac{T_D}{T_s}\Delta^2\right) \quad (3)$$

$$F(z^{-1}) = \frac{1-f}{1-fz^{-1}} \quad (4)$$

$$P(z^{-1}) = \frac{z^{-(d_m+1)}B(z^{-1})}{A(z^{-1})}, \quad (5)$$

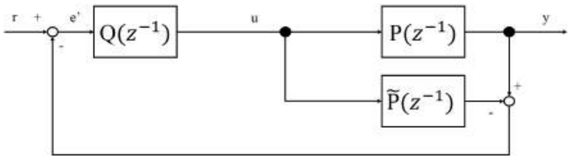

Fig. 2. Block diagram of the IMC system.

where k_c, T_I, T_D, T_s and f denote the proportional gain, reset time, derivative time, sampling time and lter parameter respectively.

Furthermore, Fig. 2 shows the block diagram of the IMC system. In Fig. 2, $Q(z^{-1})$ and $\widetilde{P}(z^{-1})$ denote the controller and internal model respectively. Consider $\widetilde{P}(z^{-1})$ which approximates to the $B(z^{-1})$ of the controlled system in the following equation:

$$\widetilde{P}(z^{-1}) = \frac{z^{-(d_m+1)}B(1)\alpha(1)}{A(z^{-1})\alpha(z^{-1})}, \tag{6}$$

where, $\alpha(z^{-1})$ is a polynomial given by the following equation:

$$\alpha(z^{-1}) = 1-\alpha_1 z^{-1}. \tag{7}$$

α_1 is the user-speci ed parameter, $0 \leq \alpha_1 < 1$. The controller is expressed as:

$$Q(z^{-1}) = \frac{A(z^{-1})}{B(1)} \cdot \frac{1-\lambda}{1-\lambda z^{-1}}, \tag{8}$$

where, λ is the user-speci ed parameter, $0 \leq \lambda < 1$. Additionally, non-minimum phase systems are accommodated by using $B(1)$ and avoiding pole-zero cancellation. If the Fig. 1 is equivalent to Fig. 2, the following equation is obtained:

$$\frac{C(z^{-1})F(z^{-1})}{\Delta} = \frac{Q(z^{-1})}{1-\widetilde{P}(z^{-1})Q(z^{-1})}. \tag{9}$$

According to the relation to equation (9), PID parameters and lter parameter can be calculated as:

$$k_c = \frac{1-\lambda}{B(1)(1-f)} \tag{10}$$

$$T_I = \frac{\gamma}{\gamma+a_1\alpha_1+1}T_s \tag{11}$$

$$T_D = \frac{a_1\alpha_1}{\gamma}T_s \tag{12}$$

$$f = \alpha_1\lambda, \tag{13}$$

where, γ is given as follows:

$$\gamma = a_1 - 2a_1\alpha_1 - \alpha_1. \tag{14}$$

Depending on the design of the α_1, the control response may become oscillatory which shows over damped more. In addition, λ is determined based on desired control performance which will be explained in the next section.

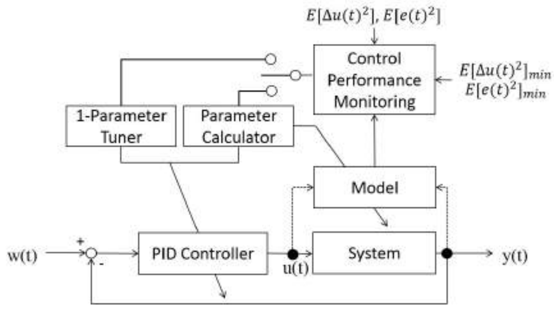

Fig. 3. Schematic gure of the Performance Adaptive Controller.

III. DESIGN OF PERFORMANCE ADAPTIVE PID CONTROLLER

A. Overview of the control system

Fig. 3 shows the schematic diagram of a performance adaptive PID control system. First, a desired control performance ($E[e^2(t)]_{min}$: variance of the control error in the steady state) is set in advance, and the $E[\{\Delta u(t)\}^2]_{min}$ is calculated, which is desired variance of variation of the control input. Second, in the "Control Performance Monitoring", current control performance ($E[e^2(t)]$, $E[\{\Delta u(t)\}^2]$) and the desired control performance are compared. Then, the PID controller is adjusted if the control performance is deteriorated. At this time, "1-Parameter Tuner" is only functioned basically. On the other hand, "Parameter Calculator" assists the maintaining desired control performance only when the characteristics of the system change signi cantly. Here, the PID parameters are calculated based on the IMC in the previous section.

B. Adjustment of λ based on the control performance evaluation

In this paper, given that λ of IMC tuning is adjusted based on the variance of the difference of the control error and the control input (Following, it is referred to as distributed control input for the sake of simplicity.). In IMC tuning, when varying the λ by a variation width $\Delta\lambda$, trade-off curve is obtained such as Fig.4. The vertical axis shows the variance of error signal control in steady-state $E[e^2(t)]$, the horizontal axis shows the distribution of the control input $E[(\Delta u(t))^2]$. A, B and C regions are described later.

In Fig.4, the variance of control error and input are changed by changing λ. At this time, it is important for the determination of λ. In this case, the user speci es the variance of error control σ_e^2 from Fig. 4, and determining λ in the variance of input control is to be smaller in satisfying the variance of error control. it corresponds to the point '•' in Fig.4. Therefore, the desired control performance is obtained by controlling to t the A region inside than desired control performance '•'.

However, it is considered that the control performance becomes bad if the characteristics of controlled system is changed in terms of time. It implies that the desired control performance is not obtained and there is the current control performance in B region or C region in Fig.4. Therefore, this

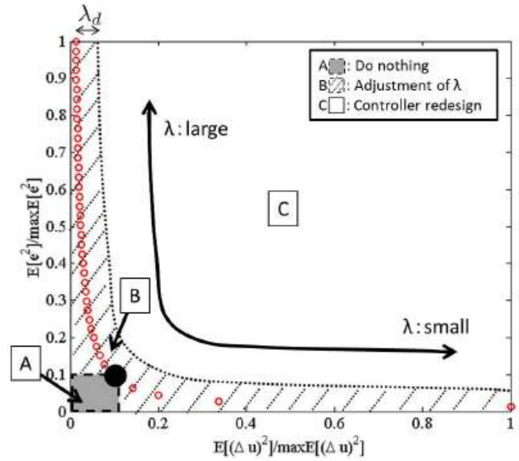

Fig. 4. Trade-off curve indicated by changing λ.

paper presents the method to maintain the desired control performance in B region by the 1-parameter tuning of only λ as control performance along the trade-off curve region. In addition, in the C area away from the trade-off curve, since it is considered adjustment by λ be a dif cult and re-adjust the control parameters using a closed-loop data. The user is arbitrarily set width λ_d to the boundary line of the C and B regions from trade-off curve.

According to the literature [7], the variance of control error $e(t)$ and the variance of input $\Delta u(t)$ can be calculated by the following equation, using the H_2 norm $||\cdot||_2$ as follows:

$$E[e^2(t)] = \left|\left| -\frac{1}{T(z^{-1})} \right|\right|_2^2 \sigma_\xi^2 \tag{15}$$

$$E[\{\Delta u(t)\}^2] = \left|\left| -\frac{C(z^{-1})}{T(z^{-1})} \right|\right|_2^2 \sigma_\xi^2, \tag{16}$$

where, $T(z^{-1})$ is de ned by the following equation:

$$\begin{aligned} T(z^{-1}): &= \Delta A(z^{-1}) \\ &+ z^{-1}B(z^{-1})C(z^{-1})F(z^{-1}). \end{aligned} \tag{17}$$

Equation (17) requires system parameters $A(z^{-1})$ and $B(z^{-1})$. These parameters are estimated by performing system identi cation by applying the least square method with input and output data.

Additionally, σ_ξ shows the standard deviation of the Gaussian white noise but the value of σ_ξ is unknown. Therefore, σ_ε is used, instead of the σ_ξ. Here, σ_ε is the standard deviation of the error of the estimation model output and actual system output ε.

IV. The proposed algorithm

Integrate the individual procedures that have been discussed so far, to build the proposed method. The algorithm is as follows by using Fig. 4. However, N is the number of data. Moreover, the variance of each is calculated as the time average on the assumption that ergodicity is established.

1^o Obtain closed-loop data using a stable control.

2^o Based on least square method, calculate $A(z^{-1})$ and $B(z^{-1})$ from closed-loop data.

3^o Calculate the equation (15) and (16) to get the trade-off curve of Fig. 4.

4^o Calculate the point ($E[(\Delta u(t))^2]_{min}$, $E[e^2(t)]_{min}$: '●' in Fig. 4) from the variance of error control σ_e^2 which is set by user, and adopt the PID parameters and λ.

5^o The following criterion J_r is obtained by using $E[(\Delta u(t))^2]_{min}$ and $E[e^2(t)]_{min}$ calculated at 4^o as the slope of the straight line passing through the origin and '●' in Fig. 4.

$$J_r = \frac{E[e^2(t)]_{min}}{E[(\Delta u(t))^2]_{min}} \tag{18}$$

6^o During N steps, control by using PID gains employed in 4^o.

7^o Using data from time t before the N steps, current variance of control error $E[e^2(t)]$ and variance of control input $E[(\Delta u(t))^2]$ are calculated. The current variance is examined whether is located any area like A, B or C.

Next, the following evaluation of the current expression J_t as the slope from origin to current variance is obtained by using $E[(\Delta u(t))^2]$ and $E[e^2(t)]$ by the same procedure as 5^o.

$$J_t = \frac{E[e^2(t)]}{E[(\Delta u(t))^2]} \tag{19}$$

8^o If the current variance $E[(\Delta u(t))^2]$ and $E[e^2(t)]$ of 7^o is located in A region, Go to 10^o. If it is located in B region, Go to 9^o. If it is located in C region, Go to 2^o (Use N data when going to 2^o).

9^o λ is re-selected and then adopted the PID gain corresponding to the λ. At this time, λ is increased or decreased by $\Delta\lambda$ in order to close current variance $E[(\Delta u(t))^2]$ and $E[e^2(t)]$ of 7^o to '●' in Fig. 4. In concretely, If satisfying following equation, $\lambda = \lambda + \Delta\lambda$. Otherwise, $\lambda = \lambda - \Delta\lambda$.

$$J(t) < J_r \tag{20}$$

10^o $t = t + 1$

11^o Return 7^o.

V. Numerical example

The effectiveness of the proposed method is veri ed by numerical examples. Furthermore, $d_m = 0$, $N = 300$, $\alpha_1 = 0.8$, $\Delta\lambda = 0.01$ are set.

[Ex.1]

First, consider the following equation system "First-order system with time-delay" as the controlled system:

$$G(s) = \frac{K}{1 + Ts} e^{-Ls}, \tag{21}$$

where, $T = 100, K = 0.1, L = 45$.

Discrete the equation (21) in the sampling time $T_s = 10.0[s]$ and the model to be controlled by adding a Gaussian white noise with mean 0 and variance 0.001 as the modeling error.

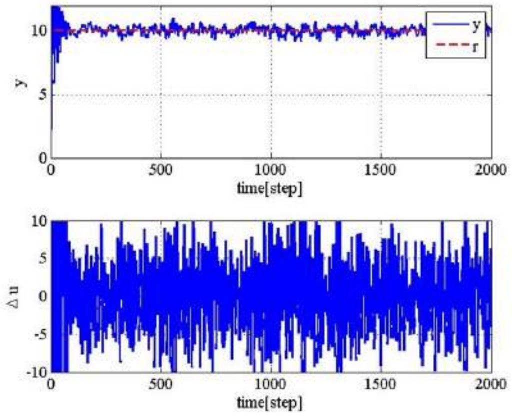

Fig. 5. Control result of $T = 100, K = 0.1, L = 45$ system by using the Conventional PID scheme.

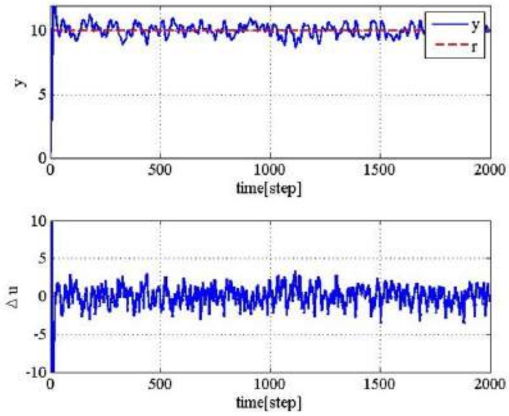

Fig. 7. Control result using the proposed control scheme in the case of $\sigma_e^2 = 0.30$.

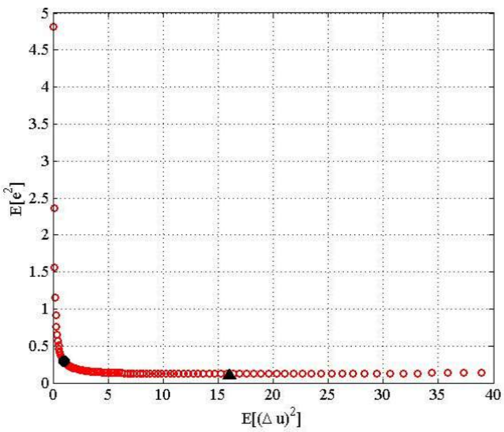

Fig. 6. Trade-off curve indicated by changing by changing λ.

First, the control result by using Ziegler-Nichols method[1] is shown in Fig. 5. At this time, PID parameters are calculated as follows:

$$k_c = 26.7, T_I = 90.0, T_D = 22.5. \tag{22}$$

Next, the trade-off curve by applying proposed method using input and output data of Fig. 5 is shown in Fig. 6. At this time, set the desired variance of error as $\sigma_e^2 = 0.30$ and desired variance of input is calculated as 1.66 by setting. In addition, the point '●' in Fig. 6 denotes the desired control performance by using proposed method and the point '▲' denotes the current control performance of Fig. 5. At this time, $\lambda = 0.84$ is determined and the PID parameters is calculated as follows:

$$k_c = 3.1, T_I = 175.6, T_D = 30.9. \tag{23}$$

Next, the control result by using proposed method is shown in Fig. 7. It is found that the variance of input is effectively suppressed by comparing Fig. 5 to Fig. 7. At this time, the variance of the error and input are 0.25 and 1.41 respectively. These variance values are close roughly to desired variance of error (0.30) and input (1.66).

[Ex.2]

In this numerical example, changing the characteristics of the system is considered. In addition, the system is same as [Ex.1] until 2000[step], however, the system gain and the time constant of the system is changed between 2001[step] to 5000[step] as follows:

$$\left.\begin{array}{l} T = 100 - \dfrac{40(t-2000)}{3000} \\[2ex] K = 0.1 + \dfrac{0.5(t-2000)}{3000} \end{array}\right\}. \tag{24}$$

Similarly, discrete in the sampling time $T_s = 10.0$[s] and the model to be controlled by adding a Gaussian white noise with mean 0 and variance 0.001 as the modeling error.

At this time, set the desired variance of error as $\sigma_e^2 = 0.30$ and desired variance of input is calculated as 1.66. The control result is shown in Fig. 8, the trajectories of PID parameters and λ are shown in Fig. 9. The variance of error and input are 0.25, 1.41 respectively in Fig. 8. These variance values are close roughly to desired variance.

At this time, T_I, T_D in Fig.9 are adjusted only one time at 4711[step], however, k_c is adjusted a lot of times before 4711[step]. This reason is that λ is changed in 9^o and only k_c depends on λ as can be seen from equation (10). From this result, for system change, one adjustment parameter λ is performed by rst. Nevertheless, if desired control performance can not be obtained, then the controller is redesigned. So, PID parameters are adjusted ef ciently.

Finally, for comparison, the control result by using Ziegler-Nichols method is shown in Fig. 10. In Fig. 10, the control system becomes unstable because there is no adjusting λ for changing the characteristics of the controlled system. From this result, the effectiveness of adjusting λ online is observed.

Finally, Fig.10 shows the control result with applying the only $1^o \sim 4^o$ of proposed method for comparison. The control system has nally fallen into unstable since the PID parameters are not adjusted. From the above results, the

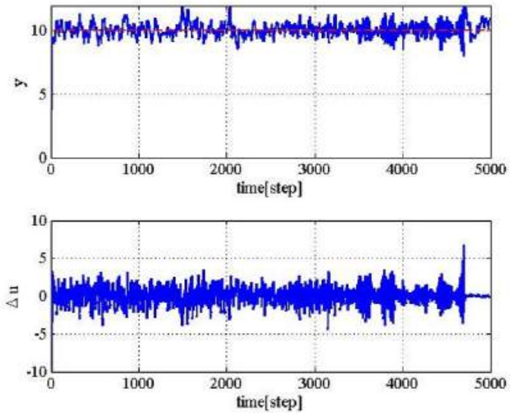

Fig. 8. Control result of changing system by using the proposed control scheme in the case of $\sigma_e^2 = 0.30$.

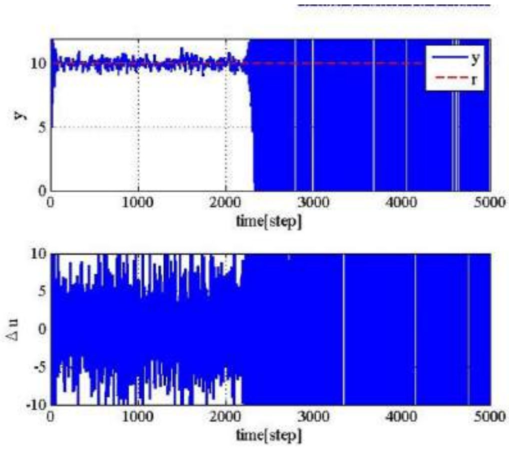

Fig. 10. Control result of changing system by using the Conventional PID scheme.

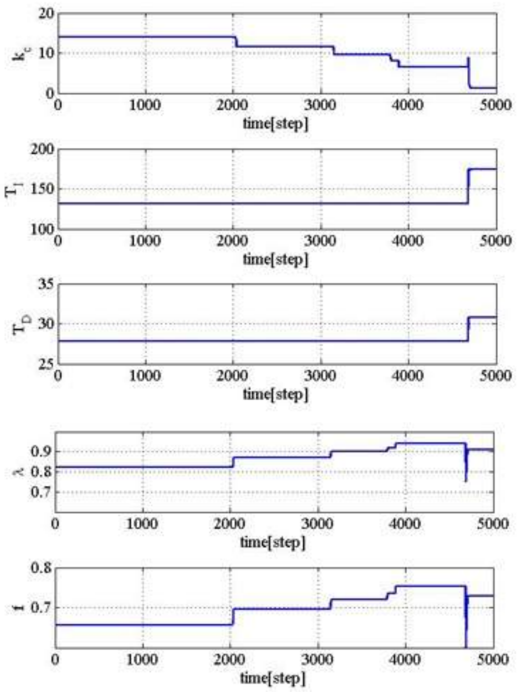

Fig. 9. Trajectories of PID parameters and λ parameter corresponding to Fig.8.

effectiveness of changing the adjustable parameters λ online and redesigning the controller as necessary are recognized.

VI. Conclusion

In this paper, performance-adaptive control for the process control systems has been proposed, which is based on IMC tuning scheme. The main feature of this scheme is that the adjustable parameter λ is tuned to achieve the desired control performance for large time-delay systems. In the numerical simulation, the control parameters to obtain the desired control performance have been con rmed to be calculated by specifying the control performance. Moreover, when the characteristics of the controlled system are changed, the desired control performance can be obtained ef ciently which has been con rmed by tuning adjustable parameters λ. In the future, the plan is to precede the effectiveness of the proposed method by using actual system of the processes.

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