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FRIT based PID parameter tuning for linear time delay systems - Simultaneous attainment of models and controllers - [1]

Osamu Kaneko * **Yusuke Wadagaki** ** **Shigeru Yamamoto** *

* *Institute of Science and Engineering, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa, 920-1192, Japan (e-mail: {o-kaneko, shigeru}@t.kanazawa-u.ac.jp).*
** *Graduate School of Natural Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa, 920-1192 Japan (e-mail: wadagaki@moccos.ec.t.kanazawa-u.ac.jp)*

Abstract: In this paper, we provide a new method of the PID parameter tuning for time-delay systems by utilizing the fictitious reference iterative tuning (FRIT), which is a controller tuning method enabling us to obtain the desired parameter with only one-shot experimental data. Here, by relating the conventional PID controller to the internal model controller (IMC), we show that PID parameters obtained as the result of the FRIT yield not only a desired controller but also a mathematical model of the controlled time delay system. In order to show the validity of the proposed method, we give an illustrative example.

Keywords: Controller tuning, PID, Data-driven control, Time-delay

1. INTRODUCTION

It is no doubt that PID controllers are widely used in many industrial applications (Astrom and Hagglind (1995), Suda (1992)). One of the reasons for this is that each component in a PID controller is intuitively understandable. Another reason is that a PID controller is with only three tunable parameters which leads to the enhancement of ease in handling. However, the latter reason does not necessarily reflect preferable features of PID controllers. One of the most bothersome drawbacks is that there is no guideline in quantitative form that is effective for the tuning of the parameters. In order to overcome this problem, it is rational to construct a mathematical model of a plant based on system identification techniques. Once we can have an appropriate mathematical model, it is possible to obtain desired parameters that reflect the dynamics of a plant and a design specification. On the other hand, there are many cases in which it is difficult to take a time and cost for some experiments required in the modeling from the view points of the management of a plant and the scheduling of a production process. As another background, there are also many cases in which it is impossible to apply high persistently excited signals to a plant for the identification of the plant from the view point of a safe operation. In these possible cases, one can not perform an ideal experiment for obtaining a model of a plant.

Thus, if the desired PID parameters can be directly obtained from the data which measured under the normal operation, then the time and cost can be reduced. Thus, an approach that directly utilizes the data for controller parameter tuning is useful and effective from the practical points of view. In this point, Iterative Feedback Tuning (IFT, Hjalmarsson et al. (1998)), Virtual Reference Feedback Tuning (VRFT, Campi et al. (2002)), Fictitious Reference Iterative Tuning (FRIT, Souma et al. (2004) and Kaneko et al. (2005)) were provided. The IFT is the most rational approaches in the sense the cost function to be minimized is directly evaluated. However, the IFT requires many experiments in order to perform the non-linear optimization. This is a crucial problem in the case where we can not take the time and the cost. The VRFT and the FRIT use only one-shot experimental data for obtaining the desired parameters. The FRIT focuses on the output while the VRFT focuses on the input, so the FRIT is intuitively understandable in the case where the objective is to achieve the desired output. From this, we also focuses on the FRIT for the direct data-driven tuning of the PID parameters.

On another front, a mathematical model is also important. The reason for this is that a mathematical model can be utilized for the estimation of the aging change, fault detection, diagnosis of malfunction, and so on. Particularly, it is usual that the dynamics of a plant is approximated as a facile mathematical model like a first-order system with a time-delay, because such a model enables us to capture the main characteristics of the plant by using only a gain, a time constant, and a time delay, which yields the ease of analysis of the plant. From this, we see that the simultaneous attainment of not only a desired controller but also a facile mathematical model is useful with respect to the practical applications. In addition, in the case where the objective of a control system is to track a given desired output, it is impossible to give the reference model of the closed loop that exceed the limit of the performance of

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a plant, like a time-delay, an initial undershoot and so on. Under the situation in which the actual dynamics of a plant is unknown, it is also impossible to give an appropriate reference model as a specification. Thus, it is meaningful to obtain the information of the plant from the data in the sense that we can also give an appropriate reference model.

Actually, the authors studied the simultaneous attainment of a desired parameter and a mathematical model of a plant by using the FRIT in Kaneko et al. (2010). Particularly, we focused on linear systems with time-delay in Kaneko et al. (2011b) and Kaneko et al. (2011a) as one of the representative systems which are used as typical mathematical model many applications. As for related studies on the parameter tuning for time-delay systems, the application of the IFT(Hjalmarsson et al. (1998)) to the IMC for the Smith compensator was studied in Bruyne (2003). The IFT requires many experiments in order to update the parameter of a controller so as to achieve the minimization of the performance index. Thus, the method in Bruyne (2003) spends considerable expense and time. Moreover, Bruyne (2003) did not take into account obtaining a mathematical model. As another related approach, Formentin et al. (2010) proposed application of the VRFT Campi et al. (2002) for time-delay system in the IMC. The VRFT enables us to obtain a desirable parameter with only one-shot experiment. In this sense, the method in Formentin et al. (2010) is effective from the practical points of view. However, the simultaneous attainment of a controller and a parameter can not be performed. As for the simultaneous attainment of a controller and a model for time-delay systems, Abe and Ichihara (1999) studied the application of wind-surfer approach (Lee et al. (1995), Lee (1999) and so on) to Internal Model Controller (IMC, Morari et al. (1984) and Morari and Zafiriou (1989)). Although the aim of Abe and Ichihara (1999) was to obtain both of a mathematical model of a plant and a desirable controller for time-delay systems, many iterative experiments are also required. Compared with these related studies, the authors developed the simultaneous attainment of a controller and a mathematical model for linear time-delay systems in Kaneko et al. (2011b) and Kaneko et al. (2011a) by using the FRIT in the IMC framework. Since the FRIT requires only one-shot experiment, the approach by the authors has a great advantage with respect to practical points of view in the sense that only one-shot experiment data yields not only a desired parameter and but also a mathematical model.

From these backgrounds, we provide a new method of the PID parameter tuning for time-delay systems by utilizing the FRIT as one of the extensions of the studies by the authors (Kaneko et al. (2011b) and Kaneko et al. (2011a)). Here, we relate the conventional PID controller and the IMC (or the Smith compensator). And then, by using such a relation, we show that the PID parameters which are obtained as the result of the FRIT yields not only a desired controller but also a mathematical model of a plant.

[Notation] For a rational transfer function $G(s)$, we denotes the output signal of G with respect to the input signal u as $y = Gu$ for the enhancement of the readability. For a time signal w, we denote the value of w at the time t as $w(t)$. For a time signal w, we denote the delayed signal as $e^{-Ls}w(t) := w(t-L)$. Under the sampling period Δ, we prepare the norm defined by

$$\|w\|_{(N,\Delta)} := \sqrt{\frac{1}{N+1}\sum_{i=0}^{N}(w(\Delta i))^2}$$

for the sampled time series of w from $t = 0$ to $t = N\Delta$.

2. PRELIMINARIES

In this paper, we assume that a plant is a linear and time-invariant system with time-delay described by

$$P = P_l e^{-Ls} \tag{1}$$

where P_l and L denote the lumped part and the time delay of P, respectively. We also assume that P_l is stable. We suppose that P_l and L are unknown. A control system we treat here is illustrated in Fig. 1. C_{PID} denotes a conventional PID controller described by

$$C_{PID} = K_P + \frac{K_I}{s} + \frac{K_D s}{\gamma s + 1} \tag{2}$$

where K_P, K_I, and K_D are a proportional, an integral, and a differential gain, respectively. All of these three parameters are tunable. We denote them as $\rho := [K_P, K_I, K_D]$ and also denote as $C_{PID}(\rho)$. The constant γ determines the frequency range over which the element $K_D s/(\gamma s + 1)$ can be approximated as a differentiator. Let $G_{ry}(\rho)$ be a closed loop transfer function with $C_{PID}(\rho)$ from the reference signal r to the output y. The input and the output of P are also regarded as functions of ρ, so they are denoted with $u(\rho)$ and $y(\rho)$, respectively.

3. PROBLEM FORMULATION

3.1 Reference models

In this paper, the objective of tuning of the PID controller is to achieve a desired output. In general, it is impossible to achieve the desired output of the reference model whose relative degree is less than that of a plant. Similarly, it is also impossible for a linear time delay system to track the desired output whose delay is shorter that of a plant. Since these limitations of performances are related to the inherent characteristics which can not be improved by controllers, a reference model should not excess these limitations. However, our setting is that the dynamics of a plant is unknown, so we can not give an appropriate reference model that does not contradicts to the actual dynamics of a plant. This means that we should obtain the information of the plant to be included in the reference model from the actual data. From these reasons, we give a reference model as

$$T_d(\lambda, \tilde{L}) = \frac{1}{\lambda s + 1} \cdot \frac{1 - \tilde{L}s/2}{1 + \tilde{L}s/2}. \tag{3}$$

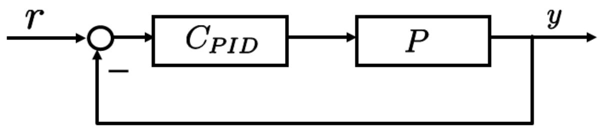

Fig. 1. A closed loop with the PID controller

In (3), λ corresponds to the time constant of the lumped part of P under the assumption that it is possible to approximate P as the series of the time-delay $e^{-\tilde{L}s}$ and the first order dynamical system as

$$P_M(K,T,\tilde{L}) = \frac{K}{Ts+1}\frac{1-\tilde{L}s/2}{1+\tilde{L}s/2}, \tag{4}$$

where the time-delay part is also described by the Pade approximation with an unknown time-delay $\tilde{L}$. Thus, it should be noted that both of λ and $\tilde{L}$ are also tunable parameters.

In Masuda et al. (2010), the idea that the unknown time-delay is included in the reference model in the framework on the tuning of a controller [2] has already been proposed. This paper proposes that not only the delay but also the lumped part are included in the reference model, which is different from Masuda et al. (2010). Moreover, the reference model with an unknown parameter is used for tuning of IMC, which is discussed in the later, which is another different point from the work of Masuda et al. (2010).

3.2 Problem formulation

In order to obtain the PID parameters that achieve the desired output, we introduce the following cost function

$$J(\rho,\tilde{L},\lambda) := \|y(\rho) - T_d(\lambda,\tilde{L})r\|^2_{(N,\Delta)}. \tag{5}$$

The objective is to find the parameters ρ, $\tilde{L}$, and λ such that $J(\rho,\tilde{L},\lambda)$ is minimized. Of course, the use of the IFT yields the optimal parameters of J. However, as stated in Section 1, it is preferred that the optimal parameters can be obtained as less experiment as possible. From this requirement, we investigate whether the optimal parameter can be obtained with only one-shot experimental data. In addition, we also investigate whether it is possible to obtain the parameters K, T, and $\tilde{L}$ such that $P_M(K,T,\tilde{L})$ is close to the actual plant P by using the PID parameters.

Problem 3.1. Set the initial parameter ρ^0 and assume that the output of $G_{ry}(\rho^0)$ is at least bounded with respect to the reference signal r in order to obtain the initial data. Perform one-shot experiment and obtain the data $u^0 := u(\rho^0)$ and $y^0 := y(\rho^0)$, respectively. Then, the problem is to find the optimal PID parameters with λ^* and $\tilde{L}^*$ such that minimize $J(\rho,\tilde{L},\lambda)$ and simultaneously the parameters K^* and T^* such that $P_M(K^*,T^*,\tilde{L}^*)$ approximate P as closely as possible based on the direct use of y^0 and u^0. □

Problem 3.1 requires the optimal parameters that yield both of the desired tracking property and the model reflecting the dynamics of the actual plant.

In Abe (2003), it was shown that the PID parameters are related to the parameters of the mathematical model described by (4) by rewriting the PID controller as the IMC controller (Morari and Zafiriou (1989)). The result of this paper is also based on this idea, which will be given in the following section. However, their idea is that the parameters for the facile mathematical model can be utilized for the desired controller parameter. Compared with this, our approach also uses not only this idea but also the converse direction, that is, we focus on that the desired PID parameter can also be utilized for attaining the parameters of the mathematical model.

[2] Masuda et al. (2010) also treats the application of FRIT to tuning of a controller for linear time-delay system

4. FICTITIOUS REFERENCE ITERATIVE TUNING (FRIT)

In this section, we give a brief review of the fictitious reference iterative tuning (FRIT) based on the references (Kaneko et al. (2005), Souma et al. (2004)) which is a main tool for solving Problem 3.1.

Fig.2 illustrates a conventional feedback control system that consists of a plant and a controller $C(\rho)$ with a tunable parameter ρ. Consider the problem on finding the parameter ρ^* minimizing $J(\rho) = \|y(\rho) - T_d r\|_{(N,\Delta)}$ with T_d which is a desired transfer function from r to y. First, by using the initial parameter ρ^0, perform the first experiment on the closed loop system with $C(\rho^0)$ and obtain the initial data $u^0 := u(\rho^0)$ and $y^0 := y(\rho^0)$. Here we also assume that $C(\rho^0)$ tentatively stabilize the closed loop so as to yield the bounded input and output. By using them, we compute the fictitious reference signal $\tilde{r}(\rho)$ (which was introduced by Safonov and Tsao (1997) in the unfalsified control framework) described by

$$\tilde{r}(\rho) = C(\rho)^{-1}u^0 + y^0. \tag{6}$$

Next, we introduce the cost function described by

$$J_F(\rho) = \|y^0 - T_d\tilde{r}(\rho)\|_{(N,\Delta)}. \tag{7}$$

Then we minimize $J_F(\rho)$ and implement $\tilde{\rho}^* := \arg\min_\rho J_F(\rho)$ to the controller. Note that (7) with the fictitious reference $\tilde{r}(\rho)$ in (6) requires only u^0 and y^0. This means that the minimization of (7) can be performed *off-line* by using only one-shot experimental data. As for the relationship between the minimization of $J(\rho)$ and that of $J_F(\rho)$, it was shown in Theorem 3.1 in Souma et al. (2004) that $J(\tilde{\rho}^*) = 0$ is equivalent to $J_F(\tilde{\rho}^*) = 0$. Although it is difficult to ideally minimize the cost function $J_F(\rho)$ to be zero, this relation implicitly means that the minimization of $J_F(\rho)$ is deeply related to that of $J(\rho)$.

5. MAIN RESULT

5.1 Simultaneous attainment and the IMCs

First, in addition to the closed loop in Fig. 1, we consider the IMC structure illustrated in Fig. 3 (Morari and Zafiriou (1989)). In Fig. 3, C_{FB} is a feedback controller. From the preceding result by the authors in Kaneko et al.

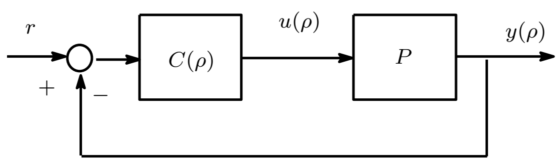

Fig. 2. A conventional feedback control system

(2010) and Kaneko et al. (2011b), if the feedback controller is constructed as

$$C_{FB} = \frac{T_d}{P_M} \tag{8}$$

then $G_{ry} = T_d$ is (generically) equivalent to $P = P_M$. That is, the desired reference transfer function by using IMC with (8) if and only if the internal model P_M identifies the plant P [3]. If a plant is with unstable zeros and/or a time-delay, P_M is described by $P = P_{Mm}P_{Mn}$ where P_{Mm} and P_{Mn} are the minimum phase and the non-minimum phase parts of P_M, respectively. Then, by setting $T_d = T_{dm}P_{Mn}$ where T_{dm} is a given reference model which is minimum phase,

$$C_{FB} = \frac{T_{dm}}{P_{Mm}} \tag{9}$$

yields the property that $G_{ry} = T_{dm}P_{Mn}$ is generically equivalent to $P = P_M$.

In this paper, these relevant transfer functions are given as follows;

$$P_{Mm} = \frac{K}{Ts+1} \tag{10}$$

$$P_{Mn} = \frac{1 - Ls/2}{1 + Ls/2} \tag{11}$$

$$T_{dm} = \frac{1}{\lambda s + 1}. \tag{12}$$

The feedback controller described by (8) or (9) is a key for the simultaneous attainment of models and controllers.

5.2 PID controllers and IMC

By using (8) or (9), we can rewrite Fig. 3 as Fig.4. Moreover, since P_M and T_d are parameterized as (4) and (3), respectively, the controller C in Fig.4 is described by

$$C(K, T, \tilde{L}, \lambda) = \frac{T_{dm}P_{Mm}^{-1}}{1 - T_{dm}P_{Mn}}$$

$$= \frac{\frac{T\tilde{L}}{2}s^2 + (T + \frac{\tilde{L}}{2})s + 1}{K\left(\frac{\lambda\tilde{L}}{2}s^2 + (\lambda + \tilde{L})s\right)} \tag{13}$$

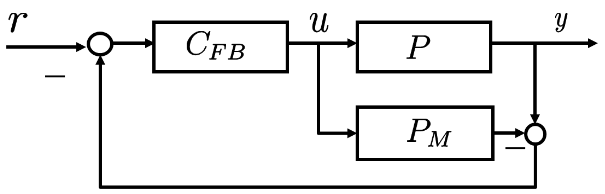

Fig. 3. The IMC structure

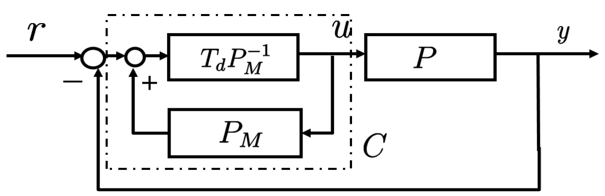

Fig. 4. The IMC structure with C_{FB} by (8)

[3] As shown in Morari and Zafiriou (1989) and so on, it is very well-known fact that $P_M = P$ implies $T_d = G_{ry}$ under $C_{FB} = T_d/P_M$. However, the converse direction is provided by the authors in Kaneko et al. (2010)

with unknown parameters $K, T, \tilde{L}$ and λ. Here, by equalizing the PID controller C_{PID} of (2) and C of (13), we can obtain the relationships between the PID gains and the parameters of the internal model can be described by

$$K = \frac{1}{K_I(\lambda + \tilde{L})} \tag{14}$$

$$T = \frac{K_P}{K_I} + \gamma - \frac{\tilde{L}}{2} \tag{15}$$

$$T = \frac{2}{\tilde{L}K_I}(K_D + K_P\gamma) \tag{16}$$

$$\lambda = \frac{-2\gamma\tilde{L}}{2\gamma - \tilde{L}}. \tag{17}$$

These relations are used for obtaining of the parameters of the mathematical model.

5.3 FRIT for the tuning of PID gains and the parameters of the model

We apply the FRIT to tuning of the PID gains. The cost function to be minimized in this case is

$$J_F(\rho) = \|y^0 - T_d(\lambda, \tilde{L})\tilde{r}(\rho)\|^2_{(N,\Delta)} \tag{18}$$

where the fictitious reference is described by

$$\tilde{r}(\rho) = C_{PID}(\rho)^{-1}u^0 + y^0. \tag{19}$$

It should be noted that λ and $\tilde{L}$ are also updated in the nonlinear optimization of (18) . At this point, it is natural to consider that λ of the reference model depends on the the time delay $\tilde{L}$. From this observation, we determine λ by using (17) with the obtained $\tilde{L}$ at each step of the iterative computation in the nonlinear optimization.

After the optimization, we can obtain the optimal parameters that minimizes J_F, say $\rho^* =: [K_P^*,\ K_I^*,\ K_D^*]$, $\tilde{L}^*$ and λ^*. By using K_I^*, $\tilde{L}^*$ and λ^*, (14) yields the parameter K. Moreover, by solving two algebraic equations (15) and (16) with respect to one unknown parameter, we can obtain the approximated value of T. As a result, by utilizing the FRIT, we obtain not only the desired PID gain but also the parameters of the mathematical model.

5.4 Algorithms

We summarize the proposed algorithm as follows.

0 Set the initial PID parameter ρ^0 and the initial reference model with λ^0 and $\tilde{L}^0$.
1 Perform one shot experiment and obtain u^0 and y^0.
2 Execute the non-linear optimization off-line:
  Set $i = 0$.
  While $J_F(\rho^i, \tilde{L}^i, \lambda^i) > \epsilon$;
    Compute the gradients $\left.\frac{\partial J_F}{\partial \rho}\right|_{\rho^i}$ and $\left.\frac{\partial J_F}{\partial \tilde{L}}\right|_{\tilde{L}^i}$.
    Compute ρ^{i+1} and $\tilde{L}^{i+1}$ by using the update computation with the gradients.
    Compute λ^{i+1} with $\tilde{L}^{i+1}$ by using (17)

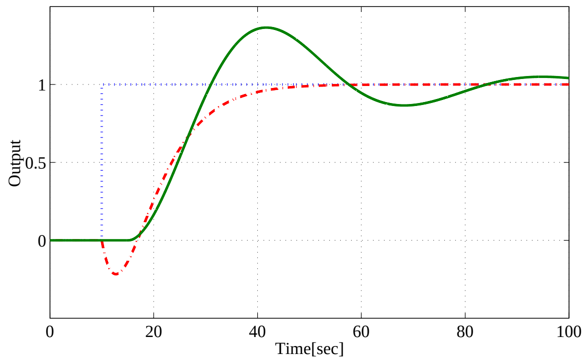

Fig. 5. The initial output $y(\rho^0)$ (the solid line), the desired output with tunable parameters $T_d(\lambda^0, \tilde{L}^0)r$ (the dot-and-dash line), and the reference signal r (the dotted line)

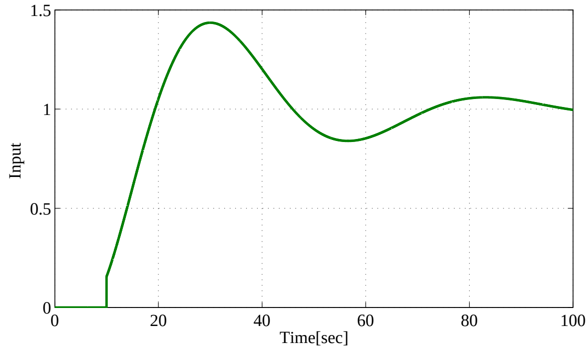

Fig. 6. The initial input $u(\rho^0)$

i=i+1;
End

3 Obtain K^* and T^* by applying ρ^*, $\tilde{L}$, and λ^*, to (14), (15), and (16).
4 Implement ρ^* and perform the experiment .

6. EXAMPLE

In order to show the validity of the result of this paper, we give a numerical example. An unknown pant we treat is

$$P_l e^{-Ls} = \frac{12s+8}{20s^4+113s^3+147s^2+62s+8}e^{-5s}$$
$$= \frac{12s+8}{20(s+4)(s+1)(s+0.4)(s+0.25)}e^{-5s} \quad (20)$$

where the lumped part is given as the benchmark problem in Suda (1992). A reference model is given as

$$T_d(\lambda, \tilde{L}) = \frac{1}{\lambda s+1}\frac{1-\tilde{L}s/2}{1+\tilde{L}s/2} \quad (21)$$

where $\tilde{L}$ and λ are also unknown. Under these settings, we perform the initial experiment with the initial parameters $K_P^0 = K_I^0 = K_D^0 = 0.1$ with $\gamma = 1.8$. The initial output and input data are illustrated in Fig. 5 and Fig. 6, respectively.

In Fig. 5, the dotted line, the slid line and the dot-and-dash line describe the reference signal, the initial output $y(\rho^0)$,

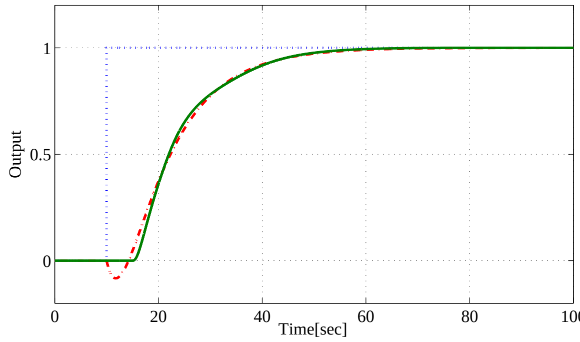

Fig. 7. The output with the optimal PID parameter $y(\rho^*)$ (the solid line), the desired output with the optimal parameters $T_d(\lambda^*, \tilde{L}^*)r$ (the dot-and-dash line), and the reference signal r (the dotted line)

and the initial desired output $T_d(\lambda^0, \tilde{L}^0)r$ with $\lambda^0 = 5.3514$ and $\tilde{L}^0 = 11$, respectively.

By using y^0 and u^0, we perform the proposed method. The optimal PID parameters are obtained as $K_P^* = 0.4282$, $K_I^* = 0.0664$, $K_D^* = 0.782$. As for the reference model, the optimal time delay and the time constant are obtained as $\tilde{L}^* = 5.8225$ and $\lambda^* = 9.4313$, respectively. In order to see whether $\rho^* = [K_P^* \ K_I^* \ K_D^*]$ satisfies the desired output of the optimal reference model, we implement ρ^* and perform the closed loop experiment. In Fig. 7, the output $y(\rho^*)$ and $T_d(\lambda^*, \tilde{L}^*)r$ are illustrated.

The reference model with $\tilde{L}^*$ and λ^* yields the initial under shoot due to the unstable zeros which are obtained by the Pade approximation of the time delay. However, we see that the delay can be approximated by the initial undershoot. Moreover, we also see that the output can tracks the desired response of the reference model . Thus, we see that the optimal parameter are desired with respect to the control.

Next, we focus on how the obtained model $P_M(K^*, T^*, \tilde{L}^*)$ approximates the actual plant. The obtained model is

$$P_M(K^*, T^*, \tilde{L}^*) = \frac{0.9879}{(5.2484s+1)}\frac{(1-2.911s)}{(1+2.911s)}. \quad (22)$$

We validate the gain and the phase characteristics in Fig. 8 and Fig. 9, respectively. From Fig. 8, we see that the gain characteristics can be identified. As for Fig. 9, we see that the phase characteristics can be identified under the cut-off frequency 1/9.4313 of $T_d(\lambda^*, \tilde{L}^*)$ over which the accurate identification is required for the desired specification.

7. CONCLUSION

In this paper, we have provided a new method of the PID parameter tuning for time-delay systems with the FRIT, which is a parameter tuning method with only one-shot experimental data. Here, we have related the conventional PID controller and a controller with some specific structure. By using such a relation, we have shown that the PID parameters which are obtained as the result of the FRIT yields not only a desired controller but also a facile mathematical model of a plant.

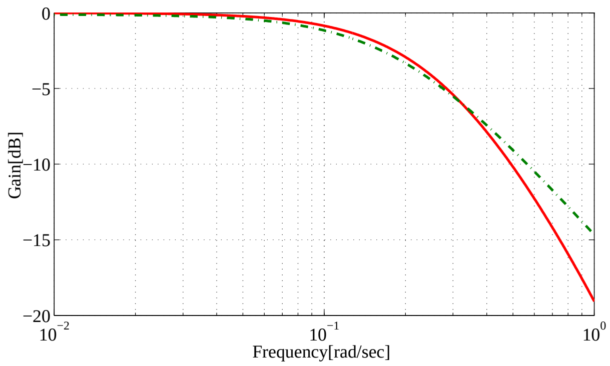

Fig. 8. The frequency characteristics(Gain): $P_l e^{-Ls}$ (the solid line), $P_M(K^*, T^*, \tilde{L}^*)$ (The dot-and-dash line)

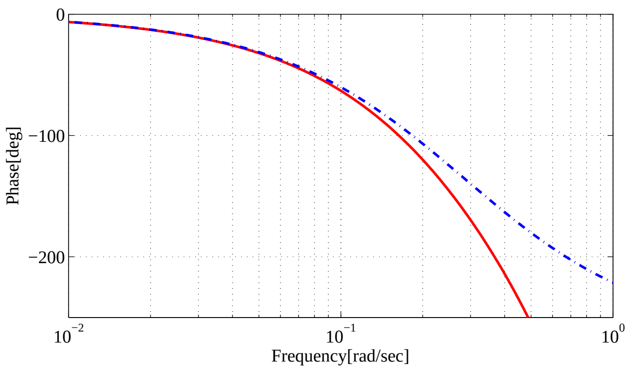

Fig. 9. The frequency characteristics(phase): $P_l e^{-Ls}$ (the solid line), $P_M(K^*, T^*, \tilde{L}^*)$ (The dot-and-dash line)

Future direction of this study is to apply the proposed method here to many various applications in order to show that the result is useful and effective for the actual problem. In addition, the effect of noise and the stability of the obtained parameters should be clarified so as to be utilized for industrial applications.

REFERENCES

Abe, N. (2003). Control of time delay systems (in japanese). *http://www.messe.meiji.ac.jp/~abe.*

Abe, N. and Ichihara, H. (1999). Closed-loop identification and imc design for system with an input time delay. *Proceedings of European Control Conference 1999*, CD-ROM.

Astrom, K. J. and Hagglind, T. (1995). *PID Controllers: Theory, Design, and Tuning*. Instrumentation Systems.

Bruyne, F. D. (2003). Iterative feedback tuning for internal model controllers. *Control Engineering Practice*, 11, 1043–1048.

Campi, M. C., Lecchini, A., and Savaresi, S. M. (2002). Virtual reference feedback tuning: a direct method for the design of feedback controllers. *Automtica*, 38, 1337–1446.

Formentin, S., Corno, M., and Savaresi, S. (2010). Virtual reference feedback tuning of internal model controllers. *Proceedings of the 49th IEEE Conference on Decision and Control*, 5542–5547.

Hjalmarsson, H., Gevers, M., Gunnarsson, S., and Lequin, O. (1998). Iterative feedback tuning:theory and applications. *IEEE control systems magazine*, 1, 26–41.

Kaneko, O., Souma, S., and Fujii, T. (2005). A fictitious reference iterative tuning (FRIT) in the two-degree of freedom control scheme and its application to closed loop system identification. *Preprints of The 16th IFAC World Congress*, CD-ROM.

Kaneko, O., Wadagaki, Y., Nguyen, H. T., and Yamamoto, S. (2011a). Fictitious reference iterative tuning for a system with a time-delay and/or unstable zeros in the internal model control architecture. *Proceedings of the 2011 IEEE Multi-conference on Systems and Control (CCA)*, 7684–7689.

Kaneko, O., Wadagaki, Y., and Yamamoto, S. (2010). Fictitious reference iterative tuning for internal model controllers. *Proceedings of the 10th IFAC Workshop on Adaptation and Learning in Control and Signal Processing.*

Kaneko, O., Yamamoto, S., and Wadagaki, Y. (2011b). Simultaneuos attainment of a controller and model for linear-time delay systems with the data-driven smith compensator. *Preprits of the 18th IFAC World Congress*, 7684–7689.

Lee, B. K. (1999). Closed-loop system identification using dual youla control parameterization. *International Journal of Control*, 62, 1175–1195.

Lee, W. S., Anderson, B. D. O., Mareels, I. M. Y., and Kosut, R. L. (1995). On some key issues in the windsurfer approach to adaptive robust control. *Automatica*, 31, 1577–1594.

Masuda, S., Kano, M., Yasuda, Y., and Li, G. D. (2010). A fictitious reference iterative method with simultaneous delay parameter tuning of the reference model. *International Journal of Innovative Computing, Information and Control*, 6, 2927–2939.

Morari, M., Skogestad, S., and Rivera, D. E. (1984). Implications of internal model control for PID controllers. *Proceedings of American Control Conference*, 661–666.

Morari, M. and Zafiriou, E. (1989). *Robust Process Control*. Prentice-Hall, Inc., New Jersey.

Safonov, M. G. and Tsao, T. C. (1997). The unfalsified control concept and learning. *IEEE Transactions on Automatic Control*, 42, 843–847.

Souma, S., Kaneko, O., and Fujii, T. (2004). A new method of controller parameter tuning based on input-output data, –fictitious reference iterative tuning. *IFAC Workshop on Adaptation and Learning in Control and Signal Processing (ALCOSP 04)*, 789–794.

Suda, N. (1992). *PID Control (in Japanese)*. Asakura Shoten.