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A TDOF PID CONTROL SYSTEM DESIGN BY REFERRING TO THE MD-PID CONTROL SYSTEM AND ITS SENSITIVITIES

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***Abstract*— PID controls are widely used as a basic control technology in the industrial control system today. However, tuning of PID control systems is not always easy, because of their simple control structures for wide classes of industrial control processes. The tuning of a two-degree-of-freedom(TDOF) PID control system which is increased configuration parameters, is more difficult. In order to obtain good control performances for wide classes of process control systems, we developed a Model-Driven PID(MD-PID) control system[15], [16], [17], [18], [19], [20] about ten years ago, by extending the "Model Driven control" concept proposed by Kimura[1].The MD-PID control system has a cascade control structure that is an Internal Model Control(IMC) by Morari[10] as the main controller and a PD control loop as the lower loop including the control process. In this paper, after reviewing the design method for a MD-PID Control system with new PD feedback design method, we propose a new design method for a TDOF PID control system by referring to the Model-Driven PID control system and its sensitivities.**

I. INTRODUCTION

PID control systems [2], [3] are widely used as a basic control technology in the industrial control system today, due to well-known simple control structure, which composed of proportional (P), integration (I), and differential (D) operation. However, the tuning of PID control systems is not always easy, because of its simple control structure for wide classes of industrial control processes, such as long dead-time processes, oscillatory processes, unstable processes and processes with zero. It is even more difficult to manually tune these processes because it may spend work time and generate loss.The tuning of a two-degree-of-freedom(TDOF) PID control system[8], [9] which has more configuration parameters, is more difficult. Dave Ender [4] reported that more than one-third are in manual, and also more than one-third are poor or fair. Desborough et al. said that the situation is basically unchanged today at Industrial Computing.[5] It may be thought that it is difficult and unfamiliar to tune PID control systems to some class of processes and the unnecessary losses have been generated. PID τ_d [11], [12]by Shinskey is a challenge for a first-order lag process with specialized dead time, and Internal Model Control(IMC)[10] by Morari is also a general challenge for specialized non-minimum phase and unstable processes.The IMC gives us good suggestions such as a reference model to be designed, a control system structure and a general-purpose industrial process controller which is composed of only fixed control elements. Kimura proposed the concept of "model driven control (MDC)" in CDC2000 Sydney[1] which is "A control system architecture which uses a model of the plant as a principal component of controller". Merits of the MDC are that control structure is easier to understand and easy tuning capability as well as the IMC. In order to realize good control performances for wide classes of process control systems with fixed control elements, we developed a Model-Driven PID control system, named MD-PID Control system, by extending the "model driven control" concept and combining with a TDOF IMC and a PD feedback control about ten years ago.

This paper provides a new design approach from MD-PID control to TDOF PID control with numerical examples, after introducing the structure of MD-PID control system, the design steps, including a new PD feedback design method.

II. STRUCTURE OF MODEL-DRIVEN PID CONTROL SYSTEM AND ITS DESIGN APPROACH

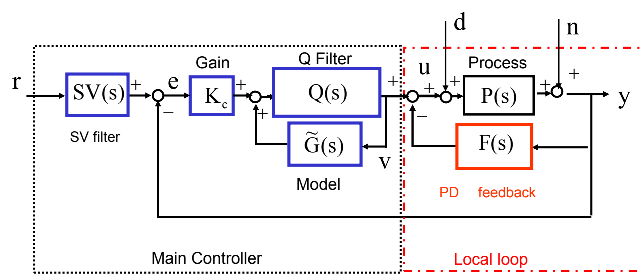

Fig. 1. A Model-Driven PID Control System

Figure 1 shows a block diagram of a Model-Driven PID control system, where P(s), r, e, v, u, y, d and n are controlled process,set point signal, deviation signal, internal controller output, process input signal, process output signal, disturbance and noise respectively. The dynamics of the control process is expressed as in (1)

$$y = P(s)(u+d)+n \tag{1}$$

A. MD-PID CONTROL BLOCKS

The control system is composed of model, Q filter, gain, SV filter and PD feedback.

1) The model representing dynamics of the local loop, is

using a fixed structured normalised first order delay system with dead time as in (2) .

$$\tilde{G}(s) = \frac{exp(-L_c s)}{1+T_c s} \quad (2)$$

2) The $Q(s)$ filter of the main controller is using as expressed in (3)

$$Q(s) = \frac{(1+T_c s)(1+\alpha T_c s)}{(1+\lambda T_c s)^2} \quad (3)$$

λ and α are adjustable parameters for the response of the control system and described precisely in the following section. And K_c is a Gain of the main controller.

3) The PD feedback $F(s)$ as shown in (4) is using for the dynamics of the local loop is compensated to be a first order delay system with dead time.

$$F(s) = K_f \frac{1+T_f s}{1+\kappa T_f s} \quad (4)$$

where K_f, T_f and κ are a gain, differential parameters and differential gain, respectively of the PD feedback $F(s)$.
4) SV filter as in (5) is used in order to obtain quick and no-overshooting output response to the set point signal r.

$$SV(s) = \frac{1+\lambda T_c s}{1+\alpha T_c s} \quad (5)$$

B. PD FEEDBACK DESIGN

If the process $P(s)$ has a dead time, then the PD loop $G(s)$ expressed as in (6) has infinite number of poles mathematically. However, as described before, the $G(s)$ should be designed to be a first order delay system with dead time in (7) as in Fig.2. Where K,T and L are gain, time constant and dead time representing the PD local loop.

$$G(s) = \frac{P(s)}{1+F(s)P(s)} \quad (6)$$

$$G(s) \cong \frac{Kexp(-Ls)}{1+Ts} \quad (7)$$

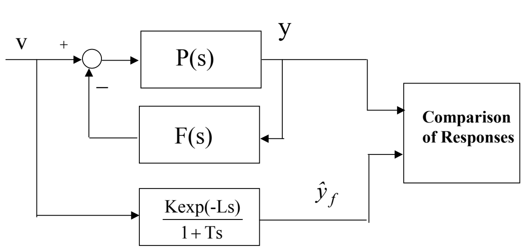

Fig. 2. A PD feedback loop and the equivalent first order delay system with dead time

Various design methods can be considered, such as, a determining method from the step response and the simulation, model reduction method in low frequency region, a partial model matching method [6], [7] by Kitamori and so on.
Denominator of (6) and (7) can be expressed as (8).
By substituting (9),(10) and (11) in Taylor expansion forms into (8) and matching the low-order coefficients at powers of s between both side in (8), nonlinear equations as shown in (12) $\sim$ (16) are obtained.

$$P(s)^{-1} + F(s) = \frac{(1+Ts)exp(Ls)}{K} \quad (8)$$

$$P(s)^{-1} = p_0 + p_1 s + p_2 s^2 + p_3 s^3 + p_4 s^4 + \quad (9)$$

$$F(s) = K_f + K_f T_f (1-\kappa)s - K_f T_f^2 \kappa (1-\kappa) s^2 + K_f T_f^3 \kappa^2 (1-\kappa) s^3 - \cdots \quad (10)$$

$$\frac{(1+Ts)exp(Ls)}{K} = \frac{1}{K} + \frac{T+L}{K}s + \frac{TL+L^2/2}{K}s^2 + \frac{TL^2/2+L^3/6}{K}s^3 + \cdots \quad (11)$$

$$\frac{1}{K} = p_0 + K_f \quad (12)$$

$$\frac{T+L}{K} = p_1 + K_f T_f (1-\kappa) \quad (13)$$

$$\frac{TL+L^2/2}{K} = p_2 - K_f T_f^2 (1-\kappa)\kappa \quad (14)$$

$$\frac{TL^2/2+L^3/6}{K} = p_3 + K_f T_f^3 (1-\kappa)\kappa^2 \quad (15)$$

$$\frac{TL^3/6+L^4/24}{K} = p_4 - K_f T_f^4 (1-\kappa)\kappa^3 \quad (16)$$

By solving these equations of (12) $\sim$ (16), optimal PD feedback parameters K_f, T_f and the first order delay system with dead time K, T and L can be obtained.
Remark: This approach does not work for processes with too long dead time. However, these processes are very minor in real industrial processes. So the approeach can be used practically for real industrial processes.

C. MAIN CONTROLLER DESIGN

The PD local loop is compensated to be a first order delay system with dead time in (7), then the model and the gain at the main controller can be determined as like the well-known IMC way.

$$K_c = 1/K, \ \ T_c = T, \ \ L_c = L \quad (17)$$

Since there is a pole at $s=0$ in the main controller composed of the $Q(s)$ filter and the model, an integral mode is prepared automatically. After all the steady state offset of a control deviation is regulated to zero for a class of step disturbances and step references. Finally the output y can be expressed as in (18) in the case of the nominal case.

$$y = \frac{exp(-Ls)}{1+\lambda Ts} r + \frac{Kexp(-Ls)}{1+Ts}\left(1 - \frac{(1+\alpha Ts)exp(-Ls)}{(1+\lambda Ts)^2}\right) d \quad (18)$$

The λ is an adjustment parameter of the response speed from set point r as shown in Fig. 3, and the α is also an adjustment parameter of the regulation speed from disturbance, without affecting the response speed from set point as shown in Fig.4.

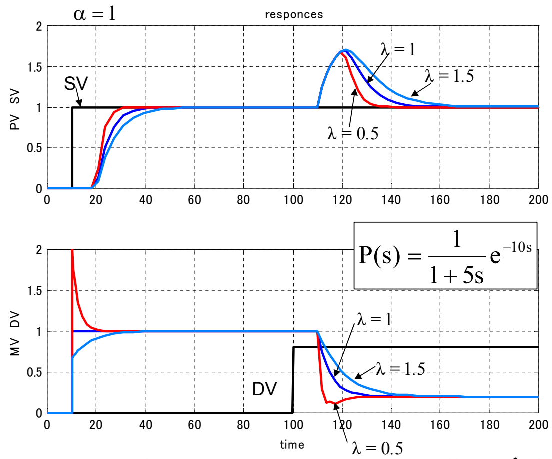

Fig. 3. Response of MD-PID control system with different λ for long dead time process $G(s)$

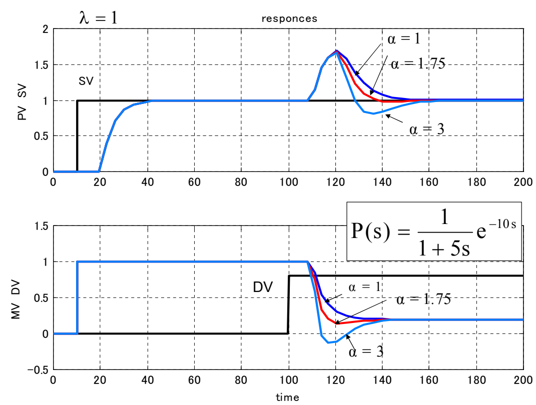

Fig. 4. Response of MD-PID control system with different α for long dead time process $G(s)$

The optimal α can be obtained as in (19), by canceling the slowest pole of the process and a zero of the controller concerning the α,

$$\alpha = 1-(1-\lambda)^2 exp(-L_c/T_c) \quad (19)$$

The output y can be expressed as (18) in the case of the nominal case, however, there is a modelling error in practice at the PD feedback design phase. Practical robust stability of the MD-PID control system can be evaluated by using well-known stability measure, the Nyquist plot of the control system as shown in Fig. 5. Astrom recommends reasonable values of maximum sensitivity Ms[14] is between 1.2 and 2.

D. Features

Due to well-designed PD local loop,the MD-PID control system can be applicable for not only long dead time processes, but also integral processes, oscillatory processes, small dead-time processes and even unstable processes.
The λ and the α of the MD-PID controller play a role of an on-line tuning parameters without re-design.

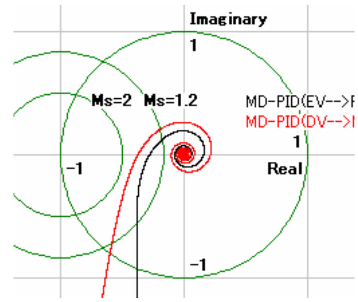

Fig. 5. Nyquist plot of the control system

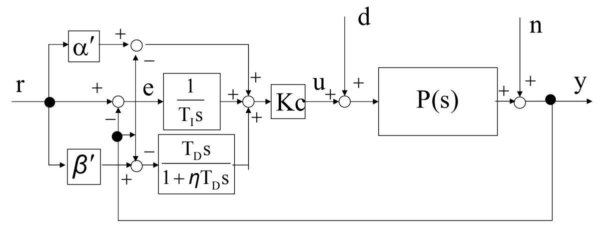

Fig. 6. A two degrees of Freedom PID control system

III. DESIGN APPROACH FOR A TDOF PID CONTROL SYSTEM FROM THE MD-PID CONTROL SYSTEM

Figure 6 shows a block diagram of a TDOF PID control system should be designed. Where K_C,T_I, T_D and η are gain, integral time constant, derivative time constant and derivative gain in the TDOF PID control, respectively. And α' and β' are feed-forward gain in proportional portion and derivative portion concerning the reference signal, respectively. In order to convert a TDOF PID control system from the MD-PID control system, we applied a well-known Taylor expansion method as in [13]. $C(s)+F(s)$ from y to u of the MD-PID control system becomes as (20). And the PID controller $C_{PID}(s)$ can be expressed in a series form as (21). From the Taylor expansion $CF(s)$ as in (22), the PID series parameters $C_i, i=0,1,2$ becomes (23) $\sim$ (25) in MAXIMA representation. Finally the PID parameters can be obtained as (26) $\sim$ (28).

$$C(s)+F(s) = K_c \frac{(1+T_c s)(1+\alpha T_c s)}{(1+\lambda T_c s)^2-(1+\alpha T_c s)exp(-L_c s)} + K_f(\frac{1+T_f s}{1+\kappa T_f s}) \quad (20)$$

$$C_{PID}(s) = \frac{C_0+C_1 s+C_2 s^2}{s} \quad (21)$$

$$CF(s) = \text{taylor}(s(C(s)+F(s)),s,0,2) \quad (22)$$

$$C_0 = \text{coeff}(CF(s),s,0) \quad (23)$$

$$C_1 = \text{coeff}(CF(s),s,1) \quad (24)$$

$$C_2 = \text{coeff}(CF(s),s,2) \quad (25)$$

$$K_C = C_1 \quad (26)$$

$$T_I = \frac{C_1}{C_0} \quad (27)$$

$$T_D = \frac{C_2}{C_1} \quad (28)$$

IV. SENSITIVITY COMPARISON

Fig. 7 shows a general TDOF control system with reference signal r , disturbance d and noise n. Sensitivity

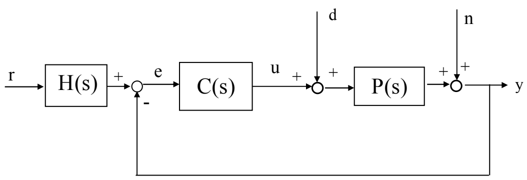

Fig. 7. A general TDOF control system

function $S(s)$, Complementary sensitivity function $T(s)$, Input sensitivity function $CS(s)$ and Disturbance sensitivity function $DS(s)$ are expressed as (29), (30), (31), and (32), respectively[14]. By comparing the sensitivity functions of the MD-PID control system and the TDOF PID control system, the TODF parameters η ,α' and β' can be designed.

$$S(s) = \frac{1}{1+P(s)C(s)} \quad (29)$$

$$T(s) = \frac{P(s)C(s)H(s)}{1+P(s)C(s)} \quad (30)$$

$$CS(s) = \frac{C(s)}{1+P(s)C(s)} \quad (31)$$

$$PS(s) = \frac{P(s)}{1+P(s)C(s)} \quad (32)$$

V. NUMERICAL EXAMPLES

We applyed the method to several processes. Some typical examples; a first order delay system with dead time $P_1(s)$, a integral system with dead time $P_2(s)$ and a unstable system with dead time $P_3(s)$ are shown at this section. Summary parameters designed for PD loop for P_1, P_2, and P_3 are shown at TABLE I. And also the summary parameters for MD-PID control systems and TDOF PID control systems for P_1, P_2, and P_3 are shown at TABLE II.

$$P_1(s) = \frac{exp(-20s)}{1+50s} \quad (33)$$

$$P_2(s) = \frac{exp(-20s)}{20s} \quad (34)$$

$$P_3(s) = \frac{exp(-2s)}{(11.7s-1)(1+11.9s)} \quad (35)$$

Figure 8, 11 and 14 shows step responses(Upper plot), gain frequency response(Middle plot) and phase response(Lower plot) of the PD feedback loop and its equivalent first order delay system with dead time for P_1, P_2, and P_3 respectively. Though both step responses have small error in the initial stage, both step responses are almost identical at the rising and steady stage. Though both bode plots have error at the high frequency region, both bode plots are almost identical for the low frequency region.

TABLE I

SUMMARY OF PARAMETERS DESIGNED FOR P_1,P_2, AND P_3

	P_1	P_2	P_3
K_f	0.8	0.4	2.45
T_f	7.139	7.204	11.131
κ	0.1	0.1	0.1
K	0.556	2.5	0.69
T	20.33	34.64	9.296
L	21.41	21.85	6.111

TABLE II

SUMMARY OF CONTROL PARAMETERS OF MD-PID AND TDOF PID FOR P_1,P_2, AND P_3

		P_1	P_2	P_3
MD-PID	K_c	20.33	34.64	9.296
	T_c	21.41	21.85	6.111
	L_c	20.33	34.64	9.296
	K_f	0.8	0.4	2.45
	T_f	7.139	7.204	11.131
	κ	0.1	0.1	0.1
	α	1	1	1
	λ	1	1	1
TDOF PID	K_C	0.8	0.4	2.45
	T_I	7.139	7.204	11.131
	T_D	0.1	0.1	0.1
	α'	0.556	0.5	0.69
	β'	0	0	0

Figure 9, 12 and 15 shows time response plots of the MD-PID control and the TDOF PID control for P_1, P_2, and P_3 respectively. Figure 10, 13 and 16 shows gain plots of each sensitivity functions, Sensitivity function $S(s)$ (upper left), Complementary sensitivity function $T(s)$ (upper right), Input sensitivity function $CS(s)$ (lower left) and Disturbance sensitivity $DS(s)$ (lower right) of the MD-PID control and the TDOF PID control for P_1, P_2, and P_3 respectively.
Each time responses and sensitivities of the TDOF PID control and the MD-PID control shows good coincidence.

VI. CONCLUSIONS AND FUTURE WORKS

The paper provides a new TDOF PID control system design method from the referenced MD-PID control by using Taylor expansion method and reviewed also the design method of the MD-PID control system, composed of the PD feedback loop design for the control process to be a first order delay with dead time and sensitivities comparing. As the dynamics of the PD feedback loop for practical processes can be matched to a first order delay system with dead-time, the approach is applicable for real industrial processes. We have already a process control systems simulation, design and tuning tool named PSIM tool based on these theory and are using for industrial control applications[20], [21], [22]. In order to realize recent strong requirements, such as, variable production rate, quality improvement, cost reduction

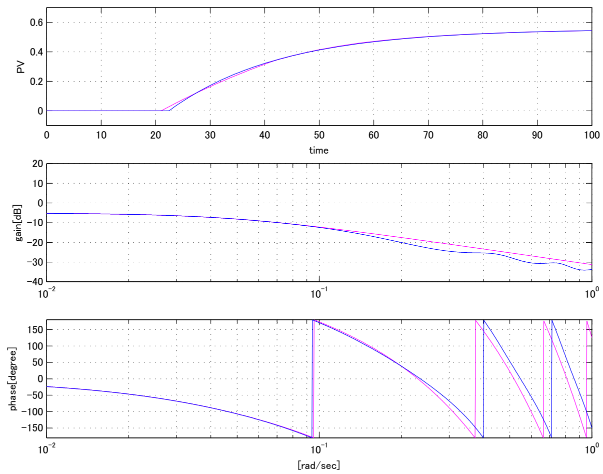

Fig. 8. Comparison of responses for P_1 Upper:Step response, Middle:Gain, Lower: Phase, (Blue line:G(s) and Magenta line: the first order delay system with dead time)

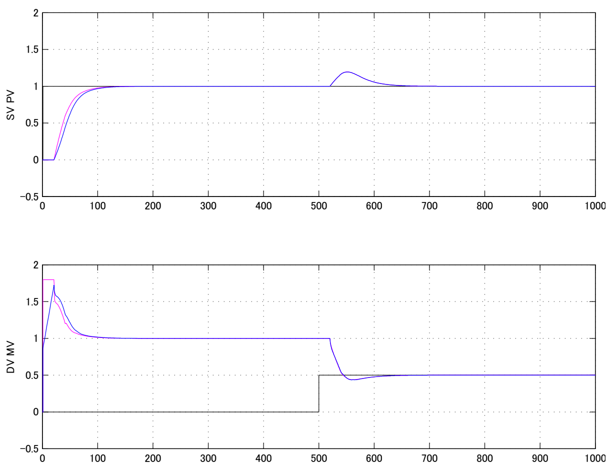

Fig. 9. Comparison of control system responses for P_1 (Blue line:TDOF PID, Magenta line:MD-PID)

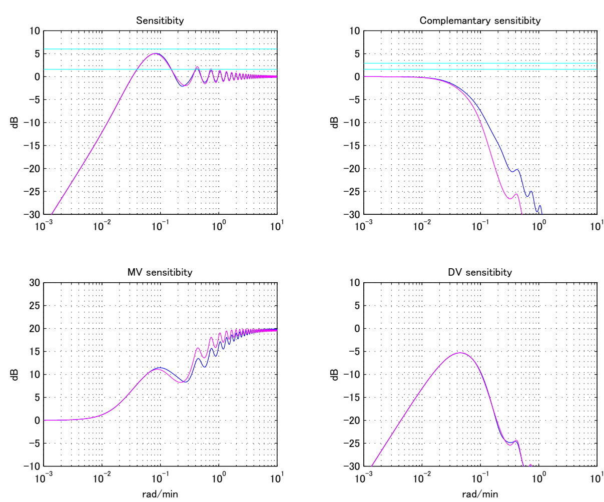

Fig. 10. Comparison of Sensitivity functions for for P_1 (Blue line:TDOF PID, Magenta line:MD-PID)

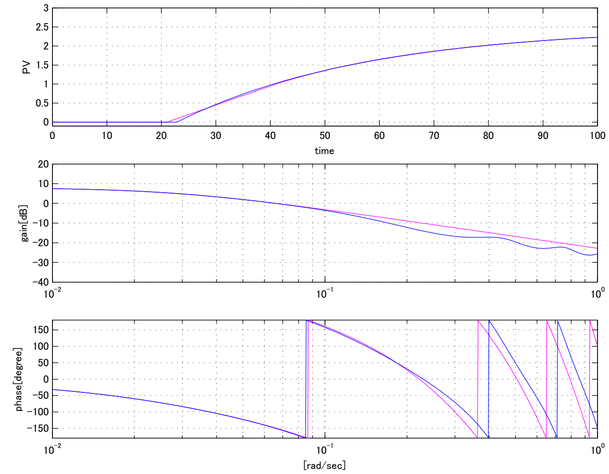

Fig. 11. Comparison of responses for P_2 Upper:Step response, Middle:Gain, Lower: Phase, (Blue line:G(s) and Magenta line: the first order delay system with dead time)

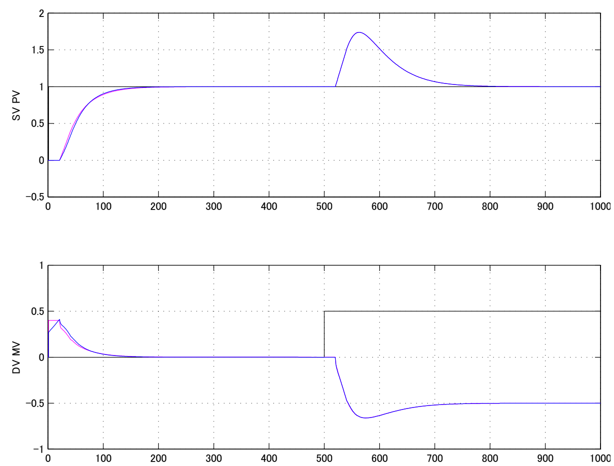

Fig. 12. Comparison of control system responses for P_2 (Blue line:TDOF PID, Magenta line:MD-PID)

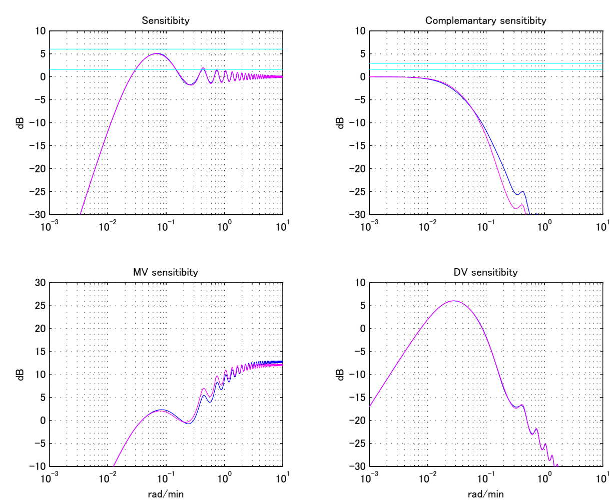

Fig. 13. Comparison of Sensitivity functions for for P_2 (Blue line:TDOF PID, Magenta line:MD-PID)

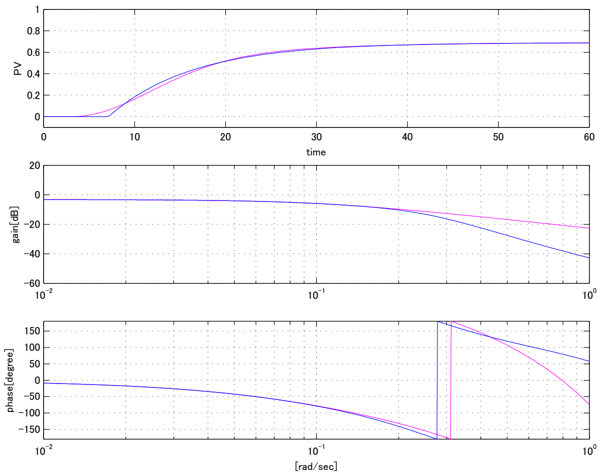

Fig. 14. Comparison of responses for P_3 Upper:Step response, Middle:Gain, Lower: Phase, (Blue line:G(s) and Magenta line: the first order delay system with dead time)

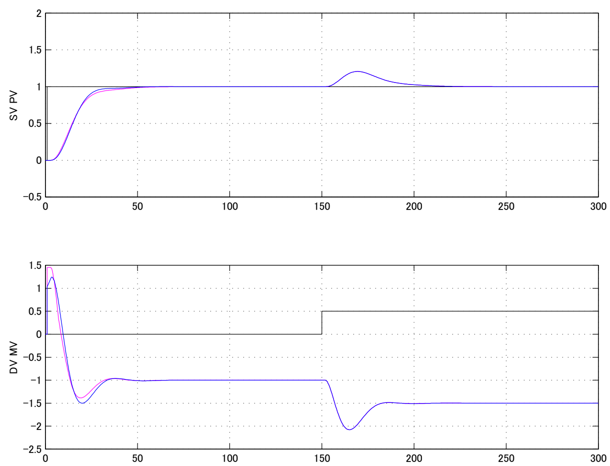

Fig. 15. Comparison of control system responses for P_3 (Blue line:TDOF PID, Magenta line:MD-PID)

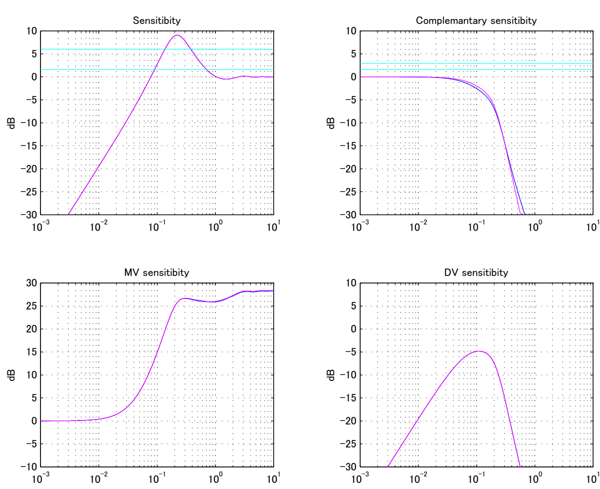

Fig. 16. Comparison of Sensitivity functions for for P_3 (Blue line:TDOF PID, Magenta line:MD-PID)

and stable operations, both the MD-PID control system and the TDOF PID control system will be effective and useful by applying to even regulatory control level.

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