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## An Industrial Model Based Disturbance Feedback Control Scheme

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**Abstract:** This paper presents a model based disturbance feedback control scheme. Industrial process systems have been traditionally controlled by using relay and PID controller. However these controllers are affected by disturbances and model errors and these effects degrade control performance. The authors propose a new control method that can decrease the negative impact of disturbance and model errors. The control method is motivated by industrial practice by Fuji Electric. Simulation tests are examined with a conventional PID controller and the disturbance feedback control. The simulation results demonstrate the effectiveness of the proposed method comparing with the conventional PID controller.

*Keywords:* Disturbance feedback control, Model based control, PID

### 1. INTRODUCTION

Unitary control such as relay control and PID control have been widely applied to industrial process systems. For a long time engineers have used relay and PID controllers because it is possible to implement those even with limited knowledge, information and low cost. However, these controllers have issues for disturbance, mutual interference, and model errors.

For disturbance problems, Two-Degree-of-Freedom PID control gives better performances than conventional One-Degree-of-Freedom PID, both w.r.t. set point and disturbance response (Horowitz, 1963; Araki and Taguchi, 2003). This controller also make possible to improve both set-point and disturbance response by tuning new parameters  $\alpha$  and  $\beta$ . However, the parameter gives the engineer an additional task, because these parameters are not tuned independently on control performance w.r.t. set point and disturbance response. More tuning parameters make it more complicated for the engineer.

Multivariable control also has been applied to industrial systems in order to solve the following control issues. Model predictive control (MPC) has been applied to overcome mutual interference by minimize objective function (Maciejowski, 2000). Examples of such methods are given in e.g. (Kawai, 2007; Larsen, 2004). However MPC originally does not consider disturbances. Thus, we need to improve and modify the MPC algorithm as needed (Tange, 2009, 2012). Furthermore, multivariable control design normally needs advanced and expensive hardware, as well as, much time and cost for model and control design, which makes a barrier for this to be in wide use.

This paper proposes a new control method in order to attenuate the impact of disturbances and model errors. The control method is motivated by industrial practice for instance used for speed control of motor drives as shown in

Fig.1 (Nishida, 1997; Miyashita, 2000). The advantage of the proposed method is examined by simulation tests by using two example models.

### 2. THE MODEL BASED DISTURBANCE FEEDBACK CONTROL METHOD

A block diagram for the proposed method is shown in Fig.2, where  $r$  is the reference input,  $u$  is the control input ( $u = u_l + u_d$ ),  $y$  is the control output,  $d$  is the disturbance,  $G$  is the controlled object,  $K$  is the feedback controller,  $G_n$  is the nominal plant,  $L$  is the gain of disturbance feedback,  $y_n$  is the output of the nominal plant,  $\varepsilon = y_n - y$  is an estimate of  $dG$ . The block diagram shows that the proposed method compensates the disturbance using  $u_d$ .

This control method compensates the error between  $y_n$  and  $y$  including the effect of disturbance and mutual interference. For this reason, the proposed method is an effective technique to reject disturbance, mutual interference and model error for various systems.

The closed loop transfer function is obtained as follow:

$$y = \frac{GK(1+G_nL)}{(1+GK)+GL(1+G_nK)}r + \frac{G}{(1+GK)+GL(1+G_nK)}d. \quad (1)$$

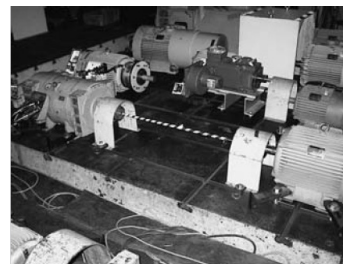


Fig.1. Example for a motor speed control by Fuji Electric.

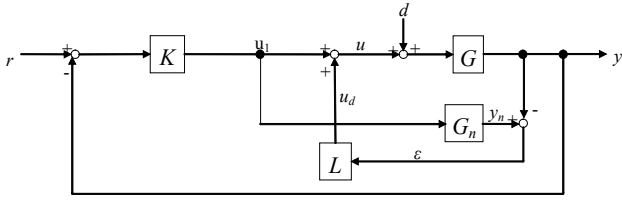


Fig. 2. A block diagram of the disturbance feedback control.

When  $G=G_n$ , namely nominal plant is equal to controlled object completely, then Equation (1) gives

$$y = \frac{GK}{(1+GK)}r + \frac{G}{(1+GK)(1+GL)}d. \quad (2)$$

Equation (2) describes that  $L$  can attenuate the disturbance.

Furthermore,  $L$  can be tuned independently for disturbance response, and  $L$  will have no impact at the set-point response.

### 2.1 Stability condition of disturbance feedback control

Consider the second term of Equation (2). This part gives

$$\frac{y}{d} = \frac{G}{(1+GK)(1+GL)}. \quad (3)$$

For example,  $G$  and  $K$  are defined as follows:

$$G(s) = \frac{G_s}{(1+T_1s)(1+\sigma)}. \quad (4)$$

$$K(s) = K_p \frac{1+sT_1}{sT_1}. \quad (5)$$

Where,  $G_s$  is the process gain,  $T_1$  and  $\sigma$  are time constants,  $T_1 > \sigma$ ,  $K_p$  is proportional gains. The long-time constant  $T_1$  is dominant in  $G$ . The long time constant  $T_1$  of the process is cancelled by the zero in the PI controller.

From (3), (4), and (5) we have

$$\frac{y}{d} = \frac{G_s T_1 s (1+\sigma)}{[(1+\sigma)T_1 s + G_s K_p] [(1+\sigma)(1+T_1 s) + G_s L]}. \quad (6)$$

From the (6), the characteristic equation is written as

$$(\sigma T_1 s^2 + T_1 s + G_s K_p) [\sigma T_1 s^2 + (T_1 + \sigma)s + (1 + G_s L)] = 0. \quad (7)$$

When a real part of a solution is negative value, then the system is stable. Stability condition of Equation (7) is given by the following inequalities:

$$-T_1 + \sqrt{T_1^2 - 4T_1\sigma G_s K_p} < 0.$$

$$-(T_1 + \sigma) + \sqrt{(T_1 + \sigma)^2 - 4T_1\sigma(1 + G_s L)} < 0. \quad (8)$$

Therefore, if  $K_p$  and  $L$  satisfy (9), the system is stable.

$$G_s K_p > 0, L > \frac{-1}{G_s} \quad (9)$$

### 2.2 An implementation method of the disturbance feedback control by a Two-Degree-of-Freedom structure

The disturbance feedback control can be changed equivalently to Two-Degree-of-Freedom (2DOF) control.

As an advantage this equivalent transformation can be implemented in the device of two-degree-of-freedom PID without having to provide a new controller for disturbance feedback control.

However, since this control device has been designed based on the disturbance feedback control method, it can be designed independently of the suppression of the disturbance unlike two-degree-of-freedom PID control.

Fig.3 shows an example of a 2DOF PID control system, which is a set-point filter type, because it is obtained by inserting a filter in the set-point path of the conventional PID controller.

Thus, the disturbance feedback control is categorized as a 2DOF control system and the controller can be treated as a PID controller. The disturbance feedback control also can be changed to other equivalent 2DOF representations such as feed forward type, feedback type, and loop type expression as shown in Fig.4, Fig.5 and Fig.6 (Araki and Taguchi, 2003).

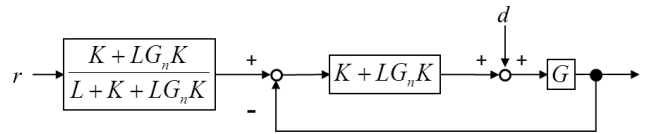


Fig.3. A set-point filter type representation.

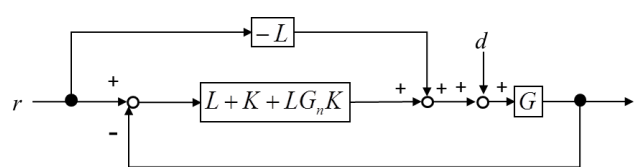


Fig.4. A feed forward type representation.

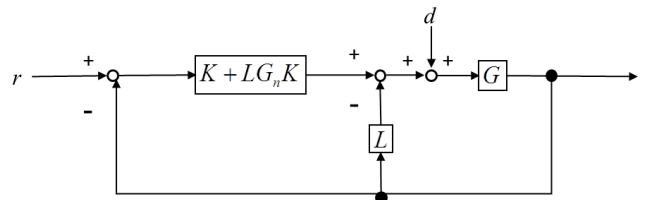


Fig.5. A feedback type representation.

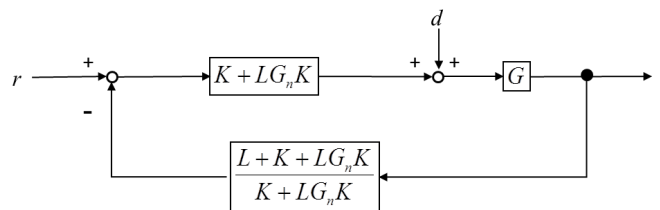


Fig.6. A loop type representation.

### 2.3 Impact of model error

From Figure 2, a loop transfer function from  $r$  to  $y$  is given by

$$G_{lry} = \frac{GK(1+G_nL)}{(1+GL)} \quad (10)$$

Where,  $G_{lry}$  is the loop transfer function from  $r$  to  $y$ .

Now consider model error when the disturbance feedback control is applied. The model error is given by

$$G = G_n(1 + \Delta G) \quad (11)$$

From (10) (11), we have

$$G_{lry} = G_n(1 + \Delta G)KL' \quad (12)$$

where

$$L' = \frac{1 + G_nL}{1 + G_n(1 + \Delta G)L} \quad (13)$$

Equation (13) shows that  $L' \rightarrow 1$  when  $L \rightarrow \infty$ . This means a larger  $L$  attenuates the effect of model error  $\Delta G$ .

Next, another loop transfer function from  $d$  to  $y$  is given by

$$G_{ldy} = G[K + L(G_nK + 1)] \quad (14)$$

where  $G_{ldy}$  is the loop transfer function from  $d$  to  $y$ .

From (11) and (14), we have

$$G_{ldy} = G_n(1 + \Delta G)K' \quad (15)$$

where

$$K' = [K + L(G_nK + 1)] \quad (16)$$

Equation (16) shows that large  $L$  makes the controller  $K'$  more sensitive.

## 3. NUMERICAL EXAMPLES

Numerical examples are examined. Example Model 1 is a second order transfer function (Åström, 2006). The example Model 2 is an unstable process (Hast, 2013).

Simulation results are estimated by Integral Absolute Error (IAE) and  $y_{max}$ , which is a maximum of  $y$  based on set point  $r$ .

$$IAE = \int_0^t |e| dt \quad (17)$$

$$y_{max} = \max(y) - r \quad (18)$$

### 3.1 Example 1 without model error

Example 1 without model error is given by

$$G_n(s) = \frac{1}{(1+s)(1+0.26s)} \quad (19)$$

The parameters of the PI controller  $K(s)$  is tuned by Betaqs method (Kawai, 2013). Betaqs method is a curve fitting method (Åström, 2006).

PI controller is given by

$$K(s) = K_p \left(1 + \frac{1}{T_i s}\right) \quad (20)$$

where

$$K_p = \frac{T_{1n}}{2G_{sn}\sigma_n}, \quad T_i = T_{1n} \quad (21)$$

The set-point response and load disturbance response are examined with and without disturbance feedback control. Disturbance feedback gain  $L$  is adjusted to  $L = 10$  by the simulation.

Fig.7 and Fig.8 show simulation results of Example 1. The set-point response of Fig.7 shows both of  $u$  and  $y$  are completely equal between PI control and disturbance feedback control. Therefore it is confirmed that the disturbance feedback has absolutely no impact on set-point response when  $G=G_n$ . Fig.8 shows a load disturbance response. The disturbance feedback control can reach the set-point faster than the PI control.

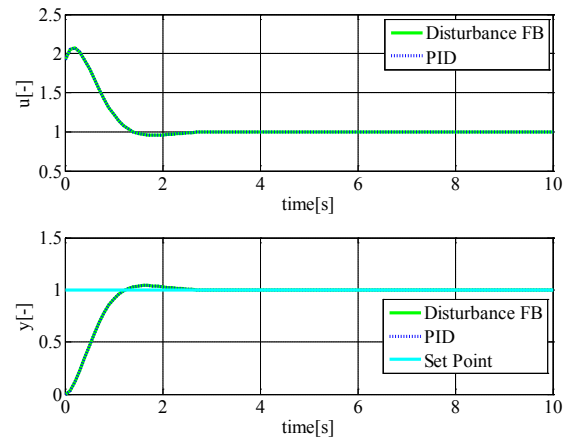


Fig.7. Simulation results of the set-point response of Example 1.

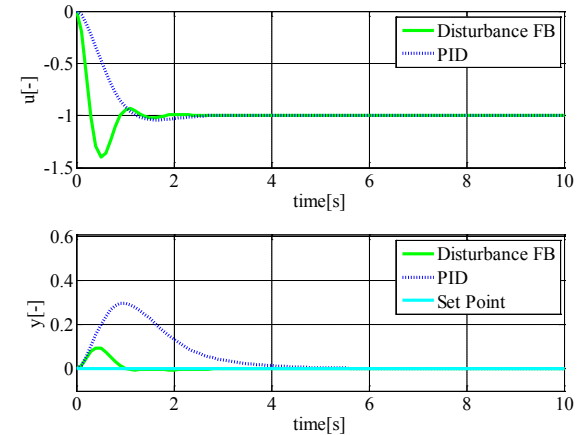


Fig.8. Simulation results of the load disturbance response of Example 1.

$y_{max}$  and IAE are shown in Table 1 and Table 2. As regarding set-point response, both  $y_{max}$  and IAE are completely equal at two control methods. On the other hand, the disturbance feedback control method of load disturbance response can obtain a much lower IAE and  $y_{max}$ .

These results demonstrate that the disturbance feedback can have a positive impact on disturbance response only. This feature gives a big advantage for engineers. Because parameter  $L$  can be tuned independently for disturbance response, additionally the disturbance feedback can improve the control performance at disturbance response.

### 3.2 Example 1 with model error

Example 1 with model error is given as

$$G(s) = \frac{1(1 + \Delta G_s)}{(1 + s)(1 + 0.26s)} \quad (22)$$

Where  $\Delta G_s$  is the model error of plant gain and the  $\Delta G_s$  is changed from -0.5 to 0.5 on simulation tests.

Fig.9 and Table 1 shows set-point response with and without model error. These results shows disturbance feedback control is less affected than PI control when model error is applied.

Fig.10 shows IAE and  $y_{max}$  of a set-point response for different  $L$  and  $\Delta G_s$ . The figure shows that larger  $L$  decrease IAE and  $y_{max}$  and the larger  $L$  also attenuate the effect of  $\Delta G_s$ .

Fig.11 shows that the proposed method improves control performance regardless of the model error at load disturbance response. The proposed method also keeps a variation value (max-min) less than 3% when model error is applied, whereas  $y_{max}$  of PI control exceeded 15% as shown in Table 2.

Fig.12 shows IAE and  $y_{max}$  of a load disturbance response for different parameters  $L$  and  $\Delta G_s$ . Similar to the results of Fig.10, a larger  $L$  decrease IAE and  $y_{max}$  and  $L$  also attenuate the effect of  $\Delta G_s$ .

Table 1. IAE and  $y_{max}$  at the set-point response of Example 1. DFC: Disturbance feedback control.

	$\Delta G_s=0$	$\Delta G_s=-0.5$	$\Delta G_s=0.5$	max-min
IAE of PI	0.6429	<b>1.0900</b>	<u>0.5393</u>	0.5507
IAE of DFC	0.6429	<b>0.8079</b>	<u>0.6102</u>	0.1977
$y_{max}$ of PI	0.0430	<u>0.0000</u>	<b>0.1074</b>	0.1074
$y_{max}$ of DFC	0.0430	<b>0.1215</b>	<u>0.0309</u>	0.0906

Table 2. IAE and  $y_{max}$  at the load disturbance response of Example 1. DFC: Disturbance feedback control.

	$\Delta G_s=0$	$\Delta G_s=-0.5$	$\Delta G_s=0.5$	max-min
IAE of PI	<b>0.5200</b>	<u>0.5199</u>	<b>0.5200</b>	0.0001
IAE of DFC	<b>0.0557</b>	<u>0.0701</u>	0.0536	0.0164
$y_{max}$ of PI	0.2979	<u>0.2075</u>	<b>0.3578</b>	0.1503
$y_{max}$ of DFC	0.0950	<u>0.0781</u>	<b>0.1044</b>	0.0263

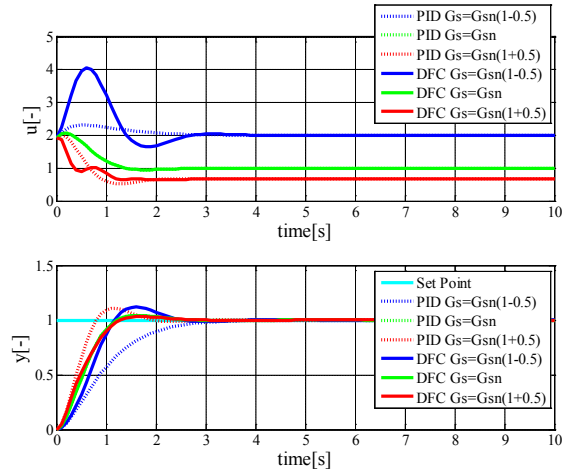


Fig.9. Impact of the model error. Set-point response of Example 1. Parameter  $L = 10$  at DFC.

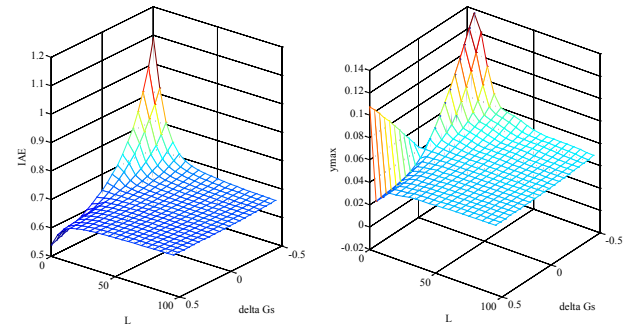


Fig.10. IAE and  $y_{max}$  of the set-point response of Example 1 with the proposed method. Impact of parameter  $L$  and model error  $\Delta G_s$ .

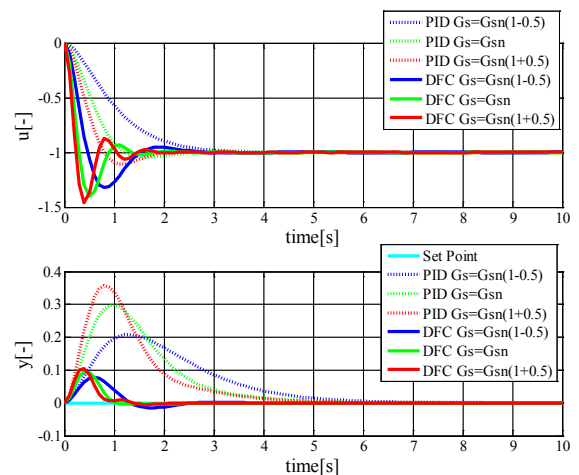


Fig.11. Impact of the model error. Load disturbance response of Example 1. Parameter  $L = 10$  at DFC.

Now consider the stability and sensitivity of the disturbance feedback control. Fig. 13 shows Nyquist plots of loop transfer function by changing the parameter  $L = 1, 10, 100$ . A plot with  $L=100$  is close to the critical point  $(-1, 0)$ . The results demonstrate a characteristic of the (14) such the large  $L$  makes the controller more sensitive.

Fig. 14 also shows that larger  $L$  improves control performance and attenuates the effect from  $\Delta G_s$ . However, at the same time, larger  $L$  gets the controller more sensitive as shown at Fig.13. Therefore,  $L$  should be tuned by some constraints such as maximum sensitive circle, which range of 1.2 to 2.0 in order to avoid an effect from measurement noise.

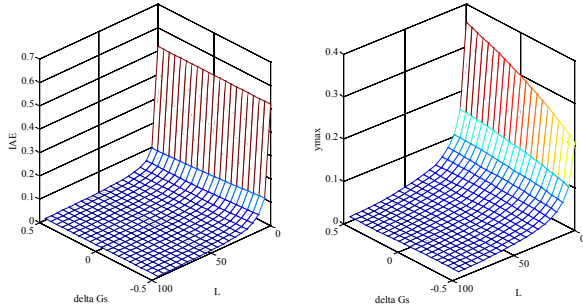


Fig.12. IAE and  $y_{max}$  of the load disturbance response of Example 1 with the proposed method. Impact of parameter  $L$  and model error  $\Delta G_s$ .

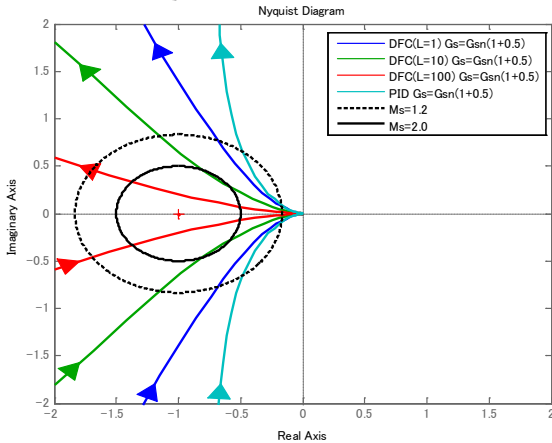


Fig.13. Nyquist plots of the loop transfer function in Example 1. Ms: Maximum sensitive circle.

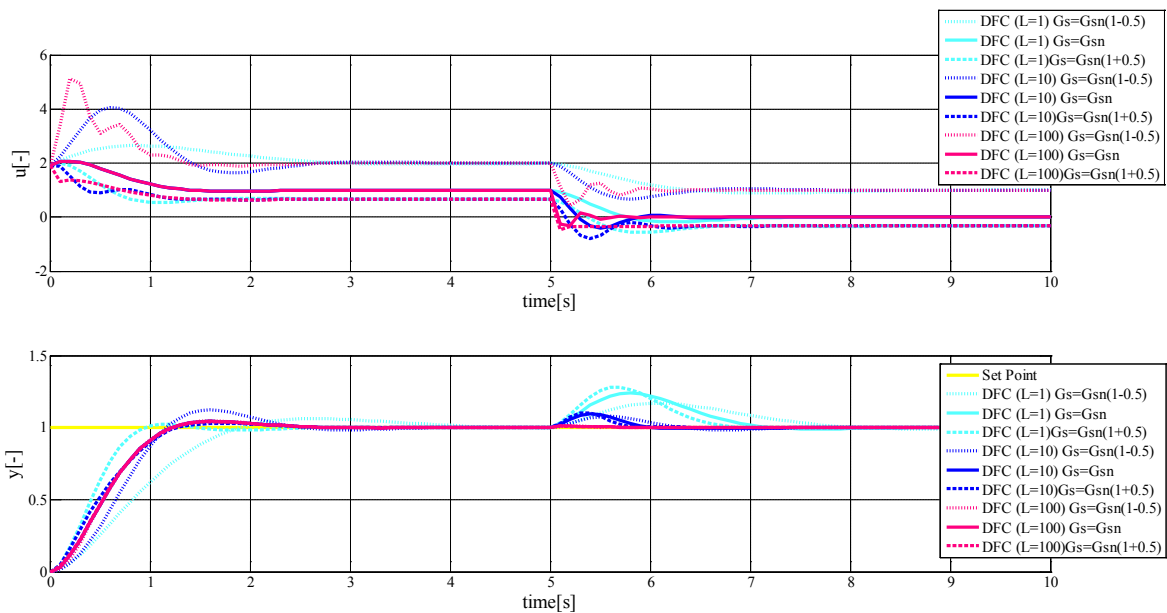


Fig.14. Impact of parameter  $L$  and model error.  $L=1, 10, 100$ .  $\Delta G_s=-0.5, 0, 0.5$ .

### 3. 3 Example 2

The model for Example 2 is given as

$$G(s) = \frac{1}{(1-s)(1+0.1s)} \quad (23)$$

The PID controller  $K$  is tuned by Convex-Concave optimization (Boyd, 2004; Hast, 2013). This parameter tuning method gives  $K_p=3.81$ ,  $T_i=3.33$ , and  $T_d=4.25$ .

$$K(s) = K_p + \frac{T_i}{s} + T_d s \quad (24)$$

The set-point response and load disturbance response are examined with and without disturbance feedback control. The disturbance feedback gain  $L$  is 20 tuned by simulations.

Fig.15 shows that  $u$  and  $y$  are completely equal for the two methods. Therefore it is confirmed that disturbance feedback has absolutely no impact on the set-point response when  $G=G_n$ .

Fig.16 shows a load disturbance response. The disturbance feedback control can reach the set-point much faster than the Convex-Concave optimization method.

Table 3 shows  $y_{max}$  and IAE. As regarding set-point response, both  $y_{max}$  and IAE are completely equal for the two control methods. On the other hand, the disturbance feedback control,  $y_{max}$  and IAE are significantly improved compared with the Convex-Concave optimization at the load disturbance response.

Consideration of the simulation results with the open loop unstable plant of Example 2 show the same effectiveness as seen in Example 1.

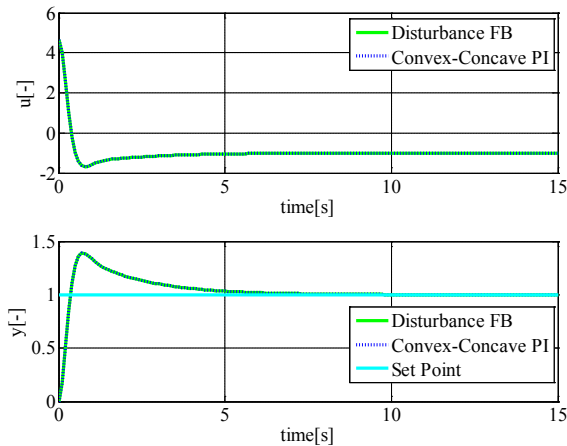


Fig.15. Simulation results of set-point response of Example 2.

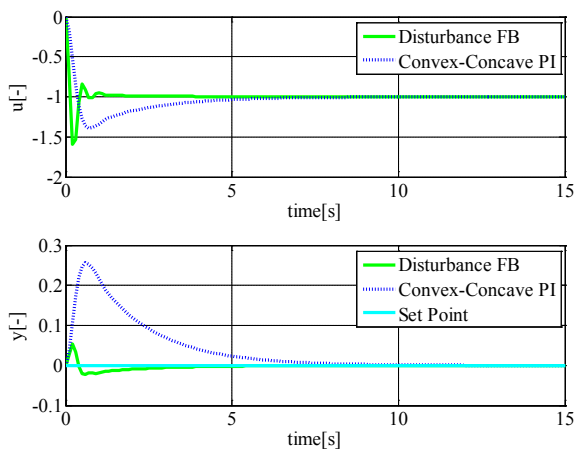


Fig.16. Simulation results of load disturbance response of Example 2.

Table 3. IAE and  $y_{max}$  at the set-point response of example model 2. CON: Convex-Concave optimization, DFC: Disturbance feedback control

	Set point response	Load disturbance response
IAE of CON	1.0107	0.5681
IAE of DFC	1.0107	0.0533
$y_{max}$ of CON	0.3884	0.2563
$y_{max}$ of DFC	0.3884	0.0536

#### 4. CONCLUSIONS

This paper proposes a new control strategy that uses disturbance feedback control with PID controllers. Simulation results show the effectiveness of the proposed method comparing to the conventional PID controller.

As future work, we will examine how to decide the feedback gain  $L$  systematically.

#### REFERENCES

- Araki, Mitsuhiro., and Taguchi, Hideo. (2003). Two-Degree-of-Freedom PID Controllers, *International Journal of Control, Automation, and Systems*, Vol. 1, No. 4, 401-411.
- Åström, Karl., and Hägglund, Tore. (2005). *Advanced PID Control*, The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC 27709.
- Hast, M., Åström, Karl J., Bernhardsson, B., Boyd, S. (2013). PID Design by Convex-Concave Optimization, In Proceedings of the European Control Conference 2013, Zürich, Switzerland.
- Horowitz, I. M., (1963). *Synthesis of Feedback Systems*, Academic Press.
- Kawai, Fukiko., et al.(2007). Automatic Tuning for Model Predictive Control: Can Particle Swarm Optimization find a better parameter?, IEEE International Symposium on Intelligent Control - ISIC , pp. 646-651.
- Kawai, Fukiko. Rasmussen, Henrik and Stoustrup, Jakob. (2013). Model based control design for refrigeration systems, In Proceedings of SICE, Fukuoka, Japan, In Japanese.
- Larsen, L.F.S., C. Thybo, J. Stoustrup, and H. Rasmussen. (2004). A method for online steady state energy minimization, with application to refrigeration systems. In Proceedings of the 43rd IEEE Conference on Decision and Control.
- Maciejowski, Jan. (2000). *Predictive Control with Constraints*, Prentice Hal.
- Miyashita, Tsutomu., Nishida, Hideyuki. and Ito, Shinichi (2000). New Drive Control Technologies for Industrial Plants, FUJI ELECTRIC JOURNAL 2000 Vol.73-No.11 in Japanese.
- Nishida, Hideyuki., Fujimori, Akira., and Ito, Shinichi.(1997). Control Technologies for Industrial Plants with Motor Applications. FUJI ELECTRIC JOURNAL Vol.70-No.10, in Japanese.
- Smith, O. J. M. (1959). A controller to overcome dead-time. ISA Transactions, 6. (2):28-33, .
- Tange, Yoshio., Nakazawa, Chikashi and Matsui, Tetsuro. (2009). A multi-variable disturbance observer for model predictive control, Proceedings of the 2009 17th Mediterranean Conference on Control and Automation, pp. 856-861.
- Tange, Yoshio and Nakazawa, Chikashi. (2012). Optimal Tuning for Disturbance Suppression Mechanism for Model Predictive Control, Transactions of the Society of Instrument and Control Engineers, Volume 47, Issue 9, pp. 380-387, in Japanese.
- Wang, Qing-Guo, Zhiping Zhang, Karl Johan Åström, Yu Zhang, and Yong Zhang. (2008). Guaranteed Dominant Pole Placement with PID Controllers, Proceedings of the 17th World Congress, The International Federation of Automatic Control, Seoul, Korea.