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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 α and β. 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 ($u = u_1 + u_d$), 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:

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

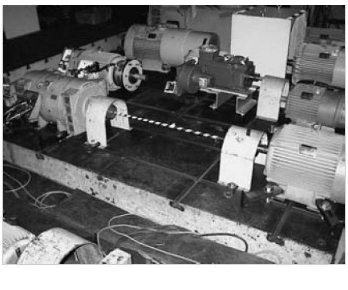

Fig.1. Example for a motor speed control by Fuji Electric.

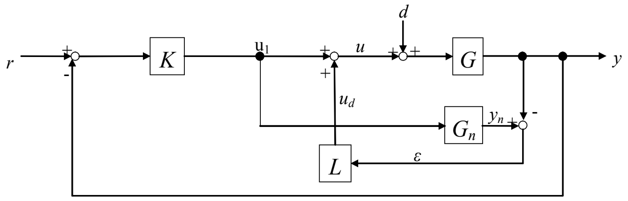

Fig. 2. A block diagram of the disturbance feedback control.

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

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

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

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

For example, G and K are defined as follows:

$$G(s)=\frac{G_s}{(1+T_1 s)(1+\sigma s)}. \tag{4}$$

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

Where, G_s is the process gain, T_1 and σ 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

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

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

$$\left(\sigma T_1 s^2+T_1 s+G_s K_p\right)\left[\sigma T_1 s^2+(T_1+\sigma)s+(1+G_s L)\right]=0. \tag{7}$$

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:

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

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

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

$$G_s K_p>0,\ L>\frac{-1}{G_s} \tag{9}$$

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).

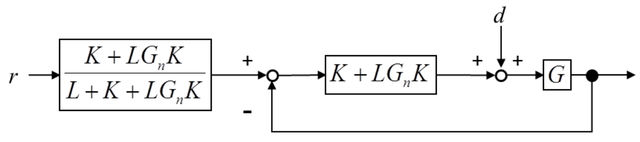

Fig.3. A set-point filter type representation.

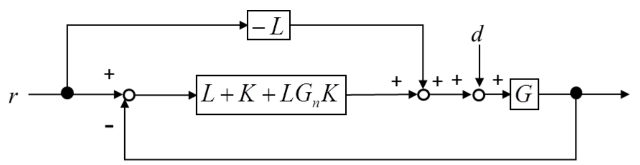

Fig.4. A feed forward type representation.

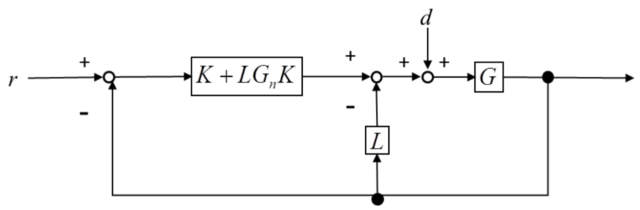

Fig.5. A feedback type representation.

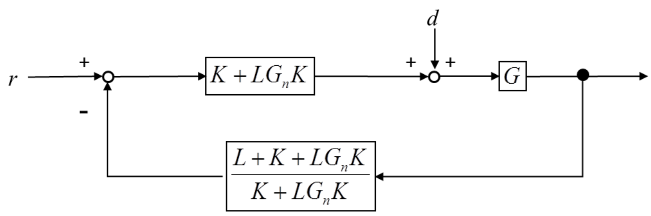

Fig.6. A loop type representation.

2.3 Impact of model error

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

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

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

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

Equation (13) shows that L'→ 1 when L→∞. This means a larger L attenuates the effect of model error ΔG.

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

$$G_{ldy} = G\left[K + L(G_n K + 1)\right], \quad (14)$$

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

$$K' = \left[K + L(G_n K + 1)\right]. \quad (16)$$

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 Betraqs method (Kawai, 2013). Betraqs method is a curve fitting method (Åström, 2006).

PI controller is given by

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

where

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

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.

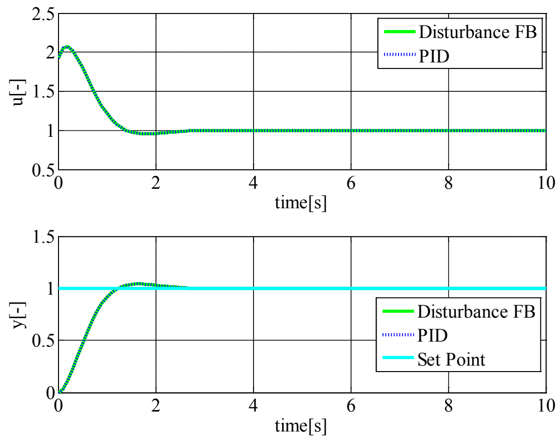

Fig.7. Simulation results of the set-point response of Example 1.

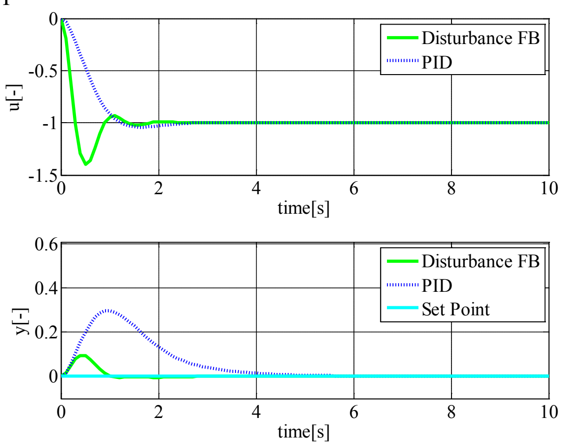

Fig.8. Simulation results of the load disturbance response of Example 1.

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

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

Where ΔG_s is the model error of plant gain and the ΔG_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 ΔG_s. The figure shows that larger L decrease IAE and y_{max} and the larger L also attenuate the effect of ΔG_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 ΔG_s. Similar to the results of Fig.10, a larger L decrease IAE and y_{max} and L also attenuate the effect of ΔG_s.

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

	ΔG_s=0	ΔG_s=-0.5	ΔG_s=0.5	**max-min**
IAE of PI	0.6429	**1.0900**	0.5393	0.5507
IAE of DFC	0.6429	**0.8079**	0.6102	0.1977
y_{max} of PI	0.0430	0.0000	**0.1074**	0.1074
y_{max} of DFC	0.0430	**0.1215**	0.0309	0.0906

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

	ΔG_s=0	ΔG_s=-0.5	ΔG_s=0.5	**max-min**
IAE of PI	**0.5200**	0.5199	**0.5200**	0.0001
IAE of DFC	**0.0557**	0.0701	0.0536	0.0164
y_{max} of PI	0.2979	0.2075	**0.3578**	0.1503
y_{max} of DFC	0.0950	0.0781	**0.1044**	0.0263

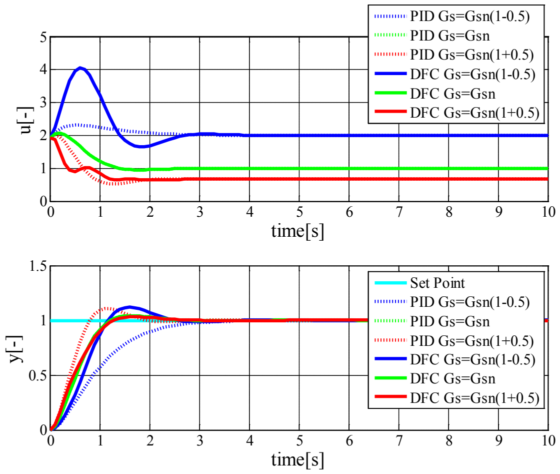

Fig.9. Impact of the model error. Set-point response of Example 1. Parameter L =10 at DFC.

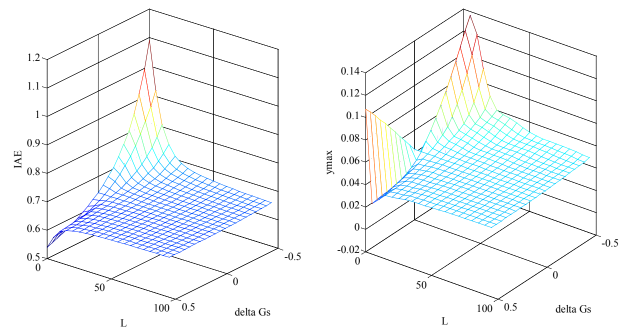

Fig.10. IAE and y_{max} of the set-point response of Example 1 with the proposed method. Impact of parameter L and model error ΔG_s.

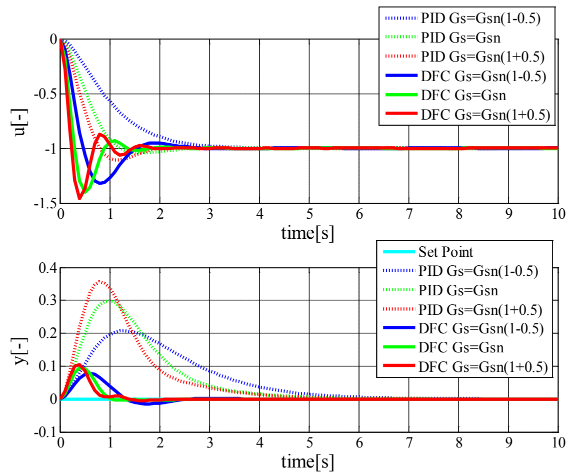

Fig.11. Impact of the model error. Load disturbance response of Example 1. Parameter L =10 at DFC.

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 ΔG_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.

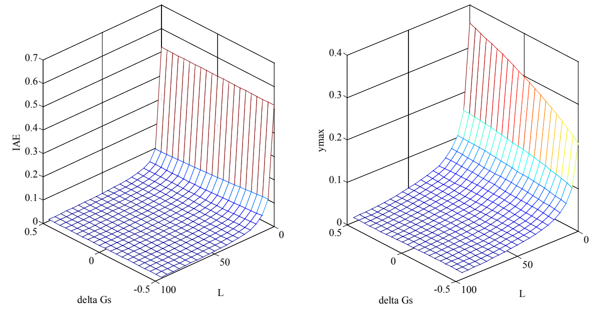

Fig.12. IAE and y_{max} of the load disturbance response of Example 1 with the proposed method. Impact of parameter L and model error ΔG_s.

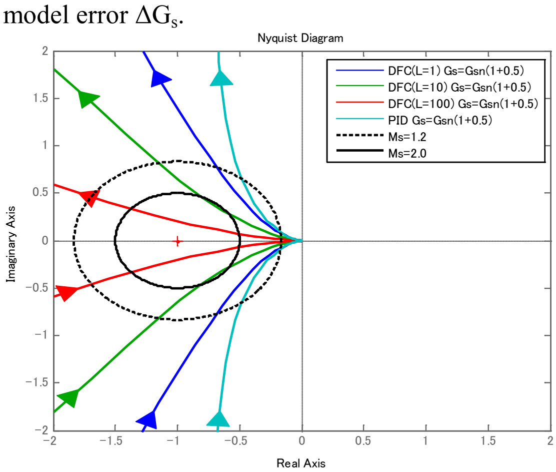

Fig.13. Nyquist plots of the loop transfer function in Example 1. Ms: Maximum sensitive circle.

3. 3 Example 2

The model for Example 2 is given as

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

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.

$$K(s) = Kp + \frac{Ti}{s} + Tds \tag{24}$$

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.

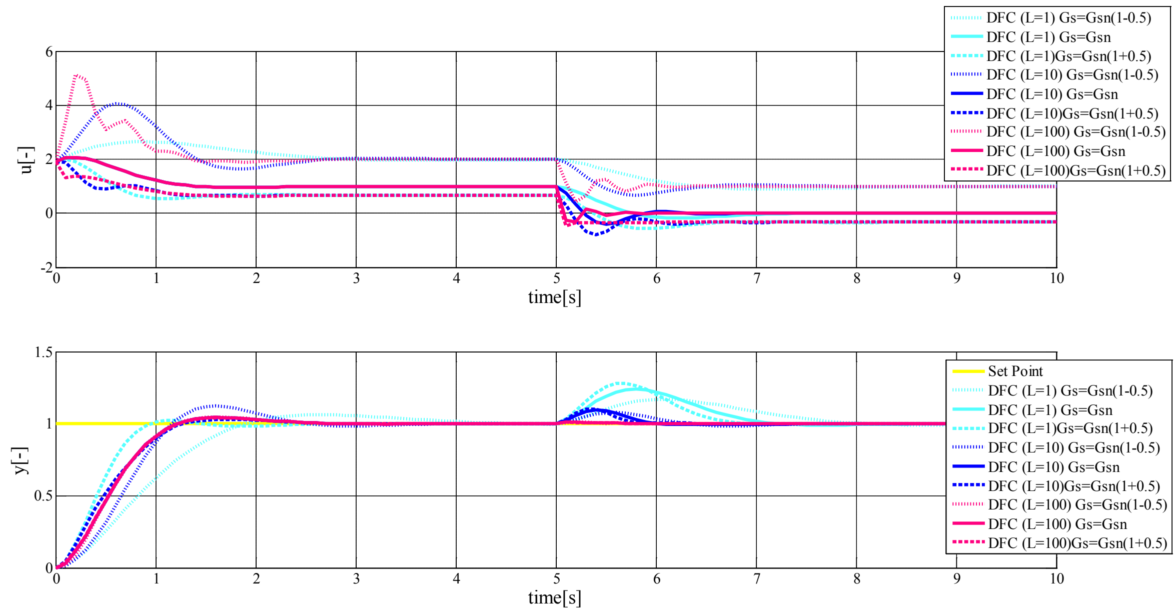

Fig.14. Impact of parameter L and model error. L=1, 10,100. ΔG_s=-0.5, 0, 0.5.

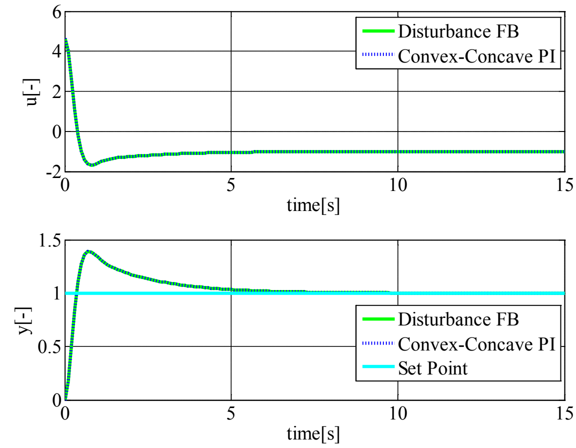

Fig.15. Simulation results of set-point response of Example 2.

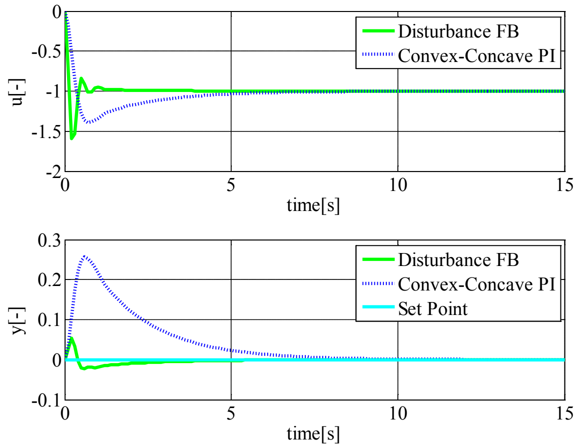

Fig.16. Simulation results of load disturbance response of Example 2.

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.

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