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ROBUST ANTI-WINDUP PID CONTROL OF A COUPLE INDUSTRIAL TANK SYSTEM

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ABSTRACT

Liquid tank systems play important role in industrial application such as in food processing, beverage, dairy filtration, effluent treatment, pharmaceutical industry, water purification system, industrial chemical processing and spray coating. A typical situation is one that requires fluid to be supplied to a chemical reactor at a constant rate. An upper tank can be used for filtering the variations in the upstream supply flow. Feedback control system such as classical PID controller based on the linear model is widely used in controlling industrial liquid level control application. However aggressive performance requirements may not be achievable with the PID controller due to the presence of nonlinear dynamics inherent in the liquid control system and system parameter variations caused by for example corrosive build-up in liquid level systems creates variation of cross section areas of the tank and discharge orifice. One of nonlinearity which exists in industrial coupled tank system is actuator saturation. It is well known that integrator windup which may cause instability and/or performance degradation. To solve this problem, in this paper, a robust Anti-windup PID controller is designed and implemented for level control of tank system. The experimental results show that the proposed robust Anti-windup PID controller effectively reduces for the effect of actuator saturation

Keywords: Robust, PID, controller, anti-windup, saturation, coupled tank.

1. INTRODUCTION

Liquid tank systems play important role in industrial application such as in food processing, beverage, dairy, filtration, effluent treatment, pharmaceutical industry, water purification system, industrial chemical processing and spray coating. A typical situation is one that requires fluid to be supplied to a chemical reactor at a constant rate. An upper tank can be used for filtering the variations in the upstream supply flow.

In order to achieve high performance, feedback control system is adopted. Classical Proportional Integral Derivative (PID) controller based is widely used in controlling industrial liquid level control application [1,2]. Advanced control methods also have been proposed by several researchers such as sliding mode control [3] and nonlinear backstepping control [4]. Nevertheless, PID controllers are still widely used in industrial applications including for process control. The reason is that PID controller has a simple structure which is easy to be understood by the engineers who design it.

However aggressive performance requirements may not be achievable with the PID controller due to the presence of nonlinear dynamics inherent in the liquid control system and system parameter variations caused by for example corrosive build-up in liquid level systems creates variation of cross section areas of the tank and discharge orifice. One of nonlinearity which exists in industrial coupled tank system is actuator saturation. It is well known that integrator windup which may cause instability and/or performance degradation.

In order to solve the above-mentioned problem, robust anti-windup PID controller is adopted for level control of industrial coupled tank system. In order to achieve a robust system, the PID controller parameters are designed based on the ITAE performance, while an anti-windup scheme is added to overcome for the effect of saturation due to power limitation of the actuator. The effectiveness of the proposed controller is evaluated experimentally using a lab-scale industrial coupled tank system. The experimental results show that the proposed robust anti-windup PID controller is effective for controlling the level of the industrial coupled tank system even if the actuator saturation occurs.

2. INDUSTRIAL COUPLED TANK SYSTEM

Figure 1 shows the lab-scaled coupled tank system. This system consists of two tanks with orifices and level sensors, a DC motor driven pump and a liquid basin. The two tanks have same diameters and can be fitted with different diameter outflow orifices. The input is supplied by a DC motor driven variable speed pump which supplies fluid to Tank 1. The orifice, which is connected between Tank 1 and Tank 2, allows the fluid to flow into Tank 2. The other orifice at Tank 2 flows back the fluid to the liquid basin. Two potentiometers are used to measure level of the fluid in the both Tank 1 and Tank 2.

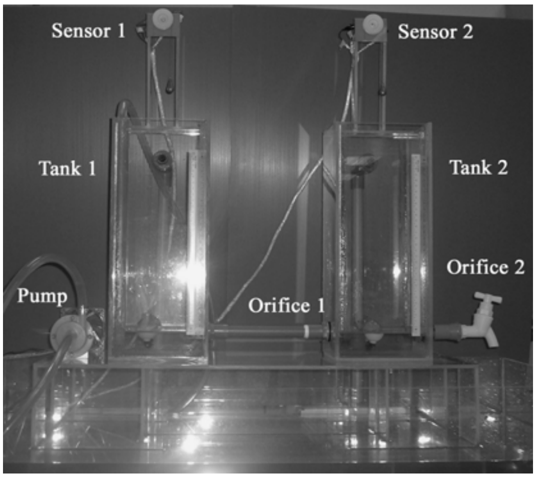

Fig 1: Lab-scale couple industrial tanks

As most of the feedback control system design process including classical PID controller design needs the dynamics model of the plant as well as its parameters [5], a mathematical model of the industrial coupled tank system was developed and its parameters are identified [6]. The developed dynamics model of the tank system is

$$\frac{H_2(s)}{V(s)} = \frac{3.58}{5169s^2 + 196s + 1} \qquad (1)$$

where V(s) and H_2(s) are input voltage of the DC motor driven pump and level of the second tank.

3. ROBUST ANTI-WINDUP PID CONTROLLER

3.1 ITAE-based Robust PID Controller

In order to keep a simple classical approach, the performance of a robust control scheme based on a PID controller with two degrees of freedom consisting of a PID controller and a pre-filter is adopted. Figure 2 shows the structure of the proposed controller. The closed-loop transfer is

$$T(s) = \frac{G_f(s)G_c(s)G(s)}{1 + G_c(s)G(s)} \qquad (2)$$

The controller G_c(s) is the classical PID controller which has the following transfer function:

$$G_c(s) = \frac{K_d s2 + K_p s + K_i}{s} \qquad (3)$$

where K_p, K_i and K_d are proportional, integral and derivative gains respectively. In general, the PID controller G_c(s) is designed to make closed-loop system is robust to parameter variation as well as disturbances. On the other hand the pre-filter G_f(s) is designed to achieve a desired input/output transfer function [5].

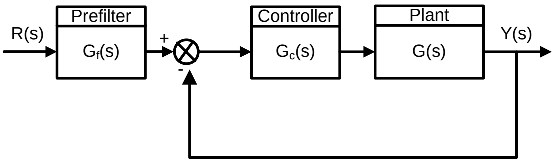

Fig. 2 Proposed control structure

The robust control method using optimal adjustment of the PID parameters based on the *integral of time multiplied by absolute error* (ITAE) performance index is considered in this paper. Hence the three PID controller parameters are selected to minimize the ITAE performance index which will produce an excellent transient response to a step input reference. The closed-loop system transfer function that will minimize the ITAE performance index for a step input for general have been determined for the following general closed-loop transfer function [5]:

$$T(s) = \frac{b_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0} \qquad (4)$$

The optimum coefficients based on the ITAE performance index for system of Eq. (4) are given in Table 1. By designing the PID controller and pre-filter such that the closed-loop system has a transfer function of Eq. (4), the closed-loop system has a zero steady-state error to a step input. In addition, since the damping ratio of 0.7 is used, the system also has a small overshoot.

Table 1: The optimum coefficients based on ITAE

$s + \omega_n$
$s^2 + 1.4\omega_n s + \omega_n^2$
$s^3 + 1.75\omega_n s^2 + 1.4\omega_n^2 s + \omega_n^3$
$s^4 + 2.1\omega_n s^3 + 3.4\omega_n^2 s^2 + 2.7\omega_n^3 s + \omega_n^4$
$s^5 + 2.8\omega_n s^4 + 5.0\omega_n^2 s^3 + 5.5\omega_n^3 s^2 + 3.4\omega_n^4 s + \omega_n^5$

In summary, the design procedure consists of the following three steps [5] :

(1) Determine the natural frequency ω_n of the closed-loop system based on the desired settling time Ts. The following equation describes the relation of settling time, the natural frequency ω_n and damping ratio ζ:

$$Ts = \frac{4}{\zeta\omega_n} \qquad (5)$$

(2) Determine the three PID controller parameters using the appropriate optimum equation (Table 1) and the ω_n of step 1.

(3) Determine a pre-filter G_f(s) so that the closed-loop system transfer function T(s) does not have any zeros as required by Eq. (4).

3.2 Anti-windup Strategy

PID control system with the wide range of the operations may result in the condition that the control signal reaches the actuator limits. In this case, the feedback is broken and the system runs as an open loop system since the actuator will remain at its limit independently of the plant output. Since the controller contains integrator action, the error will be integrated. This means the integral term become very large or, it is "windup". Then the error must have opposite sign for the long time before things returned to normal [7].

In order to reduce the effect of the integrator windup in the PID controller, the PID compensator with tracking anti-windup system is used instead of pure PID compensator. The structure of the tracking Anti-windup PID controller is illustrated in Fig. 3 where K_T is called tracking gain [7]. Once PID controller output U(s) exceeds the actuator limits, a feedback signal will be generated from the difference of the saturated and the unsaturated signals. This signal is used to reduce the integrator input. Mathematically, the output of the Anti-windup PID controller is

$$U(s) = \left[K_p + \frac{K_i}{s} + K_d s\right]E(s) - \frac{K_T}{s}\left[U(s) - U_s(s)\right] \qquad (6)$$

where K_T, U(s) and $U_s(s)$ are tracking anti-windup gain, control output and saturated control output respectively. To set the value of K_T, a rule of thumb point out that $K_T = K_i$ may give a good results but higher values may give a further improvement in performance [9]. Therefore, the performances of the tracking anti-windup system depend on selecting the suitable value of K_T.

4. EXPERIMENTAL SETUP

In order to examine the effectiveness of the proposed controllers, a series of experiment is done using the lab-scale industrial coupled system. The experimental setup is shown in Fig. 4. The proposed robust Anti-windup PID control algorithm is implemented on a personal computer and are operated with 1 ms sampling time. The MathWork's MATLAB/Simulink is used for real-time controller implementation through RTW and xPC Target. The RTW environment provides a real-time operation using personal computers and multifunction I/O boards. However, the use of RTW still requires the development of custom interface programs for correct communication with multifunction I/O boards. In order to overcome this problem, xPC Target is included in the software configuration.

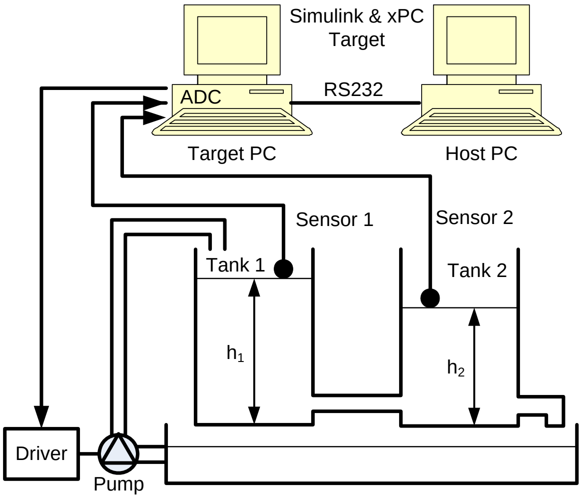

Fig 4: Setup of real-time controller implementation

The xPC Target software supports and provides built-in drivers for many industry standard DAQ card including the PCI-6024E DAQ card by National Instrument which is used in the prototype of the automatic gantry crane system. A personal computer is used as a Host Computer. Windows operating system and other required software are running in the Host Computer. The proposed controller is developed in Simulink using its blocks, and then it is built so that C code is generated, compiled and finally a real-time executable code is generated and downloaded to the Target Computer.

The Target Computer is another personal computer which is booted using xPC boot floppy disk that loads the xPC Target real-time kernel. Subsequently, the generated real-time executable code is downloaded to the Target Computer via selected communication protocol without writing any low-level code. The connection between the Host Computer and Target Computer is accomplished either through serial (RS-232) or network (TCP/IP) communications. The communication interface have to be defined during xPC setup process in the MATLAB since the communication protocol definition is required in creating the xPC boot floppy disk for the Target Computer. In the proposed system, serial communications is used since it is inexpensive, easy to install and requires only a cable for connecting serial ports of the Host Computer and Target Computer.

5. CONTROLLER DESIGN

The proposed Anti-windup PID controller has to be designed their parameters to achieve a specific desired performance of the level control system. In order to realize fast response, the proposed robust Anti-windup PID controller is designed so that the settling time of closed-loop system is less than 500 sec. Therefore, according to Eq. (6), the closed-loop system should have the natural frequency larger than 0.001143. Then the natural frequency of 0.05 is selected. As a result, the desired optimal closed-loop transfer function is

$$T(s) = \frac{1.25x10^{-4}}{s^3 + 8.75x10^{-2}s^2 + 5.38x10^{-3}s + 1.25x10^{-4}} \qquad (7)$$

The three parameters of the PID controller has to be designed is obtained by direct comparison between Eqs. (2) and (7). As the result, the PID controller parameters are as follows

$$K_p = 7.50, \qquad (8.a)$$

$$K_i = 0.181, \qquad (8.b)$$

$$K_d = 71.7. \qquad (8.c)$$

Furthermore, in order to make the closed-loop system transfer function has no any zeros, the following pre-filter transfer function is obtained also by comparing Eqs. (2) and (7):

$$G_f(s) = \frac{2.52x10^{-3}}{s^2 + 1.05x10^{-1}s + 2.52x10^{-3}}. \qquad (9)$$

Finally, in order to suppress the effect of actuator saturation, the tracking anti-windup gain K_T equals to K_i is used.

6. RESULTS

The designed robust Anti-windup PID controller is tested in the real-time experiment. The performances of the proposed robust anti-windup PID controller are compared with those of the PID control system. Figs. 4, 5 and 6 show the responses of the PID controllers when the 5 cm, 10 cm and 15 cm step input references were used respectively. The detailed performances are shown in Table 2. Here, the performances of level control system are evaluated based on overshoot, settling and error at

500 sec.

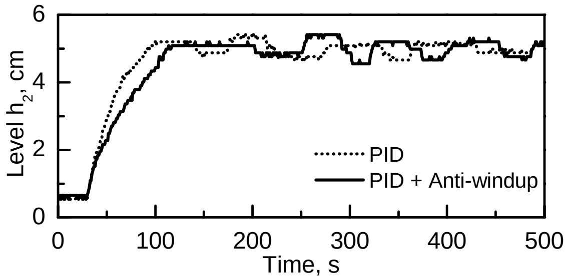

Fig 4: Experimental responses to 5 cm step input

Fig. 4 shows the step responses to a-5 cm step input when the controllers are the level of Tank 2. Their performances are summarized in Table 2. As the reference input is small enough, the 5-cm step input does not cause the saturation of the control signal. Here, all the controllers produce a similar performance in terms of overshoot and rise time. However, the error of using the proposed controller is slightly higher than that using only PID controller.

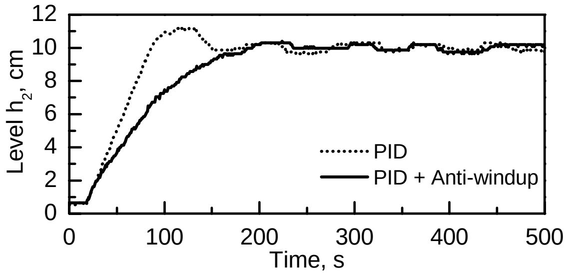

Fig 5: Experimental responses to 10 cm step input

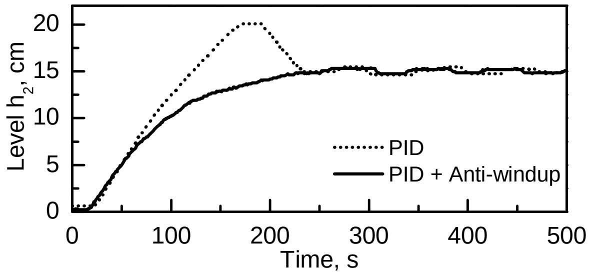

Fig 6: Experimental responses to 15 cm step input

Table 2: Performance comparisons

Reference	Performance	Anti-windup PID	PID
5 cm	Overshoot	8.31%	8.31 %
	Settling time	500 sec	498 sec
	Error	0.198 cm	0.091 cm
10 cm	Overshoot (%)	4.03%	11.6%
	Settling time	434 sec	500 sec
	Error	0.186 cm	0.248 cm
15 cm	Overshoot (%)	2.60%	33.6%
	Settling time	302 sec	393 sec
	Error	0.065 cm	-0.152 cm

Figures 5 and 6 show the step responses to a-10 and 15 cm step inputs when the controllers are the level of Tank 2. Their performances also are summarized in Table 2. As the reference input is large enough, both step inputs t cause the saturation of the control signal as indicated by a larger overshoot of the system controlled by only PID controller. As shown in the figures and Table 2, the proposed controller significantly reduced the overshoot caused by integrator windup due to actuator saturation. On the other hand, it is also shown in Table 2 that the used of anti-windup does not degrade the performances in terms of settling time and error. Therefore it can be concluded that the proposed robust anti-windup PID controller is effective control the level of Tank 2 even if the actuator saturates.

7. CONCLUSIONS

This paper has introduced the robust anti-windup PID controller for controlling the level of industrial tank system. First the three parameters of the PID controller are designed based on the ITAE performance index. Next, the pre-filter is designed so that the closed-loop transfer function does not have any zeros. Finally, an anti-windup strategy is included in the proposed controller to compensate for the effect of actuator saturation. The effectiveness of the proposed controller is evaluated experimentally to control the level of Tank 2 of lab-scaled industrial coupled tank system. The results confirm that the proposed controller is effective since it give a good performance even if the actuator saturates.

8. REFERENCES

1. Visioli, A., 2004, “A new design for a PID plus feedforward controller”, Journal of Process Control, 14: 457–463.
2. Tan, K.K., Huang, S. and Ferdous, R., 2002, “Robust self-tuning PID controller for nonlinear systems”, Journal of Process Control, 12: 753–761.
3. Almutairi, N.B. and Zribi, M., 2006, “Sliding mode control of coupled tanks”, Mechatronics, 16: 427-441.
4. Pan, H., Wong, H., Kapila, V. and de Queiroz, M.S., 2005, “Experimental validation of a nonlinear backstepping liquid level controller for a state coupled two tank system”, Control Engineering Practice, 13:27–40.
5. Dorf, R. and Bishop, R., 2007, Modern Control System, 11th Ed, Prentice Hall, New Jersey.
6. Wahyudi, Fadhil, M. and Shazri, 2007, “Modeling and Parameters Identification of a Coupled Industrial Tank System”, *Proc. National Conference on Software Engineering and Computer Systems (NaCSES’07).*
7. Bohn C. and D.P. Atherton, 1994. “A SIMULINK Package for Comparative Studies of PID Anti-windup Strategies”, *Proc. of IEEE/IFAC Joint Symposium on Computer-Aided Control System Design*, 447-452.