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COMPARATIVE REALIZATION OF 2DOF PID CONTROLLERS FOR FLOW PROCESS WITH MEASUREMENT DELAY

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ABSTRACT

Two Degree-of-Freedom (2DoF) PID control techniques presented in this paper were developed based on H_∞ *optimal control theory and with the Anti-Integral Windup (AIW) scheme. The controllers were implemented for a laboratory flow process setup. First Order Process with Dead Time (FOPDT) models had been identified by step testing. The process responses showed a significant non-minimum phase dynamics exhibited for the specific step inputs applied. The measurement delay was considered as large delay in the fast acting loop. In this work the 2DoF PID AIW control scheme was developed in association with the conventional Smith predictor to rectify the final control element's delayed actuation. The objective of this work was to compare the realization of 2DoF PID controllers tuned for the flow process on basis of time domain performances. The control system's performances were analyzed for its ability to minimize the power consumption associated with the final control element. In this paper, it is shown that the 2DoF PID AIW controller performs better than* H_∞ *PID controller and it is a simple and reliable control technique to implement for a real system.*

Index Terms - Flow process control, Two Degree-of-Freedom PID controller, Anti-integral windup, Smith predictor, large delay system

INTRODUCTION

In process industries, a system may consume high power per transported unit mass because one of its instruments has limited operating capacity [7, 8, and 9]. More specifically the Final Control Element (FCE) capacity depends on the properties of the material flowing and on the available pressure head for the material to flow. Once the FCE's physical limits are saturated then a continuing increase in input to the system (mostly because of the integral term in the controller) further has no effect on the output is referred to Integral-Windup (IW) phenomena [14]. To recover from FCE saturation, the controller waits to unwind till the error term changes its sign. This causes long time delays at input side and introduces possible instability in fast acting loops. Another degradation problem in fast acting loop is due to measurement delay. The controller may be designed to meet satisfactory performance measures, so it may generate high velocity inputs to a system. But high velocity control signals cause higher pressure drops in closed loop and the system consumes higher power to sustain such high flows. A laboratory flow process setup was found with these constraints which restrict the flow operation in the system into preferably homogeneous with a bounded control signal. The lower velocity control signals were allowed if the flow that precedes the transition from laminar to turbulent flow condition was avoided a priory. Thus, the system was stabilized for the linear homogeneous flow conditions as in [7, 9].

The 2DoF control systems constitute of two different signal transmissions, one from reference (SP) to control (MV) and other from measurement (PV) to control (MV) [Horowitz, 1963]. The advantages of 2DoF PID controller are the shortest rise time and settling time which can be achieved independently of servo tracking and load regulation in the time domain analysis. 2DoF PID controllers presented in [3] and [4] were taken for this research work based on simulated results in [6 and 10]. In this work the flow process was tested with various step changes given, to identify a specific operating condition for worst case where a violent pressure surge can cause a possible laminar to turbulent flow along the transmission line. Eventually the developed 2DoF PID controllers were realized for the control design problem for input/output long-delayed fast acting loop with FCE constraint and its time-domain performances were analysed.

II. FLOW PROCESS MODEL IDENTIFICATION

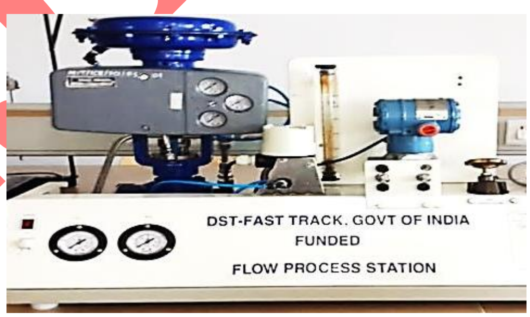

Fig. 1. Flow process setup

The experimentation was carried out in a flow process laboratory setup which is shown in Fig. 1. The material is water (ρ = 1000kg/m^3) and a discharging pump speed was linearized to provide an outflow range of 0-380lph to pipeline. The instrumentation used to identify the flow was constituted a linear control valve at the input side and a differential pressure transmitter at the output side, which is installed along the transport pipeline.

The liquid phase was varied from its zero-initial condition to several new steady states to find a specific operating condition. The open loop transfer characteristic of the flow system for the control valve openings and the measured outflows in percentage are provided in Table 1. Small openings of the control valve produced a laminar outflow where more of the water discharged from the pump was bypassed to reservoir tank, refer schematic diagram shown in Fig. 2. For a full opening of the control valve, the water flow was dispersed directly from the pump which makes the outflow full turbulent and nonlinear. From Table 1, the following inferences were made

1) The linear range of flow process is identified for control valve opening from 5% to 15%.
2) The outflow transits from laminar to turbulent for higher than 15% of valve opening, and the nonlinear dynamics were exhibited in the flow process.
3) Saturation point at <5% valve opening and >35% valve openings were found above which the outflow was dispersed and did not change.

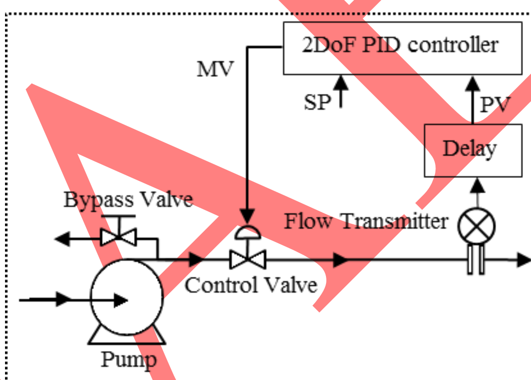

Fig. 2. Schematic of the flow process with 2DoF PID control

TABLE I

FLOW PROCESS OPEN LOOP DATA

Characteristics	Valve Opening (%)	Outflow rate (%)
Saturation	0	0
Linear	5	39.5
	10	60.5
	15	79
Nonlinear	20	84
	25	92
	30	95
	35	97
Saturation	40	100
	45	100

In this work, a choice of the worst case operating condition was based on linear characteristics and the FCE saturation limit of the flow process setup. Then a nominal process model was determined for applied 5% valve opening. The flow process responses were acquired after 4sec measurement delay which can be noted from the step response shown in Fig. 3. The intended use of the transport delay was considered as summation of the measurement delay by the data acquisition system and the process delay calcluated using 2-point method (28.3% and 63.2%) from the step response. The identified First Order Process with Dead Time (FOPDT) model is given below,

$$G_p(s) = \frac{K}{Ts+1} e^{-t_d s} = \frac{0.186}{1.35s+1} e^{-4.25s} \qquad (1)$$

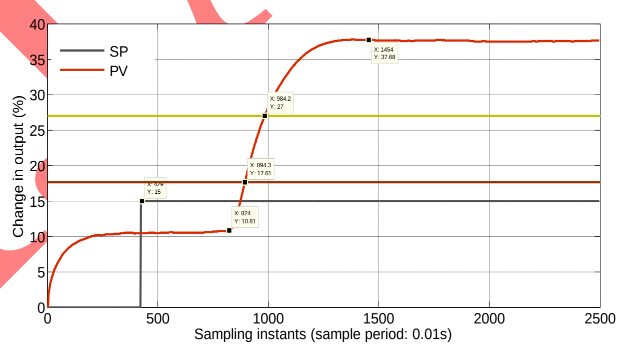

Fig. 3. Flow process reaction curve

2DOF PID CONTROL SYSTEMS FOR LARGE DELAY PROCESS

In [3] a set point response controller and an H_∞ PID feedback controller were developed based on optimal control theory, and the control parameters were derived analytically for controlling processes with large time delay in 2DoF control structure. In [4] 2DoF PID controller was proposed to combine the different anti-integral windup approaches to deal with processes which have different normalized dead times. The Smith predictor presented in [8, 13] involves effectively removing the delay from the control loop, so that a 'primary' controller can be designed for the delay free portion of the process.

A. H_∞ 2DoF PID control system: Zhang method

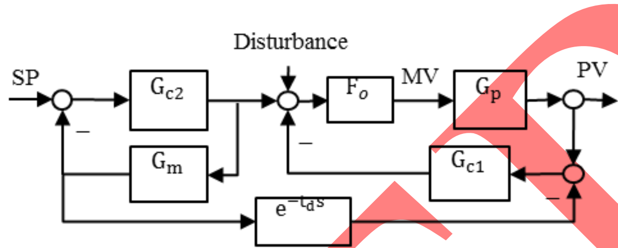

Fig. 4. 2DoF PID control system

Fig. 4 shows a 2DoF PID control scheme i.e., the set point response and disturbance response which can be controlled by controller G_{c1} and G_{c2} respectively. G_m takes the transfer function of process model without delay. The controller transfer functions were developed based on H_∞ optimal control theory for large delay process. The analytically derived G_{c1} and G_{c2} transfer functions from [3] were taken,

$$G_{c2}(s)=\frac{1}{\lambda s}\frac{Ts+1}{K} \qquad (2)$$

$$G_{c1}(s)=K_c\left(1+\frac{1}{T_i s}+T_d s\right)\frac{1}{T_F s+1} \qquad (3)$$

Where, $T_i=t_d/2+T$, $T_d=\frac{t_d T}{2T_i}$, $T_F=\frac{\lambda^2}{2\lambda+t_d/2}$, and $K_c=\frac{T_i}{K(2\lambda+t_d/2)}$.

Where λ is the performance degree and expressed as $\lambda=\alpha\cdot t_d$.

B. 2DoF PID AIW controller: proposed method

A PID controller designed in parallel form [4] can be modified into 2DoF PID controller for fast acting loops as follows.

$$G_{c1}(s)=\left(K_c e+\frac{e_i}{s}\right) \qquad (4)$$

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where

$$e_i = \frac{K_c}{T_i} e + \frac{(u_s - u)}{T_t} \tag{5}$$

$$G_{c2}(s) = \frac{T_d s}{1 + \frac{T_d s}{N}} \tag{6}$$

The controller parameters were tuned using Ziegler-Nichols method as in [1]. In (5) and (6) the choice of T_t and T_d determines the performance of overall system for servo tracking and load regulation. The integral time T_i in (5) is the time interval in which the part of the control signal increases due to integral action by the amount equal to the part of control signal due to proportional action [14]. The tracking time constant T_t in (5) was considered the time interval in which the part of the integral action decreases to the amount of difference between the required (saturated) control signal between the control valve physical limits and the generated (unsaturated) control signal. In this work, T_t was tuned in such a way that the T_t is double the tracking time based on Ziegler-Nichols method. According to (4) and (5) when the process delay expires the direction of integral action was reset to the direction of the control signal produced by proportional action so that abrupt change in controller output was avoided. In order to quantify this the tracking time constant was chosen half of integral time as,

$$T_t = \frac{T_i}{2} = \frac{2t_d}{2} = t_d \tag{7}$$

The conventional Smith predictor was incorporated to the 2DoF PID AIW control system as taking recommendations from [8] to improve the performances of designed for large delay system. The filter F in 2DoF PID AIW control system with smith predictor shown in Fig. 5 was chosen to improvise the early roll off point of loop transfer function (without G_{c2}) to offer undelayed predicted feedback.

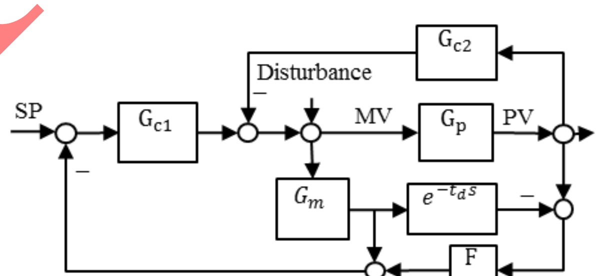

Fig. 5. 2DoF PID AIW control system with smith predictor

RESULTS AND DISCUSSIONS

The set point was chosen, based on the choice made in Section 2 for the worst case, by imposing it to be 30% (115lph) where the signal to control valve would be in saturation region and should be oscillating in closed loop. The 2DoF PID control systems performance and robustness was analysed against model uncertainty by changing the flow to nearer operating points. To be able to quantify a significant reduction in the power (associated to control signal) needed to transport the given liquid, the specified operating condition would be executed with and without adapting measurement delay with the designed 2DoF PID controllers.

A. H_∞ 2DoF PID control system: Zhang method

The H_∞ 2DoF PID controller settings were tuned and the values are for $\alpha = 3$, t_d = 4.25sec; K_c = 0.6763, T_i = 3.475sec, T_d = 0.8255sec, T_f = 5.885sec. The controller output and the corresponding process output are shown in the following Fig. 6 and 7.

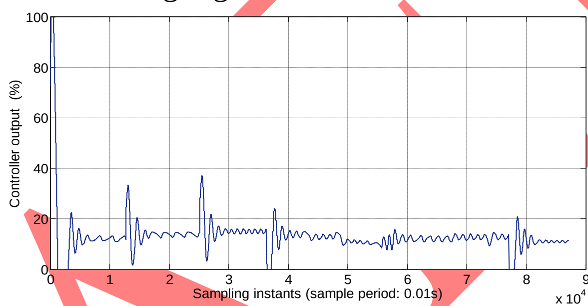

Fig. 6. H_∞ 2DoF PID controller output.

The best of α was chosen as considering the possible closed loop instability caused by large measurement delay.

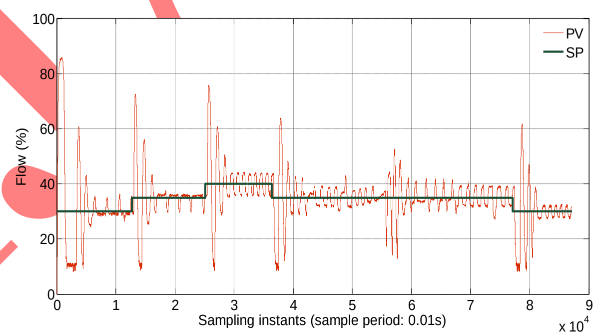

Fig. 7. Real flow system closed loop servo and regulatory responses with H_∞ 2DoF PID controller

B. 2DoF PID AIW controller: proposed method

The controller settings are for t_d = 4.25sec; K_c = 15.233, T_i = 14.025sec, T_d = 2.12sec, T_t = 4.25sec, N =10, F = 1/(20s+1). The closed loop responses of 2DoF PID AIW in association with smith predictor control system are shown in Fig. 8, and 9.

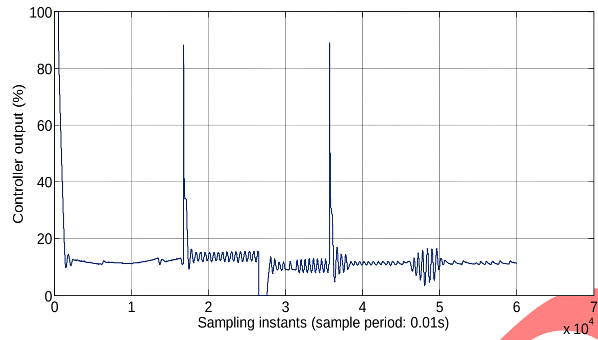

Fig. 8. 2DoF PID AIW controller output in association with Smith predictor

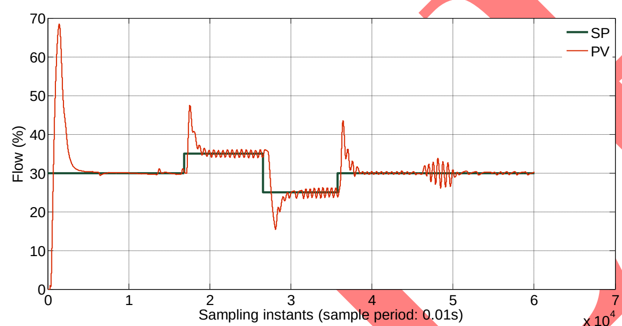

Fig. 9. Real flow system closed loop servo and regulatory responses with 2DoF PID AIW controller in association with Smith predictor

The control signals shown in Fig. 6 and 8 were compared for the reduction in power consumption. It can be seen that the 2DoF PID AIW controller in association with Smith predictor was capable of coping with model mismatch problem and produced improved performances better than and H_∞ 2DoF PID controller which can be seen in Fig. 7 and 9. The closed control systems time-domain performance measures are shown in Table 2.

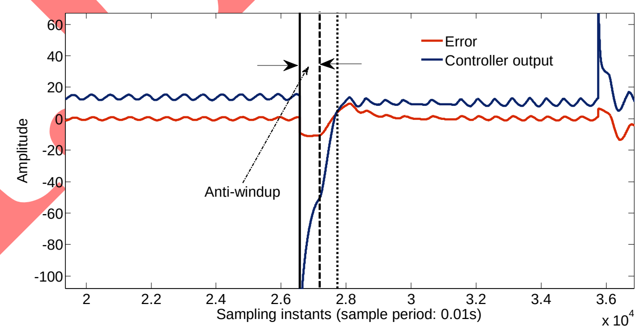

Fig. 10. Working of Anti-Integral Windup scheme

A large step change applied on reference causes the Integral-Windup, then recounting the integral term plays a vital role. The illustration of AIW is shown in Fig. 10. The final control element was released from its saturation quickly as possible as well to minimize the IAE when a large reference step change was applied.

Table 5. Performance measures of 2DoF PID controllers

***H_∞* 2DoF PID controller**					
	t_r (sec)	**t_{ss} (sec)**	**MP%**	**IAE**	**ISE**
Nominal	1.2	62.3	186.2	2.5e+4	1.2e+5
30% - 35%	3.1	44.7	844.8	2.2e+4	4e+4
35% - 40%	3.2	42.2	818	2+4	4e+4
40% - 35%	3.6	70.6	592.2	3e+4	5e+4
Load	-	-	48.8	1.2e+4	2e+4
35% - 30%	8.4	56.2	533.2	2e+4	3e+4
2DoF PID controller in association with Smith predictor					
	t_r (sec)	**t_{ss} (sec)**	**MP%**	**IAE**	**ISE**
Nominal	6.7	45	126.8	1.3e+7	1.3e+10
30% - 35%	3	20.7	250	1.8e+7	3.8e+10
35% - 25%	9	32	92.3	2.8e+7	7.9e+10
25% - 30%	3.8	26.8	270.6	3.4e+7	1.3e+11
Load	-	-	12.67	2.7e+7	1.2e+11

*The IAE and ISE values were calculated for corresponding responses shown in this paper, where each step changes were applied for different time instants and different durations.

CONCLUSION

The technique for flow operation near the minimum pressure drop line in the flow transfer characteristics was discussed. Possibilities of significant improvement in closed loop performances with 2DoF PID control were shown in this work. Experimental test performed with water flow in pipeline showed that the 2DoF PID control techniques presented in this work were capable of producing optimal control for fast acting loops. Particularly 2DoF PID AIW controller is capable of handling model uncertainty, actuator constraints and time delays. Future work will include systematic experimental test to find techniques which may minimize the IAE and ISE values further with different types of particulate and extended flow rate ranges, in order to assess the applicability of the 2DoF PID control for industrial processes.

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