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Control and Analysis of Pressure Variable in the UCP Process Control

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ABSTRACT

Objective – This paper is proposing on the pressure process control approach in Universal Control Plant (UCP) system in order to obtain the desired signal response.
Methodology/Technique – The structure of UCP is introduced and single input single output (SISO) model of pressure is designed through system identification toolbox. To achieve the best controller, analyses of traditional PID and intelligent controllers were made. The PID gains were tuned alternately in order to get the best gain. Then, a comparison of solver methods between Adam Moulton (AM) and Backward Differential Formula (BDF) for fuzzy logic techniques was highlighted. To evaluate the performance of controller system, the transient response and steady state response were analysed including overshoot, undershoot, settling time and steady state error. Finally, the comparison on the best PID gain and fuzzy logic AM solver method was concluded.
Findings – The result has shown that fuzzy logic controller generated better performance compared to PID and steady state error improved more than 99.9%.
Novelty – After evaluating the performance of controller system and analyses; the transient response and steady state response including overshoot, undershoot, settling time and steady state error, it has been proven that fuzzy logic control is better than PID control.

Type of Paper: Empirical

Keywords: Fuzzy logic controller; PID controller; Pressure; System identification; Water level

1. Introduction

Water level control is a crucial part in chemical, pharmaceutical and food industry as well as in coal mine drainage control system. This is due to the importance of chemical purity, monograph standard and maintenance of mine water storage at an optimal level. The variables in water level control is characteristically nonlinear [1-2]. Besides the water level, pressure is another factor that contributes to the system's stability. For example, in hydropneumatic tanks, pressure has to be regulated to provide a desired volume of water(O & Z 2012). Meanwhile in deaerator pressure, it is important to remove the oxygen and carbon monoxide in

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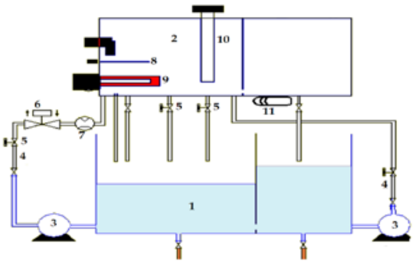
condensation water other than heating the condensed water to saturate the temperature (Wang et al. 2014). There are many types of controllers used in process control as well as for pressure specifically. They are including Proportional, Integral and Differential (PID), adaptive observer, model predictive control (MPC) and fuzzy logic control. Eastman Chemical Company reported that they have developed over 14,000 PID controller to control temperature, flow, level pressure and other related parameters in 40 plants (Paulonis & Cox 2003). While in (Gilbert et al. 2003), PID tuning was used in paper machine headbox to determine the flow velocity by controllingthe pressure variable. The method of tuning theMIMO system using a finite number of frequency response data by optimizing two PI controllers simultaneously had shown some effectiveness for paper machine. Hence, the importance of controlling pressure and flow variables in pipe of paper mill is proven. This is when the pressure loop and the flow loop were decoupled in order to get disturbance attenuation properties (Nordfeldt & Hagglund 2006). Although PID is very popular due to its simplicity, applicability and robustness, but MPC was proven for better performance. MPC framework has shown that pressure fluctuations are smaller and transition time in reverse osmosis desalination process is shorter (Bartman et al. 2009). The framework has also delivered major performance in pressure swing adsorption by integration of multi-parametric technique (Khajuria & Pistikopoulos 2011). However, integrated PID neural network had reduced the overshoot and settling time in order to overcome strong coupling between pressure and water level of deaerator in marine steam power plant (Wang et al. 2014). Fuzzy logic is also being embedded in many applications including pressure control. This is especially in the power plant process. In order to maintain the pressure and water within acceptable tolerance, Takagi-Sugeno fuzzy model is established to approximate the behaviour of boiler-turbine system together with genetic algorithms to handle nonlinear predictive control issue(Li et al. 2012). Later, the model predictive tracking controller was introduced to solve slow tracking power problem and the pressure in a wide range load variation (Wu et al. 2014).

2. Methodology

2.1 Universal Control Plant (UCP) System



Legend:
1. Bottom/storage tank
2. Process tank
3. Pumps
4. Flow meters
5. Solenoid valves
6. Proportional valve
7. Flow sensor
8. Temperature sensor
9. Electric heating
10. Level sensor
11. Pressure sensor

Figure 1. Diagram of UCP plant control system.

Figure 1 is illustrating on the diagram UCP system. The control structure consists of two tanks (process and storage), water pumps, three solenoid valves (one inlet and two outlets), proportional valve, level sensor and pressure sensor. The pump is used to pump the water from storage tank, the flow meter is to allow the water flow at required flow rate, and the solenoid valves are consumed to control on/off the flow of water at three different flow coefficients(International 2004). There are four main elements in this plant control:(i) temperature, (ii) level/height, (iii) flow rate, and (iv) pressure of the fluid in the process tank. The equations for each element were as the following listings (Massoud 2005).

For temperature:

$$\frac{dT}{dt}=\frac{1}{m_{c.v}C_p}[\dot{m}_iH_i+\dot{Q}+\dot{W}_s-V\dot{P}-(\dot{m}_{e1}H_{e1}+\dot{m}_{e2}H_{e2})-m_{c.v}v\frac{dP}{dt}-H_{c.v}A\frac{dh}{dt}] \qquad (1)$$

For level or height:

$$\frac{dh}{dt} = \frac{1}{H_{c.v}A}\left[\,\dot{m}_i H_i + \dot{Q} + \dot{W}_s - V\dot{P} - (\dot{m}_{e1}H_{e1} + \dot{m}_{e2}H_{e2}) - m_{c.v}\left(C_p\frac{dT}{dt} + v\frac{dP}{dt}\right)\right] \tag{2}$$

where

$$H = u + Pv$$
$$m_{c.v} = m_{o(c.v)} + (\dot{m}_i - \dot{m}_{e1} - \dot{m}_{e2})t$$

For flow rate:

$$\dot{V} = \left[\frac{1}{C_D}\frac{2GV_F}{A_F}\left(\frac{\rho_F}{\rho_f} - 1\right)\right]^{1/2} \frac{\pi[(b+\alpha z)^2 - S^2]}{4} \tag{3}$$

For pressure:

$$P_f = P_{atm} - \rho_f G h \tag{4}$$

Where T is temperature, m is mass of fluid, h is height, Q is power of heating element, W is power of work transfer, V is volume, P_f is fluid pressure, A is cross sectional area of tank, H is enthalpy,$\dot{V}$ is volume flow rate, G is gravitational acceleration, C_D is flow coefficient, andρ_f isfluid density. Figure 2 shows the model of pressure variable and its relationship with the pressure in water tank. The assumptions made include: perfect and instantaneous mixing, sub cooled water in the tank throughout the process, no chemical reaction and no heat loss from the tank.

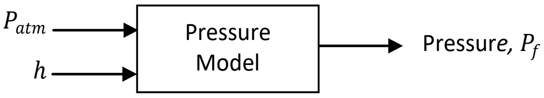


Figure 2. Model block of pressure variable

2.2 Process Identification

In this section, the identification of transfer function was developed by using System Identification Toolbox in MATLAB. The data acquisition of the input and output for the pressure variable which was acquired and plotted as in Figure 3. The result will be discussed in part 5.

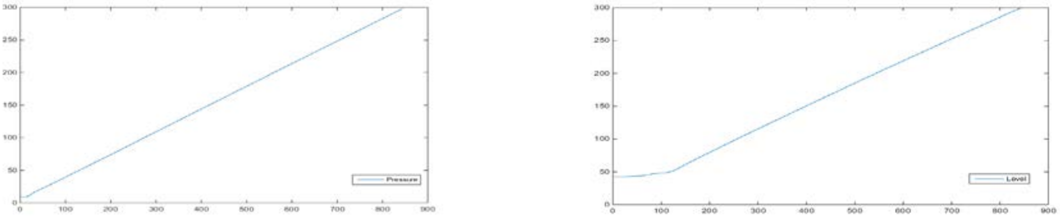


Figure 3. Input (left) and output (right) of pressure variable.

2.3 Pressure Controller

Figure 4 is illustrating on the block diagram of controller system structure.

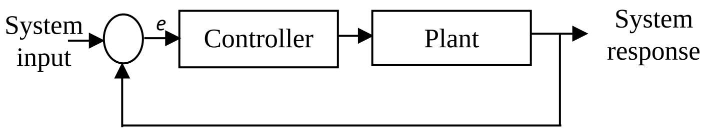


Figure 4. Block diagram of the controller system.

2.3.1 PID Controller

The formula for the basic parallel PID controller is,

$$u_c(t) = k_P e(t) + k_I \int^t e(\tau)d\tau + k_D \frac{de}{dt} \quad (5)$$

Where $k_P$is the proportional gain, $k_I$is the integral gain, k_D is the derivative gain, and the controller operates on themeasured reference error time signal(Johnson & Moradi 2005),

$$e(t) = r(t) - y_m(t) \quad (6)$$

2.3.2 Fuzzy Controller

Figure 5shows the configuration of fuzzy logic control system. The selected membership functions contain three symmetrical triangular functions with different range of input and output value. However, this is acceptable for Low range of pressure which is slightly skewed to the left when tune manually. The limitation values of the input and output were determined via data acquisitions that were done previously.

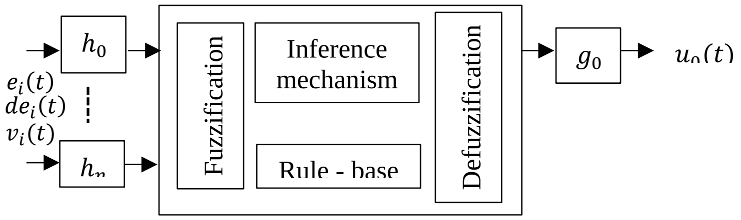


Figure 5. Fuzzy logic control configuration.

There are three simple IF-THEN rules that were applied for this control system. They are:

(1) IF ‘Error’ is ‘Low’ THEN ‘Change of Error’ is ‘Low’.
(2) IF ‘Error’ IS ‘Medium’ THEN ‘Change of Error’ is ‘Medium’.
(3) IF ‘Error’ is ‘Big’ THEN ‘Change of Error’ is ‘Big’.

The pressure output was defuzzified into a crisp output which consuming centre of area approach for defuzzification method.

3. Results and Discussion

There are few models that were introduced with different best fit with different Final Prediction Error (FPE) value. Table 1 shows the best fit and their FPE value. Based on Akaike’s theory, the selected model is chosen that has minimum FPE (Lahiri 2001) and as well as Shibata said the Minimum Squared Error (MSE) value will give asymptotically efficient (McQuarrie & Tsai 1998).Figure 6 shows the step response of the input and output pressure variables.

Table 1: Best fit with FPE and MSE value

Model	Best fit	FPE value	MSE value
Model 1	99.40	26.10	25.83
Model 2	99.01	24.87	23.81
Model 3	98.53	2.87	2.704

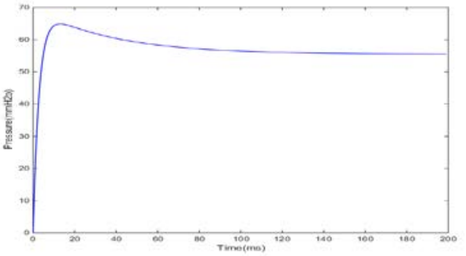


Figure 6. Step response of input output transfer function

From the results obtained, the transfer function from input to output with 98.53 was chosen since it has the smallest FPE and MSE value. The equation of the transfer function is,

$$G(s) = \frac{0.4321\mathrm{s} + 0.009419}{\mathrm{s}^2 + \ 0.3724 + 0.009335} \tag{7}$$

The experimental study on pressure of UCP plant was done in Labview and in order to evaluate the performance of controller system, analyses the transient response and steady state response were made including overshoot, undershoot, settling time and steady state error.

3.1 Simulation result of PID controller

The values of PID’s gain were done by iteration in order to obtain the best gains. Table 2 shows the readings once the effects of two gains returned constant. This is when the other gain was in increasing or decreasing mode. Generally, by applying different proportional, integral and differential gain, the step response shows different percentage improvement. However, the improvement of overshoot (OS) was contradictory after increasing or decreasing the differential proportional gains. Whilst, overshoot and rise time (RT)had also deteriorated whenthe integral gain was increased. The improvement of settling time (ST) and overshoot time were significant when proportional gain was greater than before, as well as the rise time has greatly improved when integral gain was augmented. Peak time (PT) improves to an utmost value once integral gain was increased.

Table 2: The step response output with multiple PID gain

			RT (s)	Improvement (%)	ST (s)	Improvement (%)	OS (mmH2O)	Improvement (%)	PT (s)	Improvement (%)	Peak (mm H2O)
Without PID			3.7		93.6		16.2		14.2		47.2
With											
P	I	D									
1	1	1	2.5	31.6	15.6	83.4	18.9	-13.1	6.2	55.9	47.6
3	1	1	2.1	42.7	7.7	91.8	2.6	84.8	5.9	58.7	41.0
0.5	1	1	2.5	31.9	16.2	82.7	28.9	-72.5	6.3	55.4	51.6
1	3	1	1.3	64.1	12.6	86.6	34.1	-103.5	3.9	71.9	55.6
1	0.5	1	3.9	-8.8	14.0	84.9	7.1	57.9	8.8	37.6	42.8
1	1	3	2.9	18.2	19.7	78.9	28.0	-67.3	8.1	43.1	51.2
1	1	0.5	2.3	35.1	13.8	85.2	15.7	3.3	6.32	55.0	46.8

Table 3: The step response output with PID, PI and P gain

					RT (s)	Improvement (%)	ST (s)	Improvement (%)	OS (mm H2O)	Improvement (%)	PT (s)	Improvement (%)	Peak (mm H2O)
Without PID					3.7		93.6		16.2		14.2		47.2
		P	I	D									
Gain	a	5.5	1.5	0.5	1.2	67.7	3.3	96.5	0	100	135.3	-853.8	40.0
	b	4.5	1.5	0.5	1.35	63.0	3.18	96.6	0.9	94.3	5.28	62.76	40.4
	c	5.5	3.5	0	0.8	78.8	4.72	94.97	4.8	71.4	2.9	79.8	41.9
	d	700	0	0	0.01	99.8	1.01	98.9	0.1	99.4	1.1	92.4	39.9

In addition, Table 3 is illustrating on the overall performance of the three different PID gain values. The gains were slightly tuned by augmented or reduced to get the best performance of step response signal. The overshoot and settling time gain values have improved 100% and 96.5% respectively under PID (row a) but peak time has increased tremendously. By reducing one value of proportional gain (row b), peak time shows a positive improvement with a small reduction value compared to row a. However in row c, integral gain of PI controller had increased while the performance had decreased. Although P controller with 700 gain value (row d) gave outstanding improvement, the required set point at 40mmH2O was not achieved. The peak value had returned 39.9mmH2O instead. After completing the tuning processes and analyses with different gain value, the best gains were read as 4.5, 1.5 and 0.5 for proportional, integral and differential respectively.

3.2 Simulation result of fuzzy logic controller

For fuzzy logic controller, the comparison was done between two solver methods, Adam Moulton (AM) and Backward Differential Formula (BDF). Table 4 describes the result of these two solvers. Generally, it shows that BDF has slightly improved more than AM where both had significant recovery for settling time (97.33%) and overshoot. BDF solver method has an algorithm to eliminate the overshoot (Tokić & Uglešić 2008) and this was proven when the overshoot under this solver method is zero.

The rest step response outputs signal improves faintly from without controller. Even though there are not much different between solver methods but BDF took longer time to recover the signal. Therefore, Adam Moulton solver method is more practical compare to BDF.

Table 4. The step response output for two solver method in fuzzy controller

		RT (s)	Improvement (%)	ST (s)	Improvement (%)	OS (mm H2O)	Improvement (%)	PT (s)	Improvement (%)	Peak (mm H2O)	Improvement (%)
Without Fuzzy		3.53		118.69		17.96		64.88		13.77	
Fuzzy											
Solver method	AM	1.747	50.45	3.17	97.33	0.65	96.36	55.36	14.67	3.38	75.45
	BDF	1.746	50.48	3.17	97.33	0	100	55.0	15.23	3.26	76.33

3.3 PID and Fuzzy Controller

Figure 7 and Figure 8 (a close-up of Figure10) are showing the step response of the signal without controller and fuzzy controller as well as PID controller with desired pressure value at 55mmH2O. The fuzzy controller used was Adam Moulton solver method due to less time consumption compared to BDF.

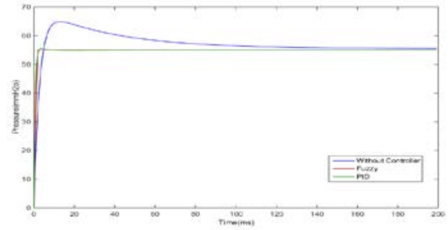


Figure 7. Step response of input and output transfer function.

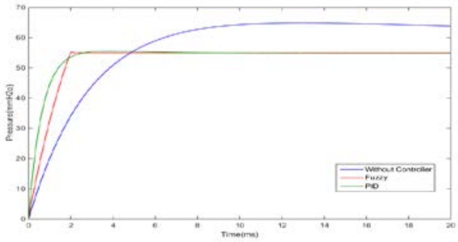


Figure 8. A close-up of Figure 10 up to 20s.

Table 5 is showing on the overall signal performance between Fuzzy and PID controllers as well as without controller. Generally, fuzzy controller contributed better improvements compared to PID except for the rise time of PID that is shorter by 0.27s. Both processes were performed without undershoot.

Table 5. Step response output between without controller, with fuzzy and PID controller

	Without controller	Fuzzy	PID	Fuzzy improvement		PID improvement	
				Diff	%	Diff	%
Rise Time	3.5254	1.5693	1.3014	1.9561	55.485	2.224	63.085
Settling Time	117.3885	1.9239	2.0829	115.46	98.361	115.30	98.225
Overshoot	17.9579	0.547	0.9099	17.410	96.953	17.048	94.933
Peak	64.8769	55.300	55.500	9.5761	14.760	9.3764	14.452
Peak Time	12.9553	2.0299	3.7581	10.925	84.331	9.1972	70.991
Steady state error	0.5613	2E-06	0.0021	0.5612	99.999	0.5592	99.625

Table 5 was also illustrating on the improvement and percentage value of both controllers after applying them to system. It has shown that the outstanding recovery with major improvement has been achieved with 90% of the completion settling time, overshoot and steady state error. The values of PID, and fuzzy had improved by 0.14% in overshoot. The steady state error shows that fuzzy controller is almost zero with 0.37% better than PID controller.

4. Conclusion

This paper is about the performance of single input single output control in experimental process of UCP plant. The control variables of pressure and height were identified by using MATLAB and LabVIEW for the PID and fuzzy controller processes. The improvement on the performance signal, real-time and online gain tuning of PID as well as the range of membership function and rules in fuzzy controller were done by iteration process. The simulation results had shown that the step responses were upgraded after applying the PID and fuzzy controller. After evaluating the performance of controller system and analyses; the transient response and steady state response including overshoot, undershoot, settling time and steady state error, it has been proven that fuzzy logic control is better than PID control.

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