Implementation PID in Coupled Two Tank Liquid Level Control using Ziegler-Nichols and Routh Locus Method

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Abstract: In this paper, we investigated liquid level controlling of coupled two tank SISO using PID controller. Zigler-Nichols (ZN) method and Routh-Locus method were compared. Three setpoint 2cm,3cm,4cm was used to show each method respond and diffrence. Output signal, error signal, and control signal of each method was analyzed. Transient parameters consist of time constant, rise time, and steady state value was demonstrated for each method. Then, those value were compared to simulation result. It results Routh-Locus method have prefer control respond.

1 INTRODUCTION

Proportional Integral Derivative (PID) is one of popular control types in industry. (Feng, 2018) used PID for controlling boom, arm, bucket of hydrolic excavator. Parameters of PID were determined by Ziegler - Nichols (ZN) method. Priyanka and Maheswari (Priyanka et al., 2018) controlled flow rate in oil pipeline transportation with PID controller. (Yadav et al., 2016) designed control system of the ball position of the magnetic levitation system (MLS) with parameter of PID. PID also was utilized to control temperature in bioreactor(Pachauri et al., 2017). Elsamahy and Shamseldin (El-Samahy and Shamseldin, 2018) was using PID for controlling speed of brushless DC motor regardless of load disturbance.

One of PID control in industry is for controlling liquid level . Liquid level control is commonly used in the water purification industry, such as the pharmaceutical, biochemical, food and beverage manufacturing industries (Başçi and Derdiyok, 2016). More than 80 % of the industry automatically used proporsional-integral-derivatif PID controllers. because PID is easier to manage, cheaper and easier to implement(Roy et al., 2017). Liquid level control is widely implemented in industries such as water level controlling in nuclear steam generator, daerator, and coupled liquid two tank system (Tan, 2011) (Liang, 2018).

Coupled two tank system is one of most plant being investigated in control study. (Roy and Roy, 2016) controlled water level of one tank to be constant as another tank level is randomly varying. (Başçi and Derdiyok, 2016) developed adaptive fuzzy algorithm to control liquid level in coupled tank. Parameter of fuzzy is identified online. They showed the result is better compared to PI controller. (Roy et al., 2017) was using fractional order PI and PD to control single input single output (SISO) coupled two tank.(Pan et al., 2005) To control a two-level and level system a backstepping controller and an adaptive backstepping controller are needed. For an exponential/asymptotic stable response using a Lyapunov machine. (Ramli, 2009) For adaptive tuning to adjust neural network weights and fine tuning controller parameters can use the particle swarm optimization (PSO) technique.They designed approach for controlling liquid levels of coupled tank Two-Input Two-Output (TITO) system by using hybrid PI-Neural Network (hybrid PI-NN) controllers. (Gouta et al., 2015) Designed a model- based step-back controller combined with high gain for two tank fluid level systems. Parameters of PID could be tuned by artificial intelligent algorithm like fuzzy, neural network, genetic algorithm, BAT algorithm, neuro fuzzy, IT2FNNC as reseachers did in (Liang, 2011) (Lian et al., 1998) (Li et al., 2008) (Katal et al., 2014). In this paper, we investigated liquid level controlling of coupled two tank SISO using PID controller. Zigler Nichols (ZN) method and routh locus method were compared.

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2 SYSTEM DESIGN

The system was a single input and single output (SISO). Beside that, there are two extra tanks were used for supporting system works. Real system is demonstrated on figure 1. Figure 2 shows the construction of coupled two tank system. The input was flow rate that was supplied from tank on the top side. Water that exit from system was collected in tank below it then directly pumped up to tank on top side.

Figure 1: System design.

Components used in this system involved two 20x19 cm3 main tanks, one 20x19 cm3 discharge tank, one 24x22 cm3 top tank as container. Figure 2 shows these component in detail. Tank 1 and tank 2 was linked by 0.5 inch pipe. This pipe has resistance R1 that handly maintained by globe valve installed on it. R1 in this case was maintained constant. The outlet of tank 2 was coupled by 90o valve that has resistance R2. Similar with R1, R2 was maintaned constant. 1 m head pump was located inside discharge tank to pump water to tank 3.

Table 1: Component and Specification.

Tag	Name	Specification
1	Tank 3	224 x22 cm^3
2	Servo (actuator)	6 Volt
3	Tank 1	20 x19 cm^3
4	Ultrasonic sensor	5 Volt
5	Microcontroller	9 Volt
6	Tank 2	20 x19 cm^3
7	Pump	18 Watt, 1m head
8	Valve 3	1/2 inch
9	Valve 2	1/2 inch

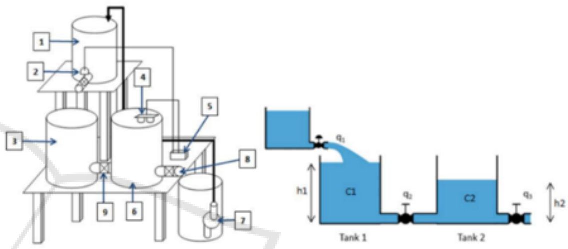

Figure 2: Construction and terminology of coupled water tank system (a) overall system (b) coupled two tank model.

Tank 2 water level h2 was sensed by ultrasonic sensor mounted on tank seal. H2 was compared with set point then error signal was appeared. Figure 3 shows a control diagram. Error signal generated control signal with PID function. Control signal actuated servo to move as error signal appearance. Flowrate was increasing proportional with servo degree.

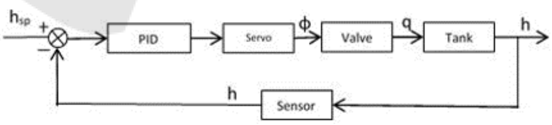

Figure 3: Control diagram.

In this system, flowrate q1 is depend on servo motor position. Figure 3 demonstrates coupled two tank system. Maximum flow rate q1 was determined by top tank level. But, top tank level was changing along with set point changing. Higher level set point, lower top tank level. In equilibrium, q1 is equal to q3. Top tank volume was decreasing, spreading in tank 1 and tank 2. Since this problem of depending flowrate to set point, relationship servo motor position in degree with h1 (cm) was non linear on all control range. To tackle this problem, control range (set point range) should be cut off to force linearity between servo motor position with h1.

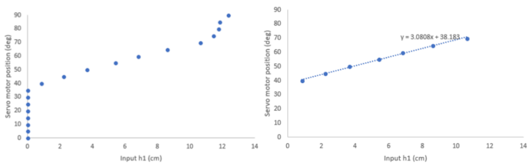

Figure 4: Servo motor position to input h1 characterization (a) original (b) after set point cutting off.

Figure 4a shows non-linearity for all output range. From 0o-35o servo motor position, system still did not give any such respond caused by too small flow rate q1. System respond started on 40o, but apparently for servo motor position more than 70o it became non-linear. Range of linerity in this system was from 40o-70o servo position or 2-10 cm. Figure 4b shows range linearity of this system. In this paper, system was analyzed in 2-4 cm set point for each method (RL and ZN). Effect of non-linearity flow rate q1 is an obstacle of each method to show their respond in control signal producing.

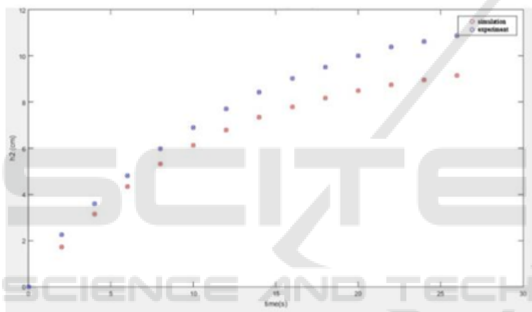

Figure 5: Validation model with step input signal.

Output from this system is level in tank 2 (h2) and the input is level tank 1 (h1). Tank 1 water level (h1) was characterized with servo 90o motor position as actuator validation. HCSR04 is ultrasonic sensor that used in output with accuracy 3-5 mm and controlled by microcontroller. Transfer function can be derived from tank equation and valve equation.

On tank 1, inlet water flow was q1 from top tank (supply tank). Outlet water flow was q2. Tank 1 has capacitance C1 and head h1. Flow rate changing (q1-q2) is proportional with rate of tank 1 volume changing that is C1h 1. Equation (1) is describing this process.

$$C_1\dot{h}_1 = q_1 - q_2 \quad (1)$$

On tank 2, inlet water flow was q2 from tank1. Outlet water flow was q3. Tank 2 has capacitance C2 and head h2. Flow rate changing (q2-q3) is proportional with rate of tank 2 volume changing that is C1h 1. Equation (2) is describing this process.

$$C_2\dot{h}_2 = q_2 - q_3 \quad (2)$$

Q2 is water flow rate caused by different head or level between tank 1 and tank 2. When water level tank 1 is higher than water level tank 2, water flows from tank 1 to tank 2 as consequence water flow rate has positive number. Water flow rate is depend on resistance of valve 1 (R1). Since in this case, resistance was dominant, inertance effect on pipe 1 was negligible. Equation 3 shows relationship between q2, h1, h2, and R1.

$$q_2 = \frac{(h_1 - h_2)}{R_1} \quad (3)$$

Similar with q2, q3 is water flow rate out from tank 2. This water flow rate is proportional to head or level tank2 and reciprocal to valve 2 resistance (R2). Inertance effect also was negligible. Equation 4 shows this process.

$$q_3 = \frac{h_2}{R_2} \quad (4)$$

In this system, resistance on valve 2 is very large compared to resistance on valve 1. Taking (1)(2)(3)(4) for R1 >> R2, function transfer h2 to h1 was determined.

$$\frac{h2}{h1}(s) = \frac{1}{[R_1C_2s + 1]} \quad (5)$$

Transfer function (5) had been validated that shows on figure 5. From validation model, time constant, settling time, and precise transfer function was generated.

Varible R1 and C2 should be analyzed to get full function transfer (5). But the way to get precise these variable needs accurately time consuming many experiments. Alternatively, value R1 and C2 could be analyzed with simple open loop experiment. These experiment also would be used for Zigler-Nichols PID parameters tuning so it will minimize time spent. From equation (5), it seen R1C1 apparently time constant of transfer function. With analyzing respond h2 to step signal h1 and getting time constant from that experiment, value R1C1 would simply get without analyze separately R1 and C1 in diffrent way of long time experiment. Figure 5 is comparison validation model with experimental data. It shows average error between model and experimen was 14%. This error was caused by dificulty of generating purely step signal of input h1 manually. Equation (6) shows the final result of open loop function transfer.

$$G = \frac{1}{10{,}59s+1} \quad (6)$$

Kp, Ti, Td with Routh locus can be obtained by deriving Gcl equation and taking $\tau_i = 2\tau, \tau_d = \frac{1}{2}\tau$ and τ value from Table 2.

$$G_{cl} = \frac{10{,}56s+1}{\left(\frac{2}{kp}+1\right)10{,}56s+1} \quad (8)$$

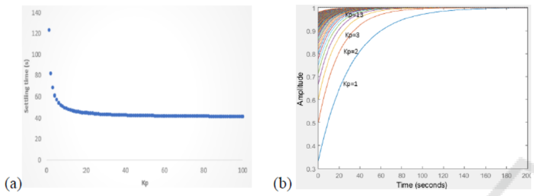

Figure 6: Kp testing graph with routh locus method (a) settling time versus Kp (b) transient respong for each Kp.

Equation (8) is PID close loop function transfer with RL method. As seen from (8), system respond depends on value of Kp. In level coupled two tank system, to reach a set point from such level is time consuming as bigger tank or smaller flowrate input. The value of Kp should be chosen to minimize time consuming. Time settling (5%) is one transient variable that could show how fast system to reach steady state condition. Value of Kp was simulated to look its effect with time settling. Figure 6a shows the result of simulation with step input. When zero Kp, system was too slow respond. As value Kp riser, time settling downed then get saturation. As seen from figure 6b, for high Kp, system respond approch to critically damped. When Kp = 13 settling time was 47.7 s and it started asymptotic. Then Kp=13 was chosen. Ti and Td was generated from it. Table 3 shows PID parameters with routh locus method.

Table 3: Component and Specification.

Parameter	Kp	Ti	Td
Value	13	21,14	5,28

With routh locus method, we could adjust PID parameters (Kp, Ki, Kd) as we desire. Time settling and others transient parameter could be chosen with analyzing PID parameters. But sometimes, analyzing PID parameters with routh locus method is complicated as higher order system. When transfer function of system cannnot be gotten , or difficult to be gotten (need long time analyses) routh locus method couldn't be implemented. Ziegler-Nichols method is easy and fast method to get PID parameters.

Table 4: PID parameter tuning with Ziegler-Nichols 1.

Type of controller	Kp	Ti	Td
P	T/L	∞	0
PI	0,9(T/L)	L/0,03	0
PID	1,2(T/L)	2L	0,5L

Ziegler-Nichols method was first introduced by J. G. Ziegler and N. B. Nichols on 1942 (Ziegler and Nichols, 1942). With these method, it does not need purely matematical approach to get PID parameters as routh locus method. By experiment, getting lag time (L) or delay and time constant (T), PID parameters could be tuned with Ziegler-Nichols rule directly (see table 4). In this system L=0.5 and T=12. Table 5 shows PID parameters with ZN method.

Table 5: PID parameters with Ziegler-Nichols method.

PID Parameter	Kp	Ti	Td
Value	10,4	60	15

Apparently Ziegler-Nichols method shown fast and simple. But it needs experiment to get PID parameters. For fast respond system, it needs varying Kp experiment make it relative time consuming. In this system, since high resistance on valve 2, minimum time to reach higher level on tank 2 was faster than to get lower level. Since this diffrence time, obvously, high overshoot was avoided. Ziegler-Nichols method and routh locus method were compared to show each respond advantages and disadvantages.

3 RESULT AND DISCUSSION

Level sensor read up and down value of ouput, not smooth graphic like simulation result. This anomaly points were caused by water ripples in tank 2. Water initially came out from top control valve. Water fell in tank 1 with such height and directly faced water surface of tank 2. This direct contant bettween water from top valve and water surface of tank 1 caused ripples. Water ripple in tank 1 affect water ripple in tank2. Water ripple in tank 2 cause anomaly reading on ultrasonic level sensor. To minimize this ripples, we implemented pipe from inlet valve to deep of tank 2. With this method, water ripples could be minimized.

Ideally, with PID parameters on table 3 and table 5, each method (RL and ZN) will create respond to exactly setpoint (0% steady state error). Routh locus method and Ziegler-Nicols method shall have small diffrence in rise time value. Routh locus will be faster to reach steady state than Ziegler-Nichols method. But in our experiment those are not exactly accurate. Figure 7 shows dinamics respond of each method with 4 cm set point. Figure 7 a shows output versus time graphic with Ziegler-Nicols. In other hand, figure 7 a shows output versus time graphic with Routh locus method. Visually, from these graphic, routh locus method has better respond than Ziegler-Nichols. It looks, Ziegler-Nichols method gives oscillation respond. This oscillation is not our desirement because it will make PID control generating control signal up and down over and over. It is energy consuming, decreasing life time of actuator (servo motor), initiating servo motor bolt joint damage. This oscillation could be looked as water ripples on tank 2. With this view, it looks clearly, Ziegler-Nichols has higher water ripples than Routh locus method. We did experiment with 3 setpoint: 2 cm, 3cm, and 4 cm and each method gave result similar water ripples level on each set point. Average water ripples of Ziegler-Nichols method and Routh locus method are 0,36 cm and 0,21 cm respectively. From water ripples view, Routh locus method has more desired method. Figure 7 c and 7 d shows error versus time graphic for setpoint 4 cm with Ziegler-Nichols method and routh locus method respectively. These graphic have strong relationship with output-time graphic on figure 7a and 7b. Error signal decreases along with output signal approach to set point. Oscillation output respond on Ziegler-Nichols method also make error signal oscillation.

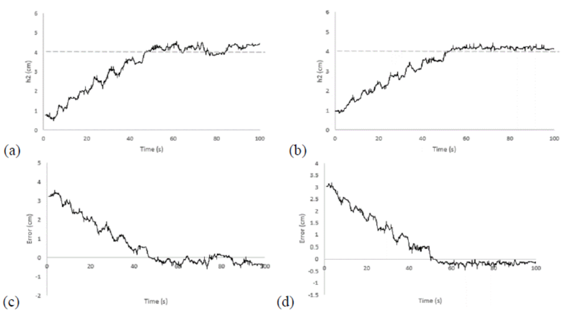

Figure 7: Output to setpoint 4 cm (a) with routh locus method (b) with zigler nichols method. Error to setpoint 4 cm (c) with routh locus method (d) with zigler nichols method.

Error signal will make PID generating control signal to operate actuator. In this case, actuator was servo motor 90o. Figure 8 shows control signal – time for set point 4 cm water level h2. As discussion earlier, Ziegler-Nichols method generates relatively high water ripples or oscillation in error signal. This oscillation have strong relationship with control signal oscillation on figure 8a. Comparing figure 8a and figure 8b, Routh locus has smoother control signal than Ziegler-Nichols. Up and down control signal on figure 8a in long time period have tendency to risk bolt joint of actuator (servo motor).

This bolt joint attach servo motor to tank 3. If servo motor move over and over in extreme oscillation, bolt joint would get high oscillation torque. It would make bolt hole falling into fatigue. In several application, bolt joint fatigue is very dangerous and avoided. Reference (Ziegler and Nichols, 1942) show bolt joint fatigue damage. In control signal point of view, Routh locus method is prefer than Ziegler-Nichols.

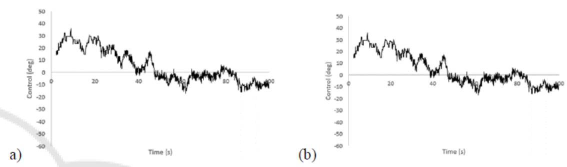

Figure 8: Control signal to setpoint 4 cm (a) with routh locus method (b) with zigler nichols method.

To compare Ziegler-Nichols method and Routh locus method, we did several experiment consist of 3 set point for each method. The result in each set point have been tabulated on table 6. Futhermore, experiment result was compared with simulation result. Rise time in simulation result should be the same in all set point that is 26,8s and 23s for Routh locus method and Ziegler-Nichols respectively. It is also valid for other transient parameters. They should be the same in all set point. But it shows value difference between experiment and simulation result. These difference was happened caused by many things of tools limited. Motion of tools platform (wood table) will cause water ripples and error sensor reading. Level sensor has limited accuracy and precission will cause output looks oscillation or changing eventhough actually it doesnt. This error appears primary because small setpoint we used for sensor spesification. Generally, from table 6, it shows Routh locus method have faster respond than Ziegler-Nichols. Also, Routh-locus method have smaller steady state error than Ziegler-Nichols. As summary, Routh- Locus have better spessification of control respond.

Table 6: System respond.

Parameter	Rise time [s]		Tou [s]		Ts 5% [s]	
	Sim.	Exp.	Sim.	Exp.	Sim.	Exp.
RL 2cm	26,8	31,1	36,5	12,2	2	2,1
ZN 2cm	23	33,1	43,1	14,5	2	2,2
RL 3cm	26,8	30,6	36,5	21,2	3	3,1
ZN 3cm	23	44	43,1	30,1	3	3,2
RL 4cm	26,8	49,4	36,5	27,9	4	4,1
ZN 4cm	23	28,7	43,1	35,1	4	4,2

4 CONCLUSION

For coupled two tank level control, tuning PID parameter with Ziegler-Nichols method is fast without long analitics formulation but respond system cannot be adjust like we want. With RL method, system respond is faster, smaller steadt state error, smaller water ripples, smoother respond. PID parameters of Routh locus method could be adjusted like we want so it made RL method powerful, more safety, more smooth, and more stable.

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