Water Level Control of a Coupled-Tank using Adaptive Fuzzy-PID Controller

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**Abstract.**  RAS technology is one of the best options for aquaculture farming because it can guarantee biosecurity by improving water quality. The RAS water circulation process requires controlling the water level, especially in the reservoir, before the clean water is returned to the fish tank. Small-scale RAS simulator modeling was carried out using a coupled-tank system approach. First, water level control is carried out using a conventional PID controller. Furthermore, a Fuzzy Logic Controller (FLC) is added by adapting the error section and error changes to produce a controlled signal that improves system response performance. The results of the study show that the controlled signal gain setting of the FLC has an impact on decreasing the settling time. In contrast, the PID's controlled signal gain setting impacts the elimination of overshoot that may appear in the system response. By adjusting the controlled signal gain of FLC and PID in AFPID, the system response performance can be obtained with no overshoot and a relatively short settling time. The study results also show that the AFPID controller can follow setpoint changes well, while the PID controller still produces a slight overshoot in its system response.

**Keywords:** small-scale RAS simulator, a coupled-tank system, PID controller, AFPID controller

# INTRODUCTION

Recirculating water in the RAS (Recirculating Aquaculture System) makes it possible to control the conditions of the aquaculture farm and collect waste. By controlling aquaculture conditions, aquaculture production in RAS facilities can be established almost anywhere [1, 2]. The basic principle of the recirculation system concerns water treatment technology, which continuously removes waste products and regenerates optimal water quality for fish. Water from the fish tank flows into a mechanical filter to filter out coarse solids. The process of nitrification and denitrification takes place in a biological filter with sufficient aeration. Clean water is returned to the fish tank [3].

RAS technology tends to be like a water treatment system where the recirculation process aims to control the quality of RAS water so that it remains at a predetermined quality standard [3, 4]. RAS can be considered a tank system that requires a water level control system. Controlling the water level of a tank system can be viewed from various aspects, from modeling the tank system (based on empirical models or experimental models) [5-10] to the control methods used (conventional and modern based) [11-17].

The model and number of tanks in a tank system depend on the needs of the industrial process. Tank system modeling is generally based on a single tank system [18, 19]. The complexity and non-linearity of the tank system tend to increase with the number and configuration of tanks used. Challenges in terms of level control are also increasing [8, 9, 11, 12, 20, 21].

This study applies the tank system concept to model a small-scale RAS with a tank configuration following the commonly used RAS water recirculation process sequence. A coupled-tank system approach is used according to the needs of the process. The control level applies a conventional PID controller as an initial control approach. Furthermore, the level control performance is improved by implementing an adaptive fuzzy-PID controller.

# METHODS

## THE COUPLED-TANK SYSTEM

The small-scale RAS built in this applied research is shown in **FIGURE 1**. The schematic model is presented in a 5-coupled tank model, as shown in **FIGURE 2**. Because and the resistance is only in the mechanic filter , then it can be assumed that and . In this case, the 5-coupled tank can be approximated with the Coupled Tank system, as shown in **FIGURE 3**.

If there is no addition of water from outside, then the balance of water volume is expressed by:

(1)

If the length of each tank, , the water level in tank 1, then . From Eq. (1) we get and . It means slightly above the mechanical filter material position.

An approximation model is used to simplify the analysis, as shown in **FIGURE 4**. Water from Tank 2 is flowed into Tank 1 by a pump through a circulation pipe with a cross section of , analogous to the flow of water to a dummy tank through the. Next, the water in the dummy tank is channeled to Tank 1 by a pump.



**FIGURE 1.** Small-scale RAS



**FIGURE 2.** Small-scale RAS in a 5-coupled tank schematic model



**FIGURE 3.** Small-scale RAS in a coupled tank schematic model



**FIGURE 4.** Small scale RAS in a coupled tank approach model

From **FIGURE 4** it can be seen that the circulation pipeline applies:

|  |  |
| --- | --- |
|  | (2) |

is the valve position constant , controlled using an actuator. is the specification of the pump flow rate used.

The flow of water from tank 1 to tank 2 creates energy, where the total energy in tank 1 equals the total energy in tank 2. It can be expressed by Bernoulli's law as follows.

|  |  |
| --- | --- |
|  | (3) |

Because Tank 1 and Tank 2 are open, the prevailing pressure is atmospheric pressure, so. is the velocity of the water flow from the circulation pipe with the valve cross-sectional area . Because it can be assumed . In Tank 2, water flows through the bottom so that it can be assumed . The Eq. (3) becomes:

|  |  |
| --- | --- |
|  | (4) |

The rate of water flowing into Tank 2 through the section can be expressed by:

|  |  |
| --- | --- |
|  | (5) |

where: and .

Resistance due to the presence of the material's mechanical filter can be defined as the difference in water level between Tank 1 and Tank 2 with respect to the flow rate into Tank 2, so that:

|  |  |
| --- | --- |
|  | (6) |

From Eq. (5) and (6), it can be obtained:

|  |  |
| --- | --- |
|  | (7) |

is in steady state.

The mass balance in Tank 1 can be expressed by:

|  |  |
| --- | --- |
|  | (8) |

In Tank 2, the total energy in Tank 2 is equal to the total energy around the pump. Since , it can be assumed . Around the pump, it can be considered , so Bernoulli's law applies as follows.

|  |  |
| --- | --- |
|  | (9) |

The flow rate at the pump outlet is analogous to the flow rate to the dummy tank, expressed by:

|  |  |
| --- | --- |
|  | (10) |

where:.

The mass balance in Tank 2 can be expressed by:

|  |  |
| --- | --- |
|  | (11) |

If , then the second-order's Taylor series is obtained:

|  |  |
| --- | --- |
|  | (12) |

Substitution Eq. (12) to (8) and (11) are obtained:

|  |  |
| --- | --- |
|  | (13) |

In steady state, and so Eq. (13) becomes:

|  |  |
| --- | --- |
|  | (14) |

Substraction Eq. (14) and (13) are obtained:

|  |  |
| --- | --- |
|  | (15) |

where:

|  |  |
| --- | --- |
|  | (16) |

Laplace transform Eq. (15) obtained:

|  |  |
| --- | --- |
|  | (17) |

where and (unit step), is in steady state.

## SYSTEM DYNAMIC MODEL EXPERIMENT

The specifications for the small-scale RAS simulator are shown in **TABLE 1**. If desired in steady state conditions, the water level in Tank 2, then from Eq. (1) we get and . From Eq. (7) the mechanical filter material resistance, .

**TABLE 1.** Small-scale RAS simulator specifications

|  |  |  |  |
| --- | --- | --- | --- |
| Description | Notation | Value | Unit |
| Cross sectional area of interaction pipe between Tank 1 and Tank 2 |  | 5.06 |  |
| Cross sectional area of outlet pipe in Tank 2 |  | 1.27 |  |
| Cross sectional area of Tank 1 |  | 8400 |  |
| Cross sectional area of Tank 2 |  | 5600 |  |
| Flow rate of pump |  | 694 |  |

From Eq. (2) and (10) are obtained and . Furthermore, from Eq. (16) and (17) obtained the transfer function of the water level in Tank 2 as follows.

|  |  |
| --- | --- |
|  | (18) |

The transfer function of closed loop system is expressed by:

|  |  |
| --- | --- |
|  | (19) |

The closed loop characteristic equation is then obtained:

|  |  |
| --- | --- |
|  | (20) |

From Eq. (20), we get and . Since then the system is classified as un-damp. The system response characteristics are as follows.

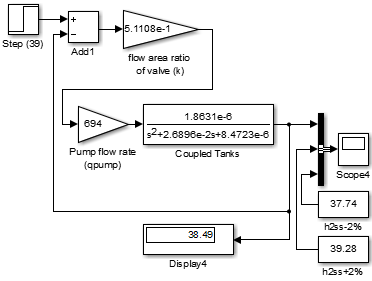
Maximum overshoot, reached at:

peak time,

settling time,

error steady state, .

The closed-loop system simulation model using Simulink is shown in **FIGURE 5**. With the input signal, the system output response is as shown in **FIGURE 6**.



**FIGURE 5.** Simulink model for closed loop system ()



**FIGURE 6.** Output respons of closed loop system ()

# RESULTS AND DISCUSSION

## CONTROLLER DESIGN

### PID Controller

The PID controller is the most widely used control mechanism, especially in industry, due to its simplicity of function and ease of use. PID works with a closed-loop system mechanism and aims to minimize errors (differences in value between the setpoint and the system response). In principle, there are 4 (four) parameters of system response characteristics, namely rise time , overshoot , settling time , and steady-state error . The effect of each part (P, I, and D) on the system response characteristics is shown in **TABLE 2**.

**TABLE 2.** Effect of P, I, and D in response system characteristic

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Term | Rise time | Overshoot | Settling time | Error steady state |
| P | decrease | increase | small change | decrease |
| I | decrease | Increase | Increase | Eliminate |
| D | small change | decrease | decrease | small change |

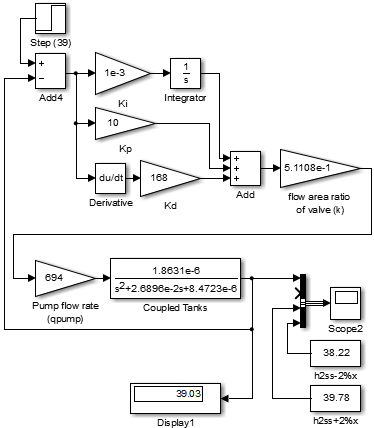
The PID-controlled signal equation and its transfer function are expressed by [22]:

|  |  |
| --- | --- |
|  | (21) |

From Eq. (18), if defined then the transfer function of closed loop system with a PID controller is expressed as:

|  |  |
| --- | --- |
|  | (22) |

Using Matlab's PID tuner, we get , , and . The Simulink closed loop system model with PID is shown in **FIGURE 7** with the system response output shown in **FIGURE 8**. The system response characteristics are as follows: no overshoot, settling time, and .



**FIGURE 7.** Simulink model for closed loop system with PID ()



**FIGURE 8**. Output respons of closed loop system with PID ()

### Adaptive Fuzzy-PID Controller

A fuzzy Logic Controller (FLC) is one of the applications of Fuzzy Logic in control systems. One of the advantages of FLC is that there is no need for a mathematical model of the plant to be controlled. The decision-making mechanism is embedded in the FLC as a basic rule when control occurs. FLC consists of four parts: fuzzification mechanism, knowledge base, inference engine, and defuzzification mechanism, as shown in **FIGURE 9**.



**FIGURE 9.** FLC configuration

The fuzzification mechanism transforms crisp input data into fuzzy values ​​in the interval {0…1} through fuzzy sets constructed with a certain of membership functions. The inference engine applies fuzzy operators from each rule-based to generate a single truth value. This value is then converted into a fuzzy output set for each rule based on the implication operator. All fuzzy outputs are then aggregated into a set of fuzzy outputs. The defuzzification mechanism transforms a set of fuzzy outputs into a single crisp output using a specific method (usually the Centroid method) [23, 24].

A system's nonlinearity impacts the variation of gain in the proportional and derivative parts of the PID controller. It impacts the variation of error-tracking actions so that the performance of the PID controller becomes less sensitive. FLC is used to optimize the performance of the error-tracking action of the PID controller. The Adaptive Fuzzy-PID Controller (AFPIDC), as shown in **FIGURE 10**, is a combination of PID and FLC controller in which the error signal and the change in error are used as FLC inputs. The AFPIDC-controlled signal equation becomes:

|  |  |
| --- | --- |
|  | (23) |

and are the controlled signal gain of PID and FLC, respectively. Further improvement of system response performance can be done by setting these two gains.

The FLC input (error signal and error change) is normalized using the reference signal value to ensure that the fuzzy input value remains within the range of the FLC values that have been created. Denormalization needs to be done in the FLC output to return it to its actual value.

FLC was built using the Fuzzy Inference System (FIS) Matlab with the following design characteristics.

FIS : Mamdani

Fuzzy operator (AND/OR) : min-max

Implication method (AND) : min

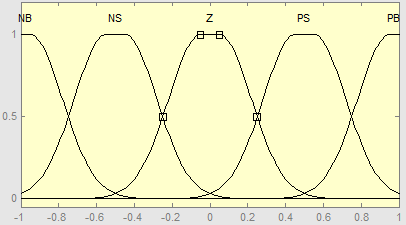
Agregation method : max

Defuzzification method : centroid

The fuzzy set for each input (error and error change) and FLC output (controlled signal) is constructed using 5 (five) linguistic values: NB, NS, Z, PS, and PB (N=negative, P=positive, B=big, S=small, Z=zero). The membership function used is a Gaussian combination to anticipate system nonlinearity. The fuzzy set is shown in **FIGURE 11**. The fuzzy inference engine uses a rule-based as shown in **TABLE 3**. The fuzzy structure based on a rule matrix is shown in **FIGURE 12**.



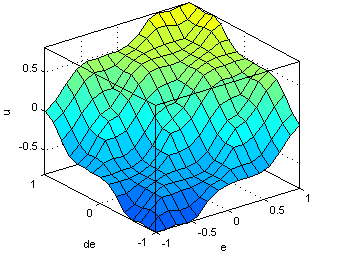
**FIGURE 10**. Adaptive Fuzzy-PID Controller



**FIGURE 11**. Fuzzy set using Gaussian combination membership function

**TABLE 3.** Fuzzy rule based matrix

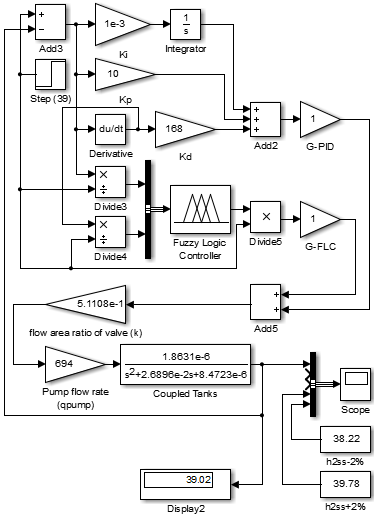
|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| e/de | NB | NS | Z | PS | PB |
| NB | NB | NB | NS | NS | Z |
| NS | NB | NS | NS | Z | PS |
| Z | NS | NS | Z | PS | PS |
| PS | NS | Z | PS | PS | PB |
| PB | Z | PS | PS | PB | PB |



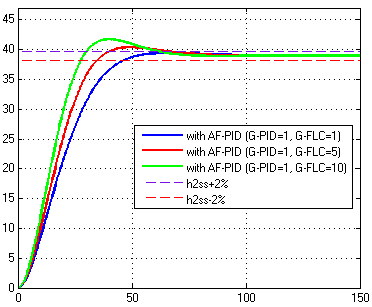
**FIGURE 12.** Fuzzy surface

After the fuzzification process, the fuzzy values of error and error changes are used to execute the FIS-Mamdani learning base through If-Then rules to produce the expected control behavior. After the defuzzification process, the crisp value of the FLC-controlled signal is added to the PID-controlled signal.

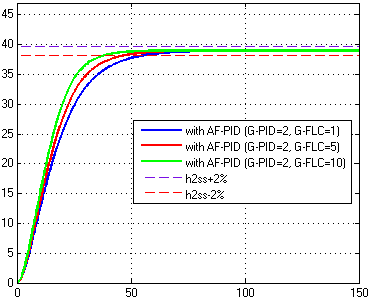
The Simulink closed-loop system model with AFPIDC is shown in **FIGURE 13**. The simulation results show that an increase in impacts a decrease in settling time. However, it also creates an overshoot, as illustrated in **FIGURE 14**. On the other hand, increasing can eliminate overshoot, as illustrated in **FIGURE 15**. Therefore, the gain controller combination selected is , .



**FIGURE 13**. Simulink model for closed loop system with AFPIDC



**FIGURE 14.** Effect of on system response



**FIGURE 15**. Effect of on system response

From **FIGURE 16**, it can be seen that the system response characteristics for all controllers are no overshoot and . The difference is only in the settling time, , for AFPIDC with and reached . Meanwhile, for AFPIDC with and reached .

The error tracking performance for each controller is also tested using a signal builder representing the change in set point. It is illustrated in **FIGURE 17**. Both the PID and AFPID controllers are capable of following set point changes. The significant difference is that the response of the PID system is slightly overshoot, while the AFPID is not.



**FIGURE 16.** The output response of closed loop system with AFPIDC .vs. PID .vs. without controller



**FIGURE 17**. The performance tracking error of PID and AFPID controllers

# CONCLUSIONS

Mathematical modeling of the small-scale RAS simulator has been carried out using a coupled-tank system approach. The first time, controlling the water level in tank 2 is done using a conventional PID controller. Adding FLC to the PID controller is proven to adapt the error portion and error changes to produce a controlled signal that improves system response performance. The study's results also show that the controlled signal gain of FLC has an impact on decreasing the settling time, while the controlled signal gain of PID has an impact on eliminating overshoots that may occur. The following study showed that the AFPID controller could follow the set point changes well, while the PID controller produced a slight overshoot in the system response.

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