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Adaptive Fuzzy-PID Controller for Liquid Flow Control in the Heating Tank System

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Abstract: Liquid flow control systems are often used in some industrial processes. One of the problems is the existence of disturbance that can cause the flow response to become unstable. Thus, it is necessary to re-tuning the controller when the disturbance occurs. This study aims to design and implement an Adaptive Fuzzy-PID (AF-PID) controller for the liquid flow control in the heating tank system. We develop an industrial plant prototype of a heating tank process to test the designed controller on a laboratory scale. AF-PID controller is used to controlling the flow rate when the disturbance occurs. This controller was chosen because it has the ability to adapt PID parameters when a disturbance occurs based on fuzzy logic. The nominal PID controller constants will adjust by additional PID parameters when there is a disturbance based on the Mamdani type fuzzy logic rule. The hardware experimental result shows that the designed controller can maintain the stability of the liquid flow when given 50% and 100% pipe leakages with maximum undershot by 3.33% and 24% respectively.

Keywords: Flow control, AF-PID, Mamdani, heating tank system

1. Introduction

Liquid flow control is commonly used in industrial processes such as in the heating tank system [1]. The flow of liquid must be kept at the set point to guarantee the best production results. Thus, there is needed a control system in the liquid flow that able to consider the disturbance when the system process occurs. Various controllers have been developed to maintain liquid flow in the tank system, such as conventional PID control [2]-[4] and intelligence Fuzzy Logic Control (FLC) [5]-[8]. Based on performance comparison that has been studied by [9] and [10], FLC produces a best control performance than the PID controller.

The development of these controllers also conducted by other researchers by combining FLC with the PID controller. The nominal constants of the PID controller will adapt through additional PID parameters generated by fuzzy logic when a disturbance occurs. This configuration is called Adaptive Fuzzy-PID (AF-PID) controller. The application of this controller produces a better response when compared to FLC in the flow control system [11]-[15]. Thus, the AF-PID controller has better robustness characteristics when compared to PID or FLC itself.

Besides having robust characteristics, AF-PID controllers are easier to implement into programming languages. Several studies on liquid flow control have been carried out using more intelligence control approaches such as Genetic Algorithm Adaptive Neural Network (GA-ANN) [16] and ANN-based Flower Pollination Algorithm (FPA) [17]. However, this approach is usually limited to testing in the form of modeling and simulation. Implementing it into the system will be more difficult because it requires a more complex programming language. To facilitate testing of the designed controllers in the real hardware, an industrial process control prototype can be developed. As has been done by [18]-[20] where a process control application module is developed on a laboratory scale.

This study aims to design and implement an AF-PID controller for a liquid flow control system based on a heating tank process module. We develop a process control module on a laboratory scale to test the reliability of the designed controllers. AF-PID controller is used because of its robustness characteristics which can overcome any disturbances.

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This research uses an Arduino Mega 2560 microcontroller in which the AF-PID controller will be embedded. Arduino is very compatible to use because it has friendly characteristics for rapid prototyping [21]-[23]. This study is a continuation of previous studies [24]-[25]. The main contribution to this paper lies in the implementation of the AF-PID controller which has been designed in the form of hardware on a laboratory scale module to determine its robustness when several disturbance scenarios occur.

2. Research Method

2.1 Liquid Flow Simple Model

The ideal mathematical model of fluid flow is quite complex to derive as it is necessary to take into account various variables such as fluid type, pressure, and installation. In this study, a simple model approach was used based on the actuator movement. In the Laplace form, liquid flow or called debit can be defined as a change in the liquid position according to the time as in the following equation [25].

$$Q(s) = sX(s) \tag{1}$$

with $Q(s)$ is liquid flow, $x(s)$ is the liquid position, and d/dt is the time change. The simple liquid flow model can be constructed by combining the liquid flow equation with the transfer function of the servo motor as follows.

$$\frac{\theta(s)}{V(s)} = \frac{K}{s(Js+b)} \tag{2}$$

with θ is angle position, V is the input voltage, K is motor constant, J is the moment of inertia, and b is friction constant. By assumming that $X(s)$ equals to $\theta(s)$ and pressure from the pump is constant, the transfer function between the servo input voltage and the flow rate is obtained as follows.

$$\frac{Q(s)}{V(s)} = \frac{K}{s^2(Js+b)} \tag{3}$$

This simple model shows the relationship between the fluid flow and the voltage applied to the servo motor. In this case, the voltage can be considered to be linear with the PWM going to the servo motor. The larger the PWM value, the greater the resulting liquid flow.

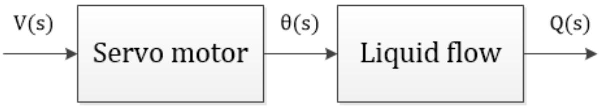


Fig. 1 - Simple model of liquid flow plant

2.2 Heating Tank System Design

The design of this process control module can be seen in Fig. 2.

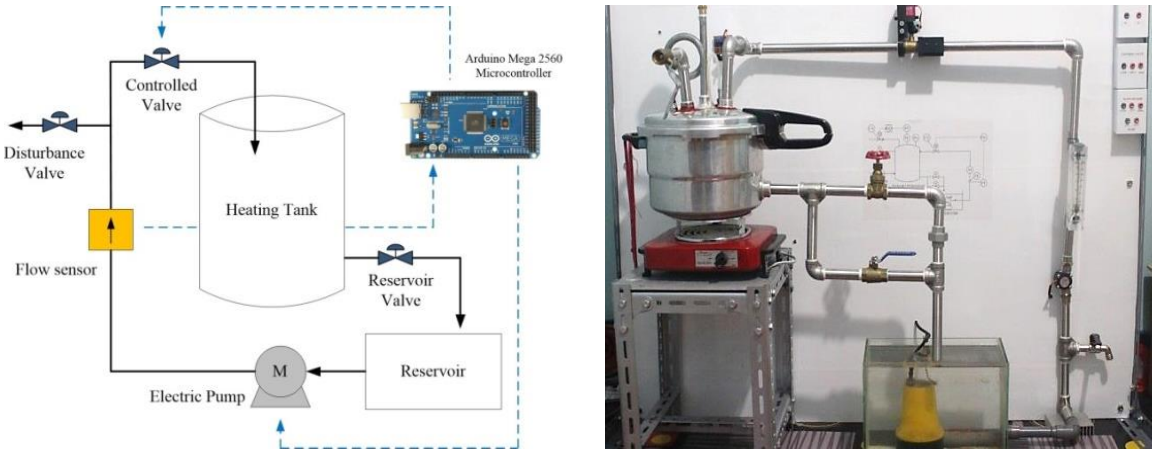


Fig. 2 - Design of process control module (left) and its hardware implementation (right)

This module was built at a cost of around 7.4 million IDR, including the simulator module, control module, and interface module. The module will control the flow of liquid so that it remains at the desired value. The flow rate of the liquid is detected by a flow sensor. The measurement data from the sensor is then sent to the microcontroller as feedback. If there is an error value, the microcontroller will calculate the control signal which is then used to adjust the valve control. This process also occurs when the flow rate is disturbed through the disturbance valve with several scenarios.

2.3 AF-PID Controller Design

AF-PID controller is one of the configurations in a hybrid control system. This controller allows the PID parameters to re-tune if there any change in the error value due to the disturbance variable. The PID parameters will adapt automatically based on the fuzzy logic rule base. The structure of the AF-PID controller is shown in Fig. 3.

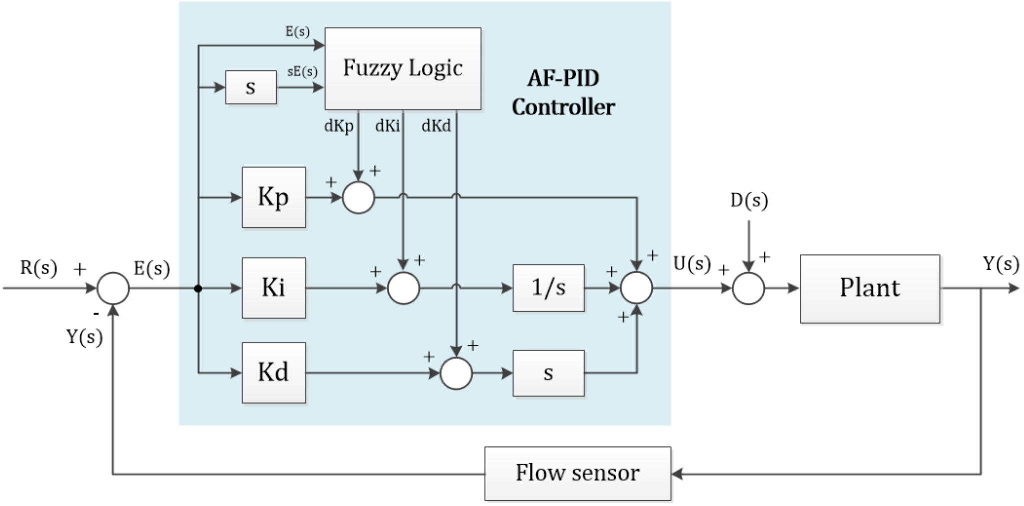


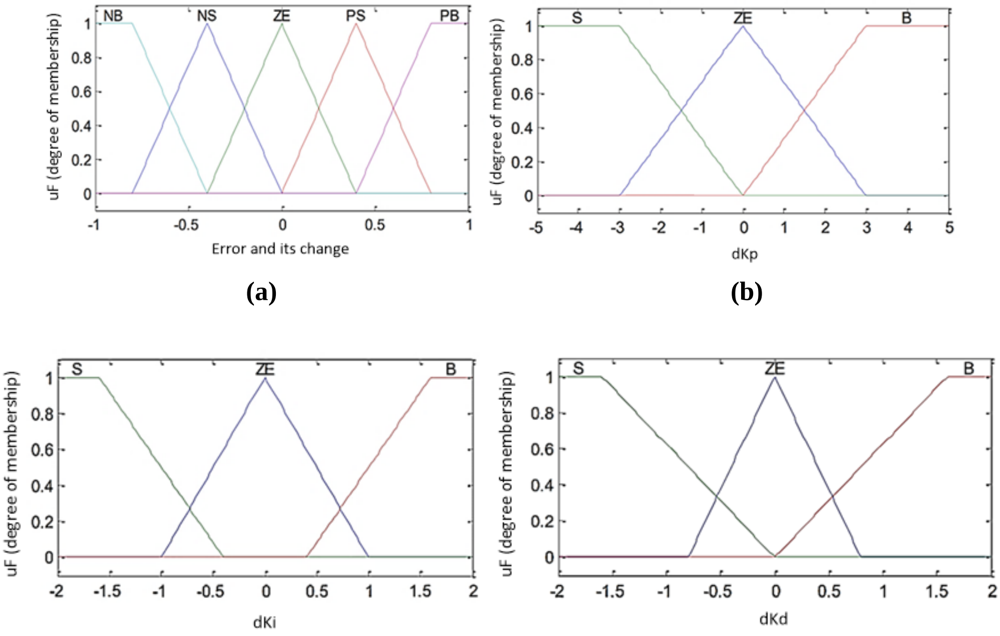
Fig. 3 AF-PID controller design

Referring to the fuzzy logic closed-loop control, there are two inputs (error and its change) to calculate the control signal based on the fuzzy rule base. The outputs generated by fuzzy logic are additional PID controller parameters, which are called dKp, dKi, and dKd respectively. These additional PID parameters are the value that interferes with the nominal PID parameter when a disturbance occurs in the plant. The additional parameters will adjust the nominal PID parameters which are obtained previously. This scheme can then make this controller robust against disturbance because the PID controller constant is capable of self-tuning automatically when there is a disturbance. Regarding the PID controller equation, the following shows the AF-PID control signal equation.

$$u(t) = [Kp + dKp]e(t) + [Ki + dKi]\int_0^t e(t)\,dt + [Kd + dKd]\frac{d}{dt}e(t) \tag{4}$$

The membership functions of these inputs fuzzy sets are shown in Fig. 4. The linguistic variables of error and its changes are determined similarly as negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB) with the values from -1 to 1. The fuzzy set of dKp is presented as small (S), zero (ZE), and big (B) with the range of values -5 to 5. The fuzzy set of dKi and dKd is also obtained as small (S), zero (ZE), and big (B) with the range of values -2 to 2 each other. The triangular membership function is made for convenience in terms of microcontroller implementation, while the value range is set arbitrarily. The largest range may impact the robustness of the controller if there is a large signal of disturbance. In contrast, the smallest range of additional PID constant only affects a small disturbance signal.

Table 1 shows the fuzzy rule base obtained from several references with some modifications to its values. When the error and the change are positive, there will be an increase in the values of Kp and Ki so that the response will return to the setpoint. When the error and the change are negative, there will be an increase in the values of Ki and Kd so that the overshoot will be dampened. This mechanism refers to the PID constant working principle where Kp produces the fastest response, Ki maintaining error, and Kd reduces overshoot.



(a) (b)

(c) (d)

Fig. 4 - Membership function of input-output: (a) error and its change; (b) dKp, (c) dKi; (d) dKd

Table 1 - Fuzzy rule base

dKp **dKi** **dKd**		**dError**				
		NB	**NS**	**ZE**	**PS**	**PB**
Error	**NB**	S B B	B S ZE	B S ZE	B S ZE	B ZE B
	NS	S B ZE	B S ZE	B S ZE	B ZE B	B S B
	ZE	S S ZE	B B ZE	ZE ZE ZE	B B ZE	B S ZE
	PS	S S B	B ZE ZE	ZE S ZE	B S B	B B ZE
	PB	S ZE B	B S ZE	ZE S B	B S ZE	B B ZE

3. Result and Discussion

In this section, we will discuss about testing without controller (open loop) and testing with controller. Control performance testing is carried out in two ways, namely testing without disturbance and testing with disturbance. These two testing mechanisms are used to compare the flow response when there is no disturbance and when there is a disturbance.

3.1 Open Loop System Testing

The open loop response of the plant needs to be known to see the working area of the fluid flow to be controlled. The test is carried out by giving the maximum PWM value to the servo motor when the flow pressure is constant with the scheme as shown in Fig. 1. In this condition the valve is fully opened (100%). Then, the sensor detects the resulting flow and sends it to the microcontroller for the data acquisition process. The resulting flow response can be seen in Fig. 5. Based on the test results obtained with a maximum water pump voltage of 12 V, the maximum steady state flow is about 9 L/min with a peak value when overshoot is close to 12 L/min. The initial response shows a fairly fast transient condition with a settling time of about 0.45 s. Thus, for testing with controllers, the largest control working area is 9 L/min even though this condition can cause saturation of the actuator.

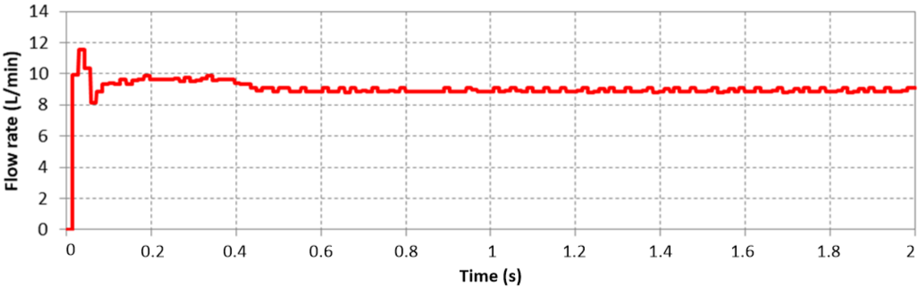


Fig. 5 - Open loop system testing

3.2 System Testing without Disturbance

The testing without disturbance was conducted to determine the flow response when the controller was implemented. Testing is done by providing a flow set point by 6 L/min and then change to be 7 L/min and then 5 L/min. The set point value does not exceed the maximum flow limit of 12 L/min according to the results of the open loop response test previously mentioned. The results of this test can be seen in Fig. 6.

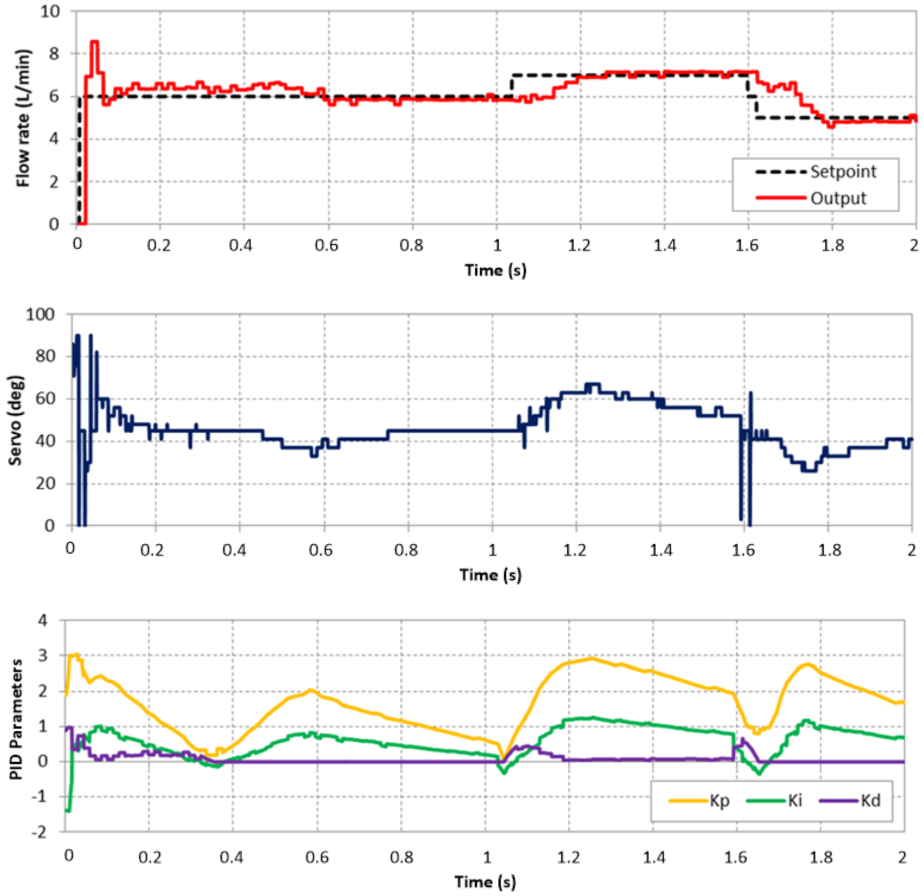


Fig. 6 - Response without disturbance: flow (top), servo (middle), and PID constant changes (bottom)

Based on the test results, it can be seen that the flow response can track the set point values. The valve opening also produces the angle according to the set point values. When a larger flow is required, the resulting angle produces a larger opening. This condition is shown at the 1 s where the set point value increases to 7 L/min. The valve opening has increased from 42° to a maximum of 65° in the 1.2 s. Conversely, the valve opening decreases to a minimum angle of 30° at 1.75

s when the set point value drops to 5 L/min. The resulting PID constant changes according to the rule basis of the designed fuzzy logic rules. The maximum PID constant value produced Kp by 3, Ki by 1.2, and Kd by 0.9.

3.3 System Testing with Disturbance

The second test is performed to determine the robustness of the flow response when given several disturbance conditions. The test is done by giving a set point value and then leak the flow pipe through the disturbance valve when the flow response has reached a steady-state condition. We obtain two scenarios valve opening by 50% and 100%. The test results with the valve openings of 50% can be seen in Fig. 7.

The test results with a 50% disturbance show that the flow response has decreased by 3.33% when given a disturbance at 1.07 s. At this time, the disturbance valve is opened manually by 45° to test the stability of the flow. Even though the system is disturbed, the flow response can return to the set point in 0.43 s. The valve opening and the PID constant are also able to respond to a given disturbance and can return the flow response to the set point value. When disturbed, the valve opening increases from about 40° at 1.07 s until 50° at 1.5 s to keep flow at the set point. The PID constant decreases when there is a disturbance, but can go back up so that it can return the flow response to the set point value.

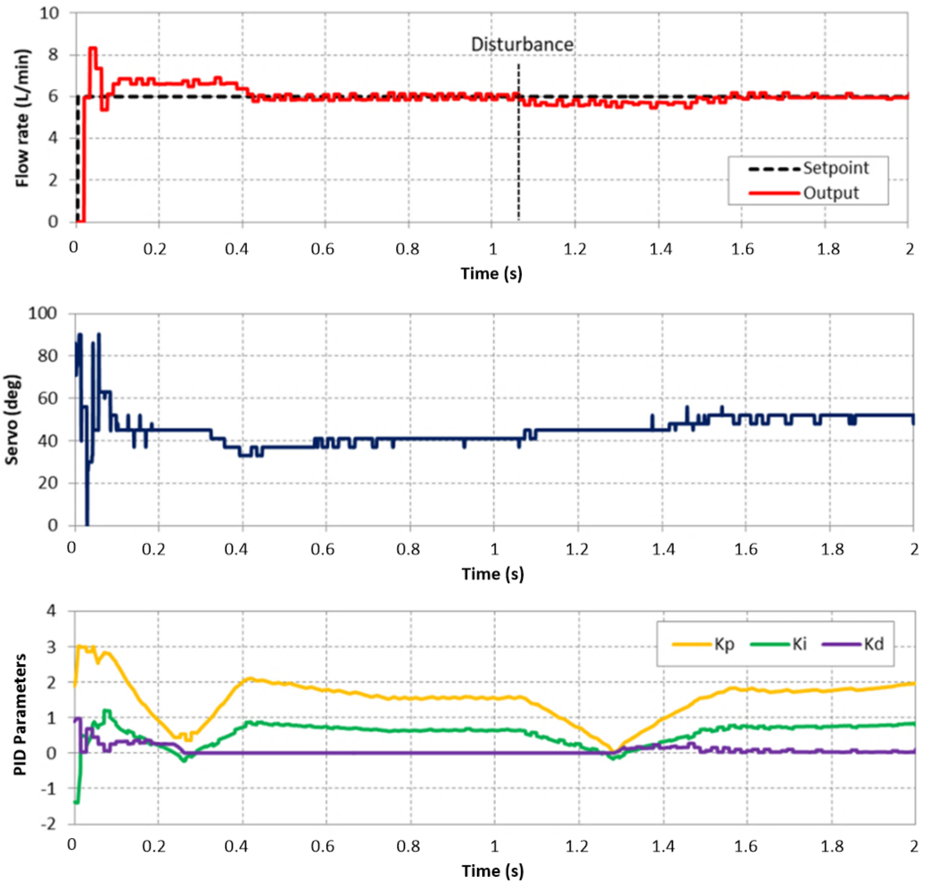


Fig. 7 - Response with disturbance valve opening 50%: flow (top), servo (middle), and PID constant changes (bottom)

To see the stability of the flow when given a greater leakage disturbance, a test is carried out with a maximum of 100% disturbance valve opening scenario. In this test, the fault valve is opened 90° to provide maximum leakage. The test results with disturbance by valve opening 100% can be seen in Fig. 8.

Based on the test results, it can be seen that the flow response has decreased when given a disturbance at 0.95 s with the resulting undershot value of 24%. However, the flow was able to return to set point t within 0.25 s. The control valve opening also increased when given a 100% disturbance from the previous 38° at 0.95 s to 60°at 1.2 s. Changes also occur in the three PID parameters when disturbed. These three PID parameters can adapt and readjust themselves when given a disturbance. This ability causes the flow response to having robust characteristics.

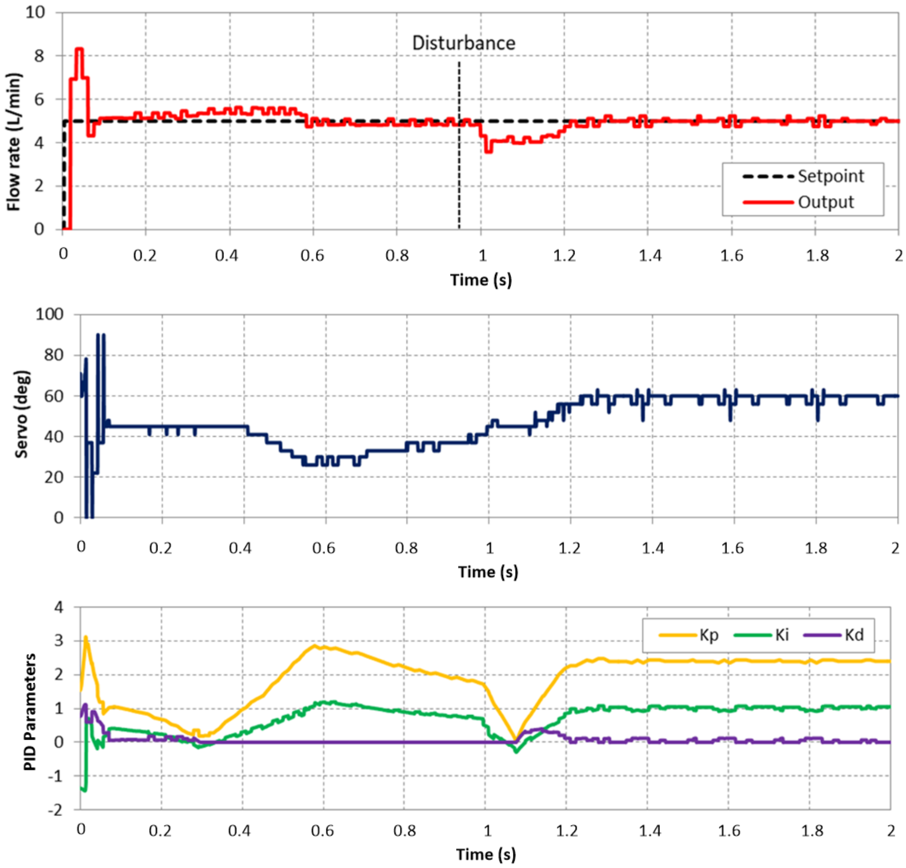


Fig. 8 - Response with disturbance valve opening 100%: flow (top), servo (middle), and PID constant changes (bottom)

4. Conclusion

The liquid flow control system based on the AF-PID controller has been successfully designed and tested with several disturbance scenarios. Based on the test results, it can be concluded that the AF-PID controller can maintain flow stability when given two leakage disturbance scenarios. A test with a 50% disturbance produced a maximum undershot of 3.33%, while a test with a 100% disturbance resulted in a maximum undershot of 24%. Further research is to develop a control method based hardware experimental which involves the actuator saturation parameter.

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