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# Improving End-Point Position Control in Hydraulic Testing Machines with a Fuzzy Logic Based Approach

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***Research Article***

**Abstract −** During the repetitive operation of hydraulic testing machines, some undesirable vibration movements and non-compliance with the set value may occur at the piston end-point, which is the output of the system. PID (Proportional-Integral-Derivative) control is widely used in such systems in practical applications. However, the use of a standard (fixed coefficient) PID control alone cannot completely eliminate problems such as endpoint vibration and/or non-compliance of the endpoint position with the set value, caused by dynamic parameter changes in the hydraulic system. In the current state of the applications, when such a situation is encountered, the controller coefficients need to be readjusted by a human operator. In this study, to avoid this need and automatically adjust PID controller coefficients, a fuzzy logic-based computation approach has been developed and applied to the existing control system. A hydraulic system was designed and realized to test the developed method. The end-point position control of the system was established and improved utilizing the developed approach. With this development, an improvement of more than 10% was achieved in the adjustment of the hydraulic testing machine end-point oscillation amplitude to the set value. The use of this method also eliminates the need for human operators to readjust the controller parameters in case of long-term operation of hydraulic test systems.

***Keywords −*** *Fuzzy logic, hydraulic test systems, industrial control, PID control, repetitive tasks*

## 1. Introduction

Hydraulic systems are frequently used in many industrial applications because they allow precise positioning even in applications requiring high force, it is easy to produce linear or angular movements, they allow sudden movements in the opposite direction, they occupy less space than mechanical or pneumatic systems, and they work less noisy. The use of electronic applications together with hydraulic systems in control systems supports the continuation of this preference (Demirel, 2016). In addition, power in hydraulic systems can be transmitted to all directions much more easily than mechanical systems, thanks to hydraulic lines (Çınar, 2013).

In a hydraulic system, it can be used sometimes for lifting heavy loads, sometimes for pressing certain loads, and sometimes for performing repetitive sensitive tasks, depending on the form/technique of force applied by the pressure applied to the fluid. Overloads in hydraulic systems can be easily controlled by safety valves. Hydraulic circuits are used in almost all automatic machines, especially those requiring high power density. As typical application areas; machine tools, presses, injection machines, test equipment, industrial robots, automotive industry, lifting and conveying machines (forklifts, etc.), construction machines (concrete pumps, graders, mobile cranes, excavators, etc.), agricultural machinery, dams, turbines, nuclear power plants, ship

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unloading and loading units, ship control systems can be cited as a wide variety of examples (Çınar, Ulaş & Bilgin, 2013; Üçüncü, 2020).

Hydraulic systems are typical nonlinear systems that combine mechanical and hydraulic structures (dynamics) within itself and have parametric uncertainties. Classical control techniques have linear properties, they are insufficient to overcome the non-linearity of hydraulic systems (Wang, Quan, Jiao, & Zhang, 2017). Thus, to improve the performance, researchers have investigated different control methods for hydraulic systems.

PID control is widely used in the control of hydraulic systems, as in many applications in the industry. There are studies in which methods such as fuzzy logic together with PID control are used to control non-linear units such as hydraulic systems more effectively (Jian, Sheng & Shu, 2009). With the use of fuzzy logic, it is possible to easily include non-linear effects such as compressibility, friction and leakage that occur in components such as servo valves, cylinders, and pumps in the hydraulic system. Thus, it is aimed to provide a precise position control in the system (Jones, Dopson & Roskilly, 2000). In addition, studies in the literature show that the use of fuzzy logic based PID controller for position control (both with and without external disturbance input) in non-linear systems is more successful than standard PID controller in reference tracking (Özdemir, Öztürk, Şengül & Kuncan, 2022). Wang et al. developed a method for estimating and compensating for mechanical dynamics uncertainties that cause mismatch problems in hydraulic systems. In this method, a state observer-based nonlinear adaptive control scheme is used to effectively predict and compensate for both hydraulic dynamic uncertainties and mechanical dynamic uncertainties (Wang et al., 2017). In the study of Yılmaz (2012), modelling of a hydraulic system was carried out using artificial neural networks. PID controller is used for the control of the system. To find the optimal values of the PID controller parameters, an optimization was carried out using genetic algorithm and particle swarm optimization. In a similar study; The modelling of the hydraulic system was carried out by artificial neural networks, and the control of the system was provided by using an integral sliding mode algorithm with fuzzy logic support. The basic concept of their methods is the use of fuzzy logic in the process of adjusting the switching gain to reduce chatter, which is the biggest problem of integral sliding mode control (Ak, Yılmaz & Kantarcıoglu, 2023).

In another study, Young and Kopp focused on creating a control signal by using fuzzy logic in hydraulic systems and developed a hydraulic forging machine working with fuzzy logic based control system (Young & Kopp, 2001). In their experiments, they controlled the movement of the cylinder used in forming (bending) three different workpieces with fuzzy logic. They also showed that there is no need to derive the mathematical model of the system due to the use of fuzzy logic, and as a result of their experiments, they obtained ±0.6 mm accuracy in sheet bending. In another study, Jian et al. controlled the pump electric motor, which determines the volume of oil sent to a hydraulic press, with the PID-Fuzzy hybrid system (Jian et al., 2009). The results show that the position tracking capability of the self-adjusting PID system has increased. Çınar et al. on the other hand, experimentally investigated the open-loop behaviour of an electro-hydraulic proportional system with fuzzy logic in a laboratory environment (Çınar et al., 2013). In their studies, they first created the rule base that defines the system and determined the input-output membership functions. The piston position information was measured by an LVDT (Linear Variable Differential Transformer) and the measurement results were transferred to Simulink and the required control signal was created by comparing the desired position and the current position of the cylinder in this way.

In this study, similar to the studies mentioned above, by developing a fuzzy logic-based approach, the existing control structure of a hydraulic system was hybridized, thereby improving the system performance (piston end-point position accuracy). An exemplary hydraulic system design and realization was carried out in the laboratory environment to test the improvements made. In this system, Beckhoff industrial control system is used as the traditional controller.

## 2. Experimental Methods

### 2.1. Hydraulic System Structure and Basic Features

Hydraulic systems are used extensively in a wide variety of applications, from small assembly operations to integrated and large-scale factory applications. The fact that force, and therefore motion, can be transmitted flexibly and through different channels utilizing fluids, constitutes the primary reason for preference for such systems. Hydraulic systems are also used as an indispensable element of testing machines. Today, testing machines, especially in the pre-production R&D stages, aid fulfilling technical specifications of the products. It is actively used in stages (trials) such as testing the suitability of materials to be used in production (metals, composites, plastics etc.), and performing the quality control of the finished products after production (Aydoğdu & Çatkafa, 2019).

In such testing machines, hydraulic systems are employed in the implementation of displacement/load-controlled movements, which often require multiple (in some cases up to a million) repetitions. In many applications, the control is performed such that the movement from the piston end point behaves as if it follows a sinusoidal signal. Examples such as engine mount testing machine, seat testing machine, tie-rod testing machine, shock absorber testing machine can be counted as a few examples of hydraulic-based testing machines frequently encountered in the industry.

In general terms, the basic components of a hydraulic system are shown in Figure 1. In this type of system, the motor is responsible for generating the movement of the pump, which creates the hydraulic pressure. The pump also functions as an element that converts the mechanical power produced by the engine into hydraulic power (creating the hydraulic pressure). It is applied to the valve element for control actions such as adjusting the pressure value produced and stored on the accumulator when necessary and determining the flow direction. The hydraulic power (pressure) whose direction and intensity are adjusted turns into mechanical power and thus a linear translational motion in the cylinder on the linear actuator element. This movement moves the mass/load at the end of the piston connected to the cylinder.

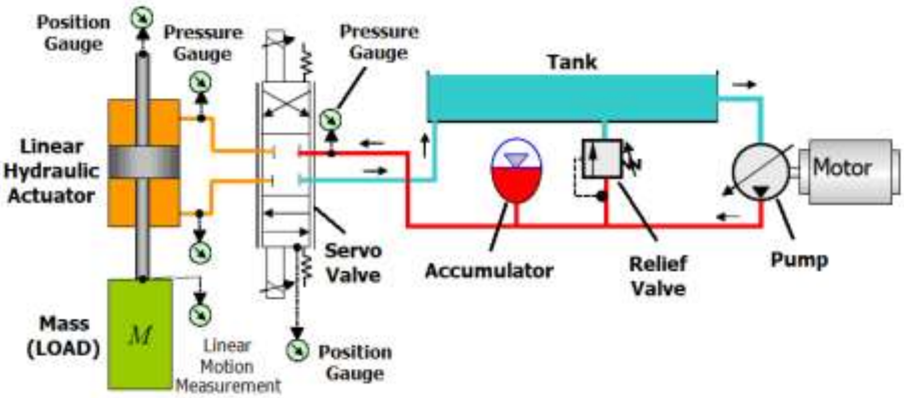


Figure 1. General structure of the hydraulic system (taken from (Kovari, 2009) and edited)

In hydraulic systems (especially in testing machines), the main aim is to determine the position of the end point of the cylinder accurately and precisely and to realize the value and profile of the force acting at this point as desired. In order to provide these, the actual controlled element is the valve. Servo valves are mostly used in such systems because they can be actuated electromechanically and controlled by electric signals. The most important step in determining the dynamic behaviour of a servo valve and hydraulic system components connected to it is to create of a dynamic model of the system. In order to control dynamic systems, a mathematical model in which the input-output relationship can be established (Yılmaz, Çakır, Gedik & Dinçer, 1999). In case of changes in operating conditions or varying input parameters, undesirable situations such as steady state errors or relatively small amplitude oscillations (which do not harm stability) may occur in hydraulic systems.

### 2.2. Experimental Setup and Standard Control Structure

In a standard application, on a hydraulic test setup, the user initially sets the desired end-point motion frequency and oscillation distance (amplitude) on the industrial controller used in the system. The control system automatically adjusts the required control (PID) coefficients according to these values and keeps these values constant until the end of the operation. No additional correction is made during operation for parameter shifts that may occur as a result of changes in the operating conditions of the system. Similarly, if a new frequency and amplitude value is set, the same procedure must be repeated from the beginning. Otherwise, steady-state errors and/or relatively small amplitude oscillations occur at the system output (at the end-point location). To overcome this problem, a fuzzy logic-based additional adjustment mechanism has been created that performs automatic re-adjustment of the control coefficients without restarting the procedure.

To observe the performance of the mechanism developed in the study, a hydraulic test system realization as in Figure 2 was carried out in the laboratory environment. This design simply consists of a hydraulic pressure pump, a piston, a servo valve that acts on this piston, a digital scale (position sensor) connected to the piston, and a controller unit. The layouts and descriptions of the elements in the structure are as given in Figure 2, according to the nomenclature indicated by letters on the picture taken from the real environment:

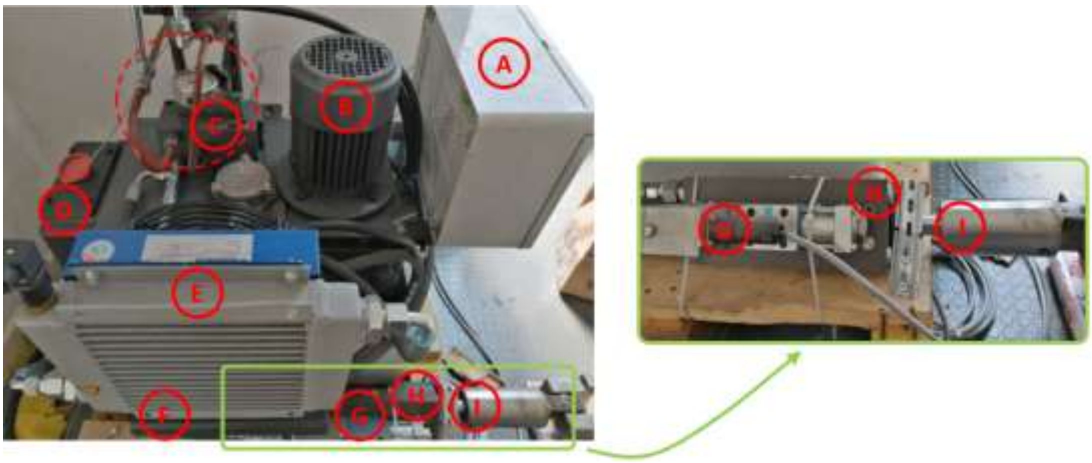


Figure 2. Established experimental hydraulic testing machine assembly

- **A.** Control Unit: It includes an industrial controller unit, data reading, acquisition and conversion units, user interface, hydraulic pump, and electromechanical drive and control units of other electrical elements,
- **B.** Hydraulic pump: Main pressure source,
- **C.** Hydraulic system pressurization valve: Constant hydraulic pressure source that feeds the servo valve,
- **D.** Hydraulic (oil) tank and built-in temperature sensor: The hydraulics in the system are stored in this unit. The PT100 sensor, which is used to instantly measure the temperature of the hydraulics, is located inside,
- **E.** Hydraulic (oil) cooling system,
- **F.** Position sensor: It is the element used to measure the position of the piston in the direction of motion, that is, the amplitude of the oscillating motion,
- **G.** Servo valve: It acts as an actuator element that provides the movement of the piston,
- **H.** Hydraulic cylinder: It is the unit in which hydraulic pressure turns into horizontal physical movement. It is acted by servo valve.
- **I.** Piston rod and connected load: The end-point of this shaft is actually the point where the desired oscillatory movements occur, which is called the system exit. An exemplary load is attached to the shaft.

As mentioned before, an industrial grade control system (manufactured by Beckhoff) is used on the assembly. The output of this system is directly used to drive the servo valve. The frequency and oscillation amplitude values of the piston end-point are applied as input to the control system, and the current position of the piston is used as a feedback signal. For the industrial controller system to perform the required control action, it must use an existing link between these inputs and the output, called the system model. Because of the complex and non-linear nature of hydraulic systems, it is not practical to use a direct mathematical model. Instead, as a solution, the system response (movement of the piston end point) against different input states is observed experimentally and an input-output table is created. These values are complemented by interpolation and a characteristic response curve is created, thus creating a model that covers the entire system (it will act like a look-up table).

To generate a characteristic response curve, a procedure as follows is employed. Firstly, a voltage signal varying within a certain range is applied from the driver circuit to drive the servo valve (actually adjusting the opening of the valve) that moves the piston. It is preferred to apply positive and negative voltages to provide movement in both directions (forward and backward). Thus, an operating zone in the range of ± maximum voltage value that can be applied to the servo valve is formed. The maximum applied voltage level is indicated by the value ±100% and represents the movement with the highest velocity in both directions. The situation where the piston does not move and has zero velocity (neutral) is represented by 0%. During the operation of the system, the voltage is applied to the servo valve by increasing it in 1% steps within the value range of [0, ±10%]. In the [-10%, -100%] and [+10%, +100%] value ranges, the voltage is applied in increments of 10%. By increasing the number of steps, piston speed information is obtained for each situation. When all this data is placed on a graph, a series of points emerge. If these points on the graph are combined by interpolation, a characteristic curve, a kind of system response, is obtained. An example characteristic curve created by this method is shown in Figure 3. Thus, in order to obtain the desired frequency and amplitude motion, the industrial controller calculates and applies the necessary control (PID) coefficients on itself using the value ranges in this table.

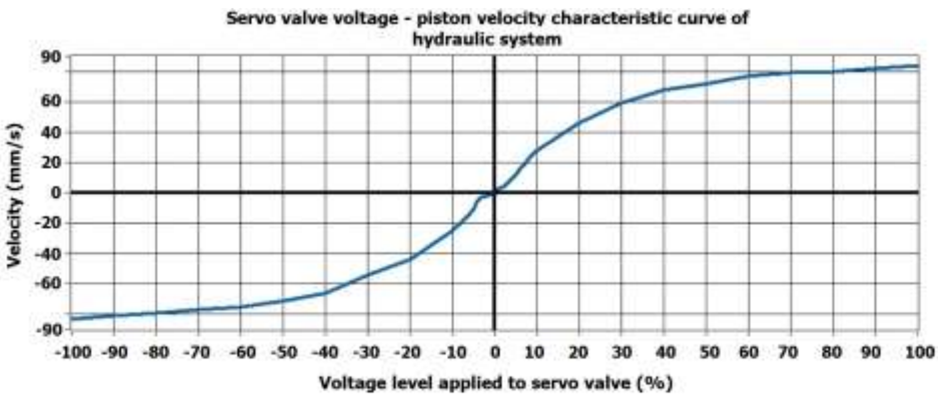


Figure 3. Example characteristic response curve of a hydraulic system showing the variation of piston speed with the level of voltage applied to the servo valve

In cases where the operating values set in the system (frequency and amplitude of oscillation) are changed or there are changes in the operating environment of the system (such as oil temperature, viscosity, value of the load), undesirable shifts occur on the system output (such as the output not oscillating at the desired amplitude). The exemplary output signal in Figure 4 can be considered to explain how such shifts are detected and converted into an operable parameter. As mentioned before, since hydraulic test systems are usually operated in such a way that the output will move in a sinusoidal form, inferences have been made on a sample signal as follows.

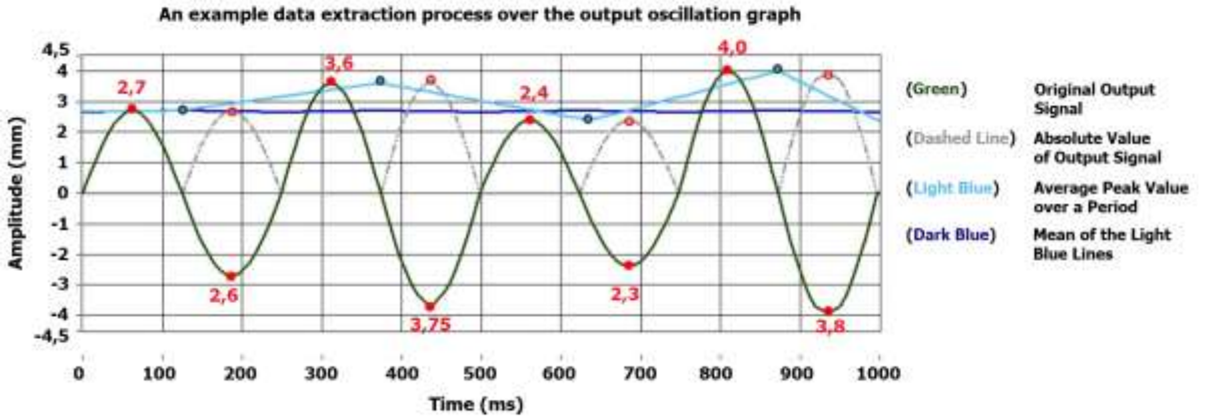


Figure 4. An example data extraction performed on a sample output signal (with an amplitude input of ±3 mm)

Assuming that the output of a system that is expected to oscillate with an amplitude of 3 mm is as in Figure 4;

- First of all, the maximum amplitude values of positive and negative alternance (red filled dots) are determined for each period of the oscillation signal (green colored solid line) obtained from the end point of the piston.
- Then, by taking the absolute value of these points (this is how the dashed line and hollow points are created in the figure), a kind of sign rectification is performed.
- The arithmetic mean of these maximum values (all solid and empty points) for each period is calculated and plotted (indicated by blue dots).
- By combining these points, the peak value oscillation graph of the output signal, which is shown in light blue on the figure, is obtained.
- Finally, a curve that can be defined as the settlement value of the oscillation amplitude is obtained by taking the moving average of these values, which are indicated by the light blue-colored dots. This curve is shown in dark blue on the figure.

After this point, in the graphs given for the comparison of the previous state and the next state, the deviation data of the amplitudes (with light color) and the settlement values (with the dark color) will be given together. Figure 5 shows an example graph given like this:

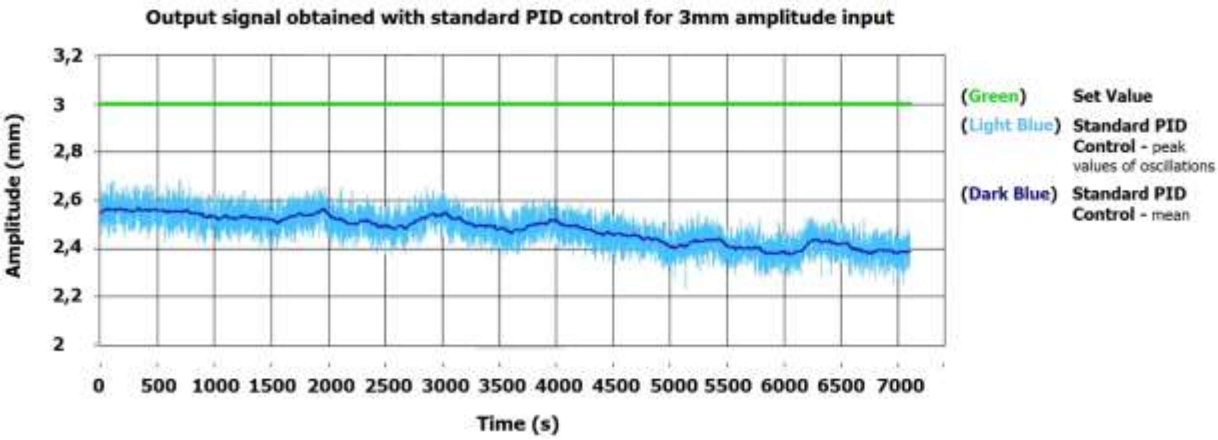


Figure 5. Comparative performance representation of the sample output signal (with an amplitude input 3 mm)

In most cases where shifts similar to those in the figure occur, the industrial control system used in the structure is insufficient to compensate for these changes. As a result, a human operator has to manually adjust the controller coefficients. As a result of the examinations made on the process and the experience gained; First of all, it has been determined that adjusting the proportional gain ($K_p$) value is quite effective on the result.

Secondly, it has been understood that it is necessary to determine two different values for this gain value ($K_p$). According to this; Two different parameters are defined, i) $K_p$_forward, which is valid in the forward movement of the piston (in the rising part of the sine wave), and ii) $K_p$_back, which is valid in the backward movement (in the falling part of the sine wave). The reason for this is that small amounts of fluid leaks occur in the forward movement of the piston, due to signal interference in servo valve control in hydraulic systems. Due to the leaks, the piston starts to move forward in a slow motion during the operation of the system. In order to keep the piston in its position, it is necessary to apply pressure as much as the leakage in the back direction. Therefore, it has been seen that determining the upper limit values for $K_p$_forward and $K_p$_back parameters to be applied as input to the industrial controller has a positive effect on the result.

After the changes in the dynamic parameters of the system, a new controller coefficient value must be determined by the human operator within certain periods and this value must be presented to the control system manually. In practice, the applicability of such a process is low in such a system that can be operated continuously for 24 hours and days in some cases. For this reason, there is a need to create an additional parameter computation method that can automatically perform the specified operation and produce results in case of parameter changes, without being dependent on a specific mathematical model. At this point, it was preferred to perform the related parameter computation processes with a fuzzy logic-based inference.

### 2.3. Fuzzy Logic Based Parameter Computation Approach

In our study, fuzzy logic design and implementation on the system were carried out on the LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) program developed by the National Instruments (NI) company. This program was also used in data collection and evaluation processes on our experimental system. Two parameters are applied as input to the fuzzy logic-based computation block we have designed;

i. The frequency value of the desired movement (oscillation) at the piston end point,
ii. The amplitude value of the desired movement (oscillation) at the piston end point,

As an output from the fuzzy logic-based computation block, two parameters are obtained that will be input to the industrial control unit of the hydraulic system;

i. The upper limit value for the proportional gain coefficient $K_p$_forward, which is valid in the forward movement of the piston,
ii. The upper limit value for the proportional gain coefficient $K_p$_back, which is valid in the backward movement of the piston,

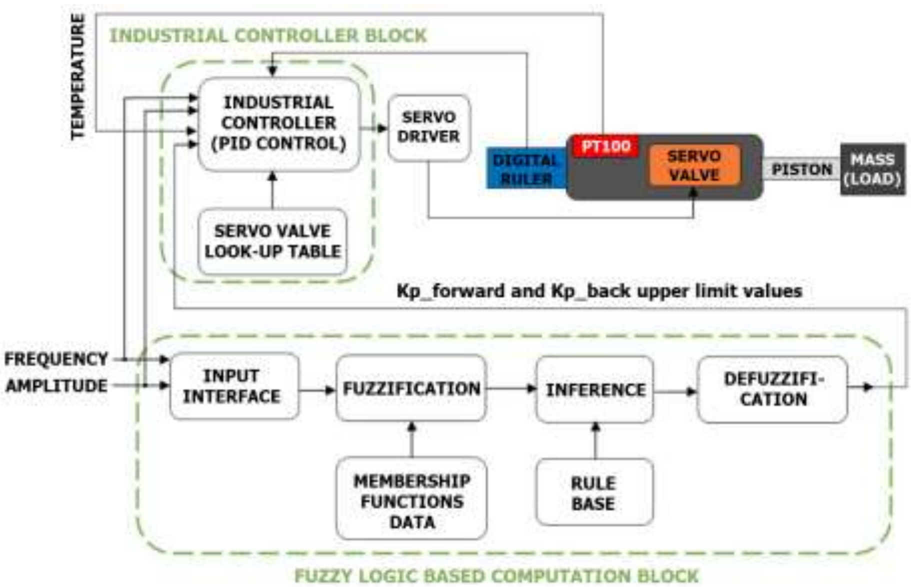


Figure 6. Block diagram of the control function of the hydraulic testing machine experimental setup

After all these definitions, the block diagram for the control of the experimental hydraulic testing machine setup used from the experiments is as in Figure 6.

When the block diagram is examined, two main function blocks stand out. The first of these is the industrial controller (PID) block, which controls the servo valve that provides the movement of the piston in the assembly. The other is a fuzzy logic-based computation block that determines the upper limit value of two different proportional gain coefficients ($K_p$) valid in this basic controller. The remaining part consists of the system block (containing the servo drive, valve, pump, piston, sensors, and other physical parts).

User inputs (set values determined for frequency and oscillation amplitude values) are presented to the system via an interface and shared with both functional blocks. Thus, the number of input parameters of the fuzzy logic block becomes two as previously stated. $K_p$_forward and $K_p$_back upper limit values, which are the output parameters of the fuzzy logic-based computation block, are also sent to the industrial controller unit as input.

The temperature measurement (parameter) seen in the block diagram is applied as an input to the standard controller in order to stop the system for safety purposes only when the piston oil temperature is out of the defined value range. This parameter has no effect (in this first phase of the study presented) on the end-point position control in the study.

#### 2.3.1. Input Output Parameters and Membership Functions

The value ranges and membership function numbers employed for the input and output parameters belonging to the fuzzy logic part of the general control structure are as indicated in Table 1 and Table 2.

Table 1
Input Parameters and Value Ranges

| Parameter | Value Range | Number of Membership Func. |
|---|---|---|
| Frequency | 0.5 – 5 Hz | 5 |
| Amplitude | 0.5 – 5 mm | 5 |

Table 2
Output Parameters and Value Ranges

| Parameter | Value Range | Number of Membership Func. |
|---|---|---|
| $K_p$_forward upper limit | 0.1 – 1.75 | 16 |
| $K_p$_back upper limit | 0.1 – 1.98 | 18 |

For the input parameter named *frequency*, *trapezoidal* membership functions are employed. The graphical representation and descriptive points of these membership functions are given in Figure 7.

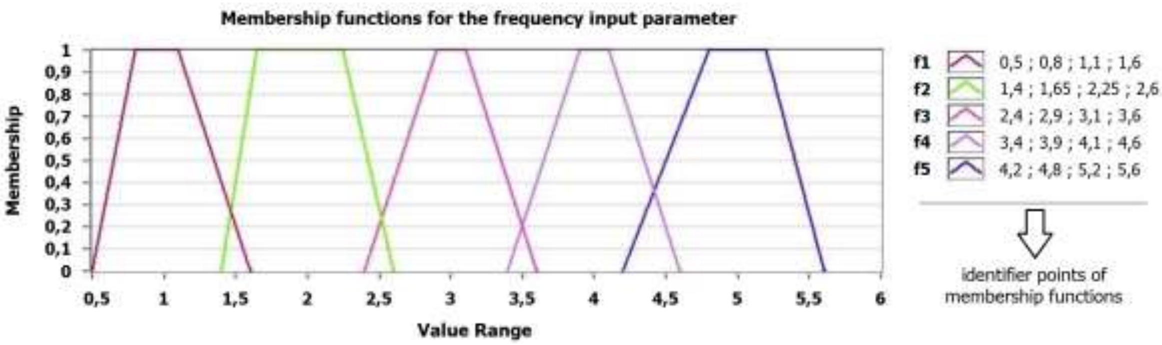


Figure 7. Membership functions and identifier points for the *frequency* input parameter

Similarly, *trapezoidal* membership functions were employed for the input parameter named *amplitude*. Their graphical representation and descriptive points are given in Figure 8.

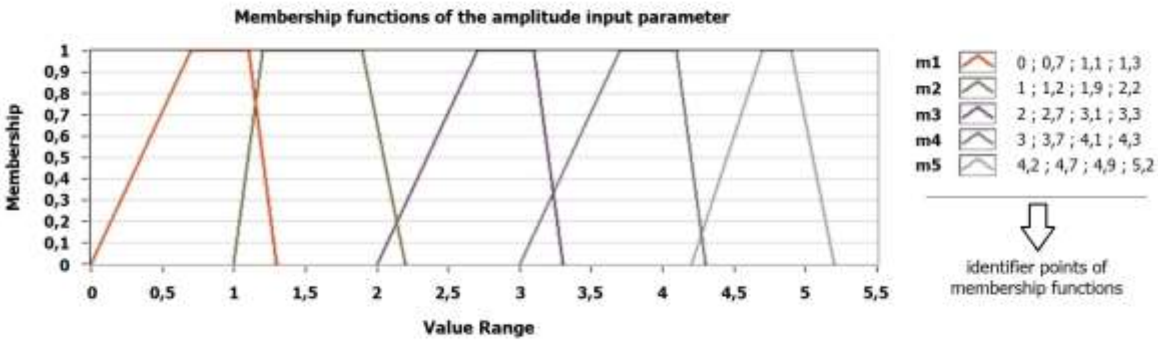


Figure 8. Membership functions and identifier points for the *amplitude* input parameter

*Triangular* membership functions are employed for $K_p$*_forward upper limit*, one of the output parameters. The graphical representation and descriptive points of these functions are given in Figure 9.

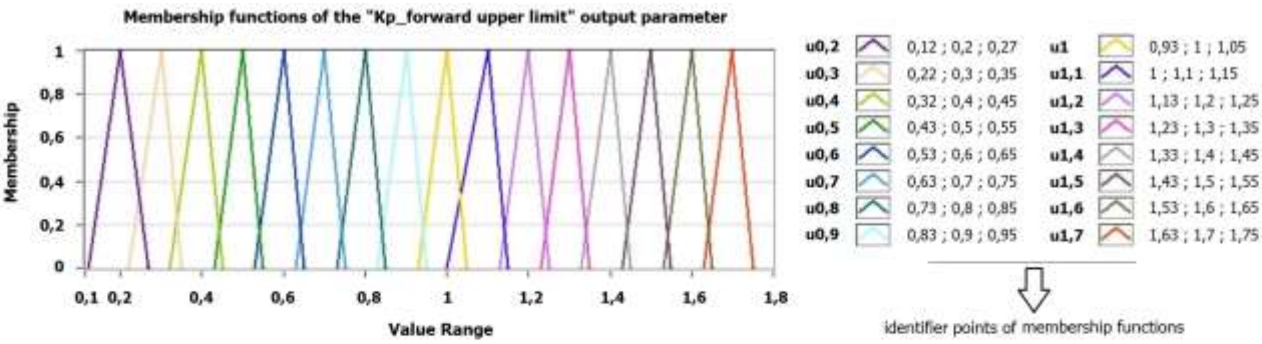


Figure 9. Membership functions and identifier points for the $K_p$*_forward upper limit* output parameter

Similarly, *triangular* membership functions were employed for the $K_p$*_back upper limit* output parameter. Their graphical representation and identifying points are given in Figure 10.

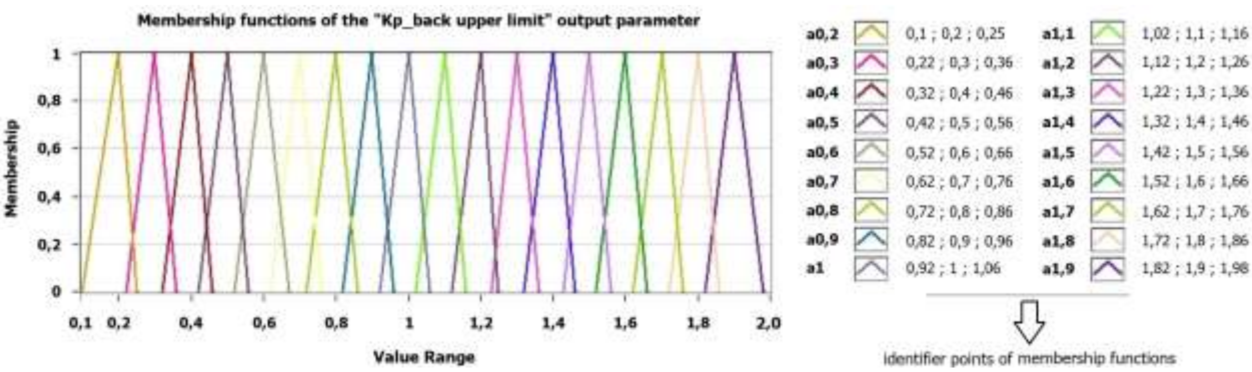


Figure 10. Membership functions and identifier points for the $K_p$*_back upper limit* output parameter

### 2.3.2. Creating the Fuzzy Rule Base

For the input and output parameters, whose membership functions are as given above, a rule base containing a total of 25 rules has been created. The list of rules showing this rule base can be shown as in Table 3, with only some lines as an example, since the lines that follow each other often proceed in a logical manner.

Table 3
List of Rules Forming the Fuzzy Rule Base

| No | Rules |
|---|---|
| 1 | IF 'frequency' IS 'f1' AND 'amplitude' IS 'm1' THEN 'Kp_forward upper limit' IS 'u0,2' ALSO 'Kp_back upper limit' IS 'a0,2' |
| 2 | IF 'frequency' IS 'f2' AND 'amplitude' IS 'm1' THEN 'Kp_forward upper limit' IS 'u0,4' ALSO 'Kp_back upper limit' IS 'a0,3' |
| 3 | IF 'frequency' IS 'f3' AND 'amplitude' IS 'm1' THEN 'Kp_forward upper limit' IS 'u0,5' ALSO 'Kp_back upper limit' IS 'a0,4' |
| 4 | IF 'frequency' IS 'f4' AND 'amplitude' IS 'm1' THEN 'Kp_forward upper limit' IS 'u0,7' ALSO 'Kp_back upper limit' IS 'a0,5' |
| 5 | IF 'frequency' IS 'f5' AND 'amplitude' IS 'm1' THEN 'Kp_forward upper limit' IS 'u0,7' ALSO 'Kp_back upper limit' IS 'a0,6' |
| 6 | IF 'frequency' IS 'f1' AND 'amplitude' IS 'm2' THEN 'Kp_forward upper limit' IS 'u0,6' ALSO 'Kp_back upper limit' IS 'a0,4' |
| 7 | IF 'frequency' IS 'f2' AND 'amplitude' IS 'm2' THEN 'Kp_forward upper limit' IS 'u0,7' ALSO 'Kp_back upper limit' IS 'a0,5' |
| … | ….. ….. ….. |
| 14 | IF 'frequency' IS 'f4' AND 'amplitude' IS 'm3' THEN 'Kp_forward upper limit' IS 'u1,3' ALSO 'Kp_back upper limit' IS 'a1,2' |
| 15 | IF 'frequency' IS 'f5' AND 'amplitude' IS 'm3' THEN 'Kp_forward upper limit' IS 'u1,6' ALSO 'Kp_back upper limit' IS 'a1,6' |
| 16 | IF 'frequency' IS 'f1' AND 'amplitude' IS 'm4' THEN 'Kp_forward upper limit' IS 'u1' ALSO 'Kp_back upper limit' IS 'a1' |
| 17 | IF 'frequency' IS 'f2' AND 'amplitude' IS 'm4' THEN 'Kp_forward upper limit' IS 'u1' ALSO 'Kp_back upper limit' IS 'a1,2' |
| … | ….. ….. ….. |
| 23 | IF 'frequency' IS 'f3' AND 'amplitude' IS 'm3' THEN 'Kp_forward upper limit' IS 'u1,6' ALSO 'Kp_back upper limit' IS 'a1,8' |
| 24 | IF 'frequency' IS 'f4' AND 'amplitude' IS 'm4' THEN 'Kp_forward upper limit' IS 'u1,7' ALSO 'Kp_back upper limit' IS 'a1,9' |
| 25 | IF 'frequency' IS 'f5' AND 'amplitude' IS 'm5' THEN 'Kp_forward upper limit' IS 'u1,7' ALSO 'Kp_back upper limit' IS 'a1,9' |

## 3. Results and Discussion

To compare the performance of the developed fuzzy logic-based computation block, experiments were carried out on the hydraulic testing machine setup with different input parameter values, first for the case where no fuzzy logic was applied (standard PID control application) and then for the case with fuzzy logic added. In these trials, system output data were extracted using the data extraction method described in Section 2.2 from the recorded oscillating motion amplitude data obtained from the end point of the piston in the test setup. In order to reduce the number of extracted data and to distinguish the changes on the plotted graphs, it was recorded as the settlement value formed by the maximum amplitude values observed in positive and negative alternances and the moving average of these values every 10-50 periods. Experiments were carried out by changing the input parameters in two different scenarios on the test setup. In the first scenario, only the standard PID control was used, and in the second scenario, the fuzzy logic-based computation block was added to the PID control. To easily compare the situation before and after the fuzzy logic based computation block addition obtained results are shown together on the following result graphs.

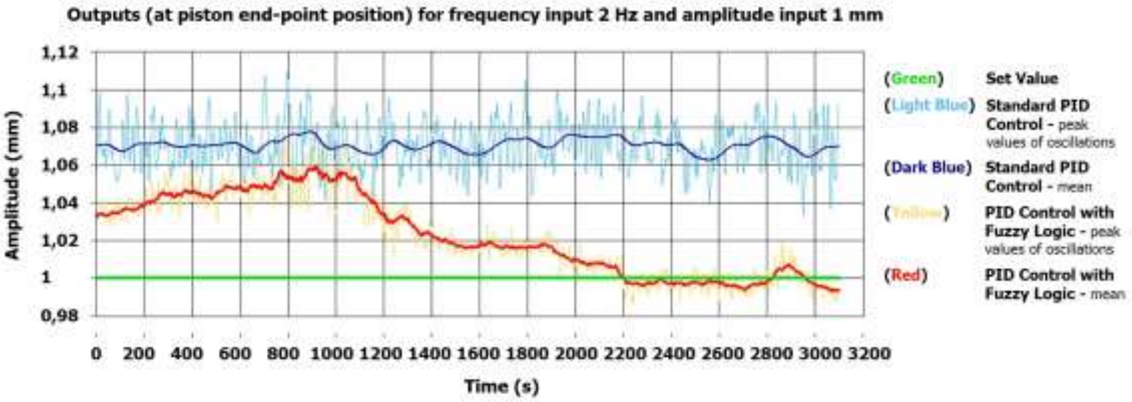


Figure 11. Comparison of output (piston end-point position) data obtained for *frequency* input 2 Hz, *amplitude* input ±1 mm

First, the results obtained before and after the fuzzy logic-based computation block addition for the 2 Hz frequency and ±1 mm amplitude input are shown in Figure 11 together with the set value (an inference is made in 20 periods for data reduction). When the figure is examined; It is seen that before the implementation of the fuzzy logic-based computation part, the system end-point settled to a level higher than 7%, but after the fuzzy logic part was activated, this difference (in the settlement value) improved to remain below the 2% level.

The next result shows the results obtained before and after applying the fuzzy logic-based computation block when the amplitude input is ±1 mm and the frequency input is increased to 5 Hz. The relevant result graphs are shown in Figure 12 together with the set value (for data reduction, an inference was made in 50 periods). A similar improvement is observed when the results here are compared. In fact, it is seen that a more proportional improvement has been achieved in this new situation.

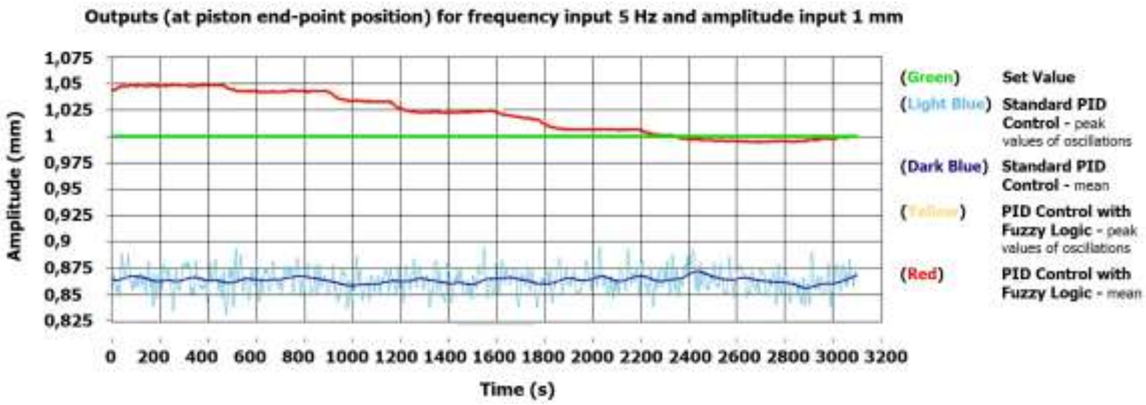


Figure 12. Comparison of output (piston end-point position) data obtained for *frequency* input 5 Hz, *amplitude* input ±1 mm

A third comparison is; It is made for the situation before and after the implementation of the fuzzy logic-based computation block for the input of 4 Hz frequency and ±3 mm amplitude. The result graphs obtained from here are shown in Figure 13 together with the set value (for data reduction, an inference was made in 40 periods). When the results obtained are examined, it is seen that with the increase of the amplitude parameter, an oscillation of about 15% differs from the desired value in the case before the fuzzy logic addition, and this value shift increases with time. The result obtained after adding fuzzy logic to the control function in the system is quite satisfactory.

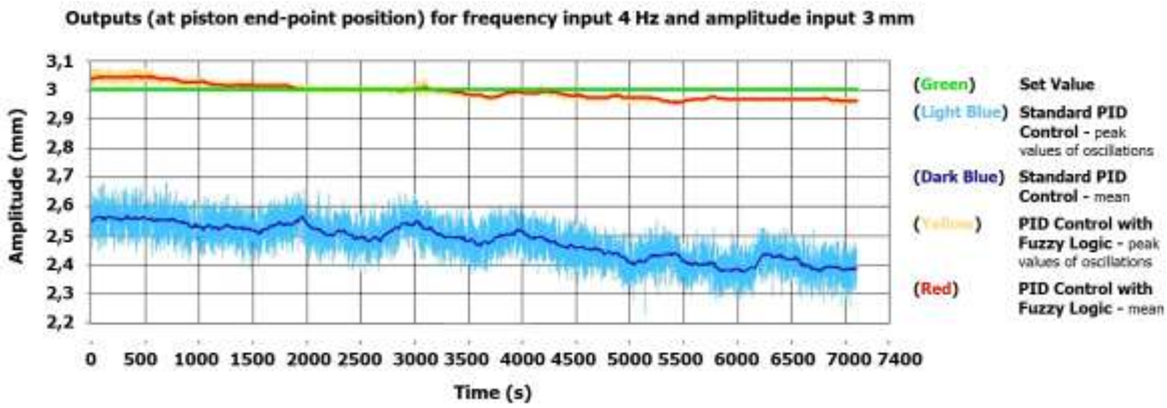


Figure 13. Comparison of output (piston end-point position) data obtained for *frequency* input 4 Hz, *amplitude* input ±3 mm

The output amplitude results and the recovery rates obtained before and after fuzzy logic application for the input sets discussed above and some other input parameter values are summarized in Table 4.

Table 4
Rates of improvement in hydraulic test system performance by applying the fuzzy logic-based approach

| Set Values | | Average Amplitude Values (mm) | | Improvement Relative (%) |
|---|---|---|---|---|
| Frequency (Hz) | Amplitude (mm) | Before fuzzy logic implementation | After fuzzy logic implementation | |
| 1 | 1 | 1.15 | 1.02 | 11.3 |
| 2 | 1 | 1.10 | 1.06 | 3.64 |
| 5 | 1 | 0.80 | 0.99 | 23.75 |
| 4 | 3 | 2.55 | 3.05 | 19.61 |
| 4 | 4 | 3.30 | 4.03 | 22.12 |

As can be seen, closer results were obtained in both experimental groups at a low frequency input such as 1 Hz, or a relatively low amplitude input values such as 1 mm. It is noteworthy that when the frequency or amplitude input parameter increases, the difference between them increases and better results are obtained when the fuzzy logic-based computation block is added.

The results of a longer trial scenario where different input parameters are applied sequentially (continuously) are shown in Figure 14. In this experiment, as in the previous ones, the following results were obtained for the state before fuzzy logic addition (standard PID control application) and after fuzzy logic addition in the system, against 4 Hz frequency and 1 mm, 3 mm, and 4 mm amplitude input values.

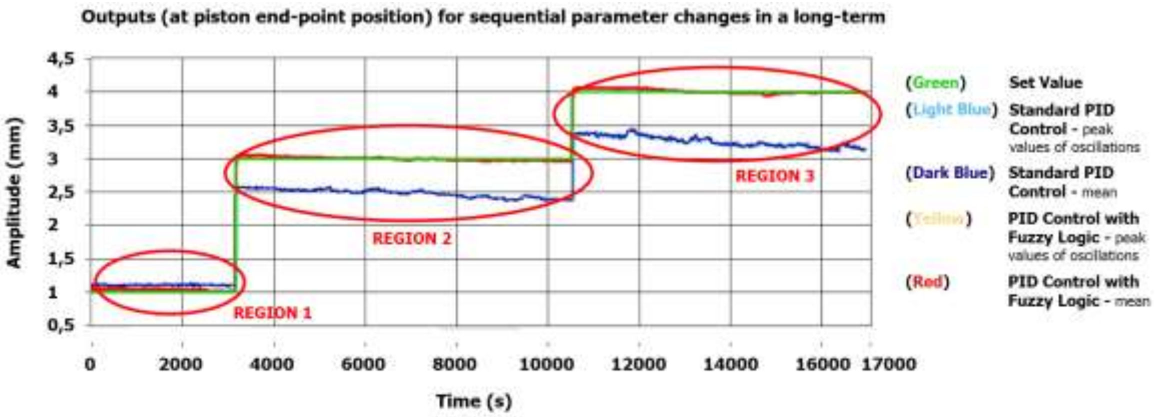


Figure 14. Comparison of output data obtained against sequential parameter changes in a long-term (~300 min) test (*frequency* input 4 Hz, *amplitude* input ±1, ±3, and ±4 mm)

If we evaluate these last results; Similar to previous experiments, it is seen that the results are closer to each other for the low amplitude input value (REGION 1). With the increase in the amplitude value, it is seen that there are significant differences between the results obtained before (with standard PID) and after the fuzzy logic based computation block addition (REGIONS 2 and 3), and this situation becomes more evident as the test period gets longer. This proves that a controller parameter readjustment is absolutely necessary as the operating time increases when only the standard PID control structure is used in the system.

When a comparison is made considering all these results; In similar studies, it is seen that complex methods such as artificial neural networks, genetic algorithm and particle swarm optimization algorithm etc. are used in addition to PID control to provide piston end-point position control for hydraulic systems. In our study, the desired performance was achieved by using the fuzzy logic method, which is much simpler to implement, while the operational complexity was kept low. On the other hand, when a comparison is made with other studies using fuzzy logic, the fuzzy logic-based calculation method developed in our study is integrated into the industrial controller used in current applications. Thus, instead of creating a new controller structure from the beginning, it was added to the existing control system and ease of implementation was ensured.

## 4. Conclusion

In our study, a hydraulic testing machine setup, on which an industrial controller is located, was initially created. When only standard PID control is applied to this structure, the end-point oscillation performance (oscillation amplitude) of the system does not occur in the desired value range. The reason for this problem is that the same controller parameters (determined and applied in the setup of the test system) are used for all different frequency and amplitude set values. It has been determined that the proportional gain coefficient $K_p$, one of the applied control coefficients, should be adjusted to overcome this negative situation observed at the system output. A fuzzy logic-based computation block has been added to the system so that this parameter determination process can be done automatically. By making such an addition to the existing control system, a structure that adjusts itself against parameter changes has been created. The experiments with different frequency and amplitude values were carried out on the new system obtained after the addition. Looking at the results (as summarized in Table 4); It is seen that determining the upper limits of the $K_p$ coefficients with a fuzzy logic-based inference gives positive results on the system performance. For the deviation of the amplitude set value, the results obtained for the different operating scenarios were mostly below ±0.1 mm and an average improvement of over 10% was achieved compared to the previous situation.

In the next stage of the study, it is considered to expand the rule bases by using different environment and system parameters such as oil viscosity and load profile. It is expected that this will enable the hydraulic test system to produce even more consistent and stable results.

## Author Contributions

Serkan Anlak: Designing and fabricating the experimental test rig. Experimental studies, measurements and theoretical calculations.

Ekrem Düven: All design activities, experimental studies, measurements and theoretical calculations, writing and editing.

## Conflicts of Interest

The authors declare no conflict of interest.

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