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POSITION CONTROL OF HYDRAULIC SERVO CYLINDER FOR WAVE CHANNEL

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Highlights

- Hydraulic servo cylinder enables precise control of wave generation.
- Real-time wave measurement and control implemented in LabVIEW.
- 24-meter water wave channel system designed for wave generation.

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ABSTRACT: This study aims to achieve position control of the hydraulic cylinder for generating a regular waveform for tsunami, flood, and coastal structure interaction studies, and to measure the generated waveform in real time to determine its conformity to the desired shape. Today, wave channel systems safeguard aquatic ecosystems and play a crucial role in understanding and mitigating natural disasters, particularly in tsunami-prone areas. The wavemaker system in the wave channel is driven by a double-acting hydraulic servo cylinder. A black-box approach is chosen for model identification, validated with real measurement data. PI parameters were initially determined using the Ziegler-Nichols method and later optimized in MATLAB using the PID Tuner and Genetic Algorithm (GA). The optimized PI parameters K_p and K_i were found [0.2989 0.0023] for GA, compared to [0.2475, 0.14] for Ziegler-Nichols, and [0.23023 0.058609] for MATLAB/PID Tuner. Real-time wave measurements were recorded with a LabVIEW-based graphical interface. The step and sinusoidal responses of the hydraulic system were analyzed using three methods for determining PI parameters. GA-optimized PI achieved the best results, with ITAE improvements of 74.82% and 69.50%, RMSE improvements of 2.15% and 3.69%, and MAE improvements of 47.02% and 49.30% compared to Ziegler-Nichols and MATLAB/PID Tuner, respectively.

Keywords: *Closed Loop Systems, Control Theory, Fluid Flow Control, Hydraulic System, System Identification, Wave Channel*

1. INTRODUCTION

Waves transport energy through oscillations on the air-water interface in the vast oceans and coastal regions of the Earth. The energy carried by waves is on the order of 40-60 kW/m for more than 70% of the Earth's surface [1]. An understanding and modeling of the kinematics of ocean waves is crucial in fields such as marine architecture, coastal protection, and offshore oil and gas [2], [3].

Furthermore, wave channel systems, where water waves are generated in a controlled manner, are widely used in hydraulic laboratories for wave generation. Typically, these structures consist of a hydraulic cylinder, hydraulic power unit, hydraulic valve, and an actuator submerged in water. The generated waves are used to model environmental conditions for physical experiments on scaled-down models. Physical experiments provide the opportunity to predict the behavior of full-scale objects and verify the results of numerical analyses. The primary objective of the conducted studies is to enhance human safety and the structural resilience of buildings.

The water waves obtained from a wave generator with a good control system are crucial for accurately modeling wave profiles, and they are of vital importance for conducting appropriate experimental tests of scaled physical models aimed at enhancing the safety and performance of marine structures such as ships, oil platforms, and wind turbines [4], [5]. The need to continuously enhance maritime safety is the driving force behind the continuous improvement of experimental testing techniques. Large-scale objects in the sea have a significant impact on people's lives and safety. Therefore, it is of utmost importance to conduct downscaled experiments accurately [6].

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The accuracy of wave simulations is of critical importance for the design and performance evaluation of marine structures. The Pierson-Moskowitz, JONSWAP, and TMA wave spectrum models are used to ensure accuracy in wavemaker systems. The Pierson-Moskowitz model represents equilibrium sea conditions, the JONSWAP model represents growing seas, and the TMA model represents wave behavior in shallow waters. The use of these models is crucial in experimental tests aimed at enhancing the safety and performance of marine structures such as ships, oil platforms, and wind turbines [7]. In wave channel systems, the waves produced are classified into two main categories: "regular waves" and "irregular waves". Regular waves are defined as a monochromatic waveform with a single distinct frequency and wave height, while irregular waves are described as the superposition of an infinite number of monochromatic waves [8].

When examining the literature on wave generator systems used in laboratories, it is observed that hydraulic, pneumatic, electronic, and electro-hydraulic structures are used as propulsion systems. Furthermore, PLCs, microcontrollers, and DAQ cards are preferred as control structures.

As an example of a study conducted in the field of wave generation, a wave generator with a small-scale wave channel, controlled by a microcontroller and using a sinusoidal wave as the control signal, was utilized. The wave generator employed a flap-type wavemaker with a multi-pedal structure. The STM32F103 development board and DC stepper motors were used in the waveform generator system to perform tests with different periods for the signal period of the pedal. The wave amplitudes generated were examined according to the applied control signal structure [9]. When examining the literature on wave generator systems used in laboratories, it is observed that hydraulic, pneumatic, servo motor, and electro-hydraulic structures are used as propulsion systems. Furthermore, PLCs, microcontrollers, and DAQ cards are preferred as control structures. Hydraulic drive units were used to measure water waves using measurement probes and record the wave profiles with a PIV system. Various experiments were conducted, and the obtained PIV data were interpreted according to different graded wave theories to analyze wave profiles, wave conditions, and reflected waves [10]. For position control in wave makers, different control algorithms are used in the control approach of both hydraulic and electro-hydraulic systems. When the literature is examined at this point, it shows that the PID controller is sufficient to control the hydraulic actuator as desired. The feedback control system design using PID controller is adopted as it is simple and robust when applied over the specified operating range. To ensure good performance of the controller, the appropriate values for each parameter K_p, K_i and K_d should be set optimally. PID tuning approaches such as Ziegler Nichols [11] and Nelder-Mead [12] are used to calculate the controller parameters.

Fuzzy logic controllers are used together with PID controller in position control. In a study using the STM 32 controller, fuzzy and PID controllers were compared in which the irregular waveform obtained with multiple sine signals at different frequencies was used as the reference signal. Accordingly, it was reported that the reference signal of the waveform with fuzzy controller provides higher accuracy. It is stated that fuzzy logic control is superior to PI control [13].

Ishak et al. developed and implemented a self-tuning fuzzy controller for position control of hydraulic actuator. In the study, the design of feedback control system using PID controller can be easily implemented because it is simple and robust when applied in the specified operating range. It is found that the performance of the self-tuning fuzzy PID controller is better than the conventional controller and the tracking error is effectively reduced. Another application of self-tuning fuzzy PID is described in, where the controller is used to control the position of an electro hydraulic actuator system. Accordingly, when the self-tuning fuzzy PID controller is applied to the system, the system response is faster and better tracking response is achieved than the conventional PID controller [14].

The optimization of PID controller coefficients for hydraulic cylinder position control can be effectively achieved using various methods, including fuzzy logic and hybrid techniques. The Beetle Antennae Search (BAS) algorithm applied for tuning PID parameters has been shown to significantly improve system performance and robustness against external disturbances compared to traditional tuning methods for the BAS-PID controller [15]. A hybrid algorithm combining PSO and GA has been used to tune PID controllers in hydraulic systems, resulting in superior performance metrics compared to conventional methods [16]. This hybrid approach provides greater efficiency and effectiveness in parameter tuning by leveraging the strengths of both algorithms."

System identification is an alternative method for obtaining a mathematical model of a system. System identification is the procedure of obtaining a model of a system using input-output data consisting of stimulus-response pairs. In order to obtain the hydraulic system model, different models of different degrees and different models are used in the literature that are most compatible with the system behavior.

The concept of system identification was first introduced by Zadeh [17] to describe the task of identifying input-output relationships using empirical data sets.

In a study by Rahmat et al. on modeling hydraulic systems, three different cosine signals were combined into a single excitation signal to identify the hydraulic system. It was reported that the best result for this system was obtained with a 4th order ARX model [18].

In another study, it was reported that the best fit was obtained with a third order ARX model using a sinusoidal signal as the excitation signal [19]. The degrees of hydraulic systems and the appropriate model for modeling or identification studies depend on the system being created. Istif used state space, arx, armax, output error and box jekins models for hydraulic system identification and reported that the best fit was achieved with a 2nd order box jekins model [20].

In a general review of studies on wave channel structures, this study makes a contribution to the control literature by implementing the position control of a wave generation system using a hydraulically double-rod and double-acting servo cylinder, following the hardware development of a wave channel system. Furthermore, the study distinguishes itself through the real-time measurement and recording of water waves in wave generation systems.

In this study, the position control of a wave channel containing a 24x1x1 meter flap type wave generator located in the Hydraulic Laboratory of Balıkesir University was realized using a Proportional-Integral (PI) controller. In the study, sinusoidal signals with frequencies of 0.8 Hz and 1 Hz were used to control the hydraulic drive system and the wave heights obtained for water levels of 40-50-60cm were recorded. The signal applied for the position control of the hydraulic cylinder consists of a single frequency and a single amplitude component. As a result of the position control of the hydraulic cylinder, the generated water waves exhibited a regular form. The wave height data were directly obtained from the wave measurement sensors.

The transfer function model of the wave generator system is obtained by black box method in Matlab/Simulink System Identification toolbox. The initial coefficients of the PID block were calculated using the Ziegler-Nichols method. Then the K_p and K_i parameters of the PI controller were determined using the PID Tuner tool and Genetic Algorithm (GA) in Matlab/Simulink. The determined parameters were applied experimentally. In the scope of this study, Material and Methods are presented in Section 2, experimental results are detailed in Section 3, and finally, the conclusions are discussed.

2. MATERIAL AND METHODS

The controlled system is located in the Balıkesir University Hydraulic Laboratory and has dimensions of 24 meters in length, 1 meter in width, and 1 meter in height. The wave generation actuator in the wave channel is of the flap type and is driven by a double-acting, double-rod hydraulic cylinder system. The cylinder has a total stroke value of 700 mm in its forward or backward movement, and the water heights for the application are selected as 40-50-60cm. A proportional hydraulic valve has been used to control the hydraulic cylinder. The hydraulic system has a capacity of 120 liters of hydraulic fluid and operates at a constant pressure of 50 bar. The hydraulic pump used in the hydraulic unit has a constant flow rate. The hydraulic valve control system utilizes the NI CRIO-9074 controller and analog input-output modules. Solid wave attenuators have been used to prevent the reflection of water waves created on both sides of the wave channel. The technical specifications of the controller used in Table 1 are provided [21].

Table 1. CRIO-9074 Technical Specifications

Feature	Spec
Processor	400 MHz Freescale MPC5200 real-time processor
FPGA	Xilinx Spartan-3 2M gates FPGA
Memory (RAM)	128 MB DRAM
Storage (Flash Memory)	256 MB
I/O Module Slots	8 hot-swappable C Series module slots
Operating System, Programming Languages	NI Real-Time OS, LabVIEW -C/C++

A sinusoidal input signal has been generated in the LabVIEW environment to control the stroke of the hydraulic system within the desired range. The input signal of the hydraulic cylinder is ensured to follow when amplitude, frequency, and offset parameters are entered by the user. The structure of the general control system is provided in Figure 1.

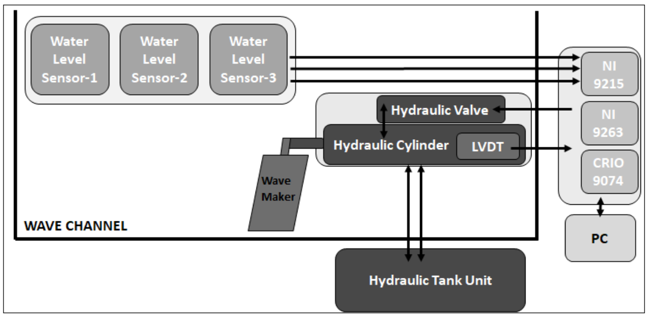

Figure 1. Structure of wave channel

Figure 2 presents the physical structure of the wave channel. The training of the coastal wave attenuator located at the end of the wave channel is 20%. Ultrasonic sensors have been used to measure waves at three different points on the wave channel. In the wave channel, h represents the constant water level, H represents the peak-to-peak height of the water waves created by the flap-type wave generator, a represents the peak point of the wave formed relative to the still water level, and lambda denotes the wave period. The wave direction refers to the direction of propagation of the waves generated by the wavemaker, which is controlled by the hydraulic cylinder.

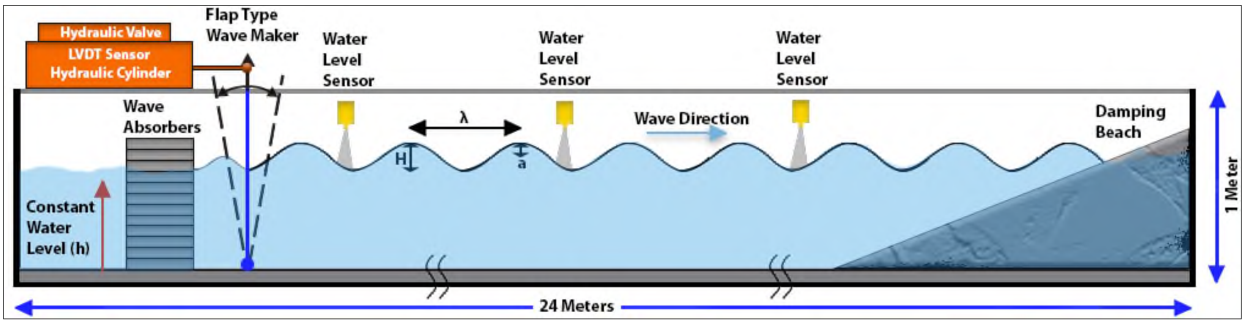

Figure2. Physical structure of wave channel

The visual representation of the wave channel in the laboratory is provided in Figure 3. The visual includes a hydraulic unit, hydraulic cylinder, hydraulic valve, flap type actuator, and wave dampers.

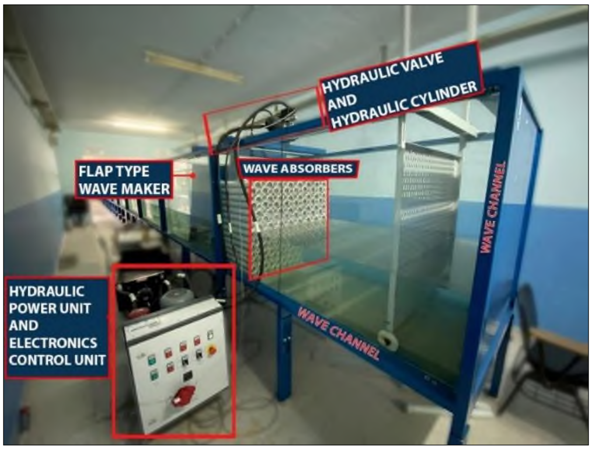

Figure 3. View of wave channel

2.1. System Model

It is crucial to model and understand the behaviors of hydraulic systems with complex mathematical models. Properly modeling the behaviors of such systems enhances the effectiveness of design and optimization processes. At this point, the "System Identification Toolbox" in Matlab/Simulink software provides a powerful and flexible tool for obtaining dynamic models of various systems. Particularly, the black box modeling approach is of critical importance when direct knowledge about the internal structure of the system is lacking or when the physical modeling of the system is challenging [22]. When creating a model of a physical system, the methods of white box, gray box, and black box can be used. Black box refers to the process of creating a mathematical model of a system using input-output data. This approach is particularly used in modeling systems with complex and unknown dynamics [23].

A LabVIEW interface has been developed to obtain the necessary data for creating the black box model of the system using the "System Identification Toolbox" in Matlab/Simulink. The front panel of the LabVIEW software is shown in Figure 4. "When examining the GUI presented in Figure 4, it can be observed that the following functionalities are provided for user control of the position of the hydraulic cylinder: manual control of the analog output, adjustment of the amplitude and frequency parameters for three different sinusoidal signals to be applied, notifications for the start and end of data recording, and the configuration of the test duration.

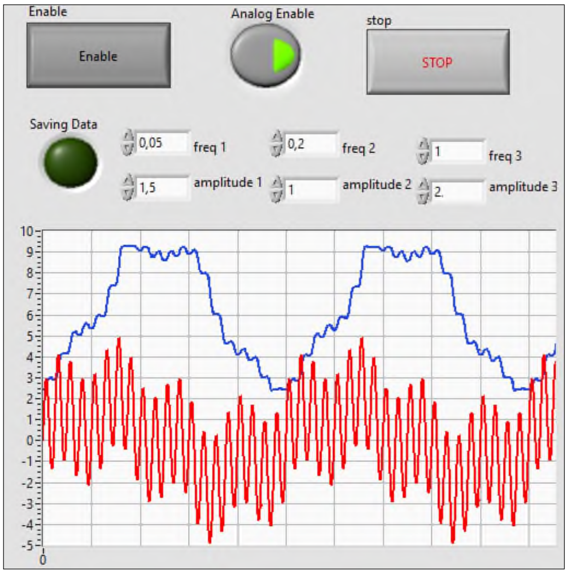

Figure 4. LabVIEW software front panel developed for system identification

The excitation signal, consisting of three different sinusoidal waveforms obtained from a sinusoidal signal generator, was applied to a hydraulic cylinder for a duration of 50 seconds without a control block, as shown in Figure 5. The positions of the hydraulic cylinder were recorded during a signal applied for 50 seconds.

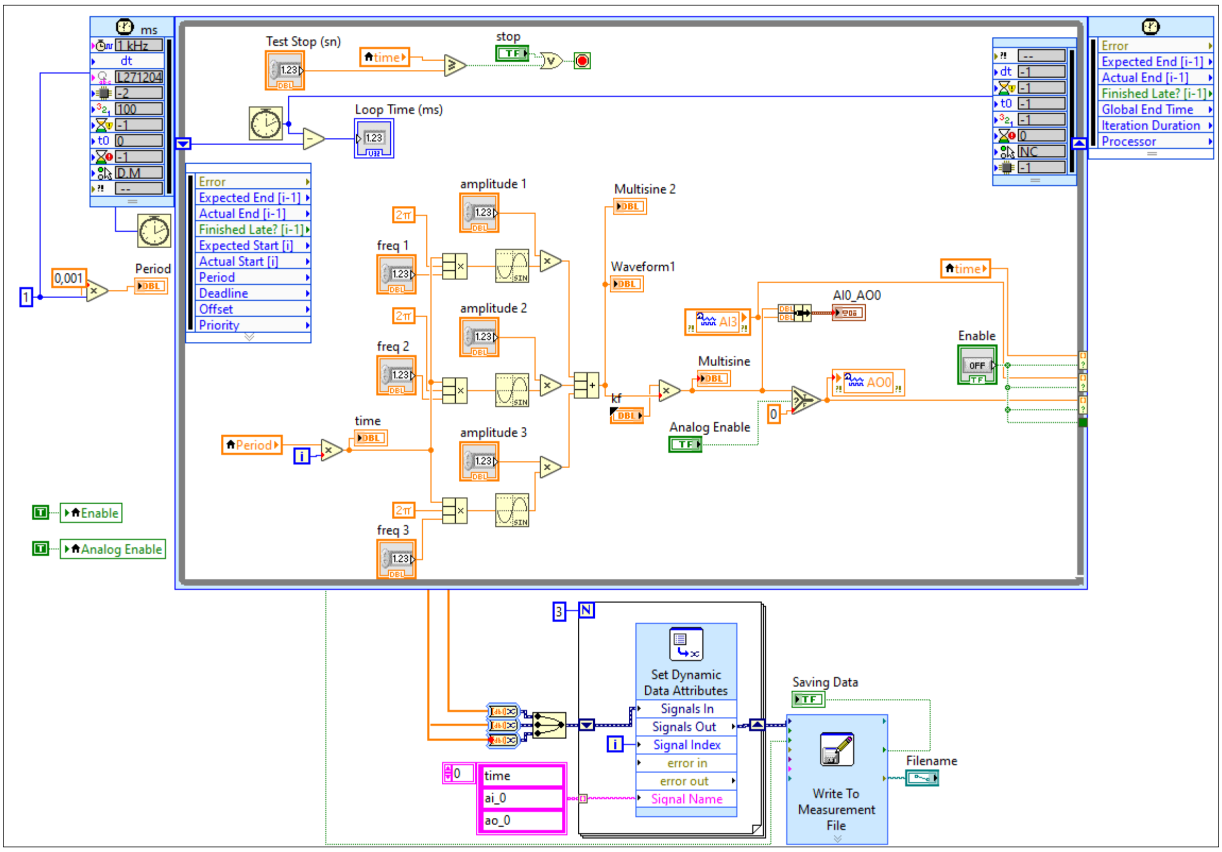

Figure 5. LabVIEW software block diagram developed for system identification

The stimulus signal applied to the hydraulic cylinder is given in equation 1. The representation of the signal in the Matlab software is given in Figure 6.

$$y = 1.5(sin2\pi(0.05 * t)) + 1(sin2\pi(0.2 * t)) + 2(sin2\pi(t)) \quad (1)$$

The measurement data obtained from the Linear Variable Differential Transformer (LVDT) sensor, which transmits the signal sent to the hydraulic valve and the position information of the cylinder, has been transferred to the Matlab software. Later, these signals were transferred to the "system identification toolbox" module with 1ms sampling intervals in the "Time domain" signal structure. The initial 40 seconds of measurement data, obtained for a data block, have been utilized for the prediction and construction of the model. The measurement data in the last 10-second segment was used to validate the created model. The transfer function model is provided in Equation (2).

$$y = \frac{61.34s^2 + 432s + 128.7}{s^3 + 5.892s^2 + 1.989s + 0.00164} \quad (2)$$

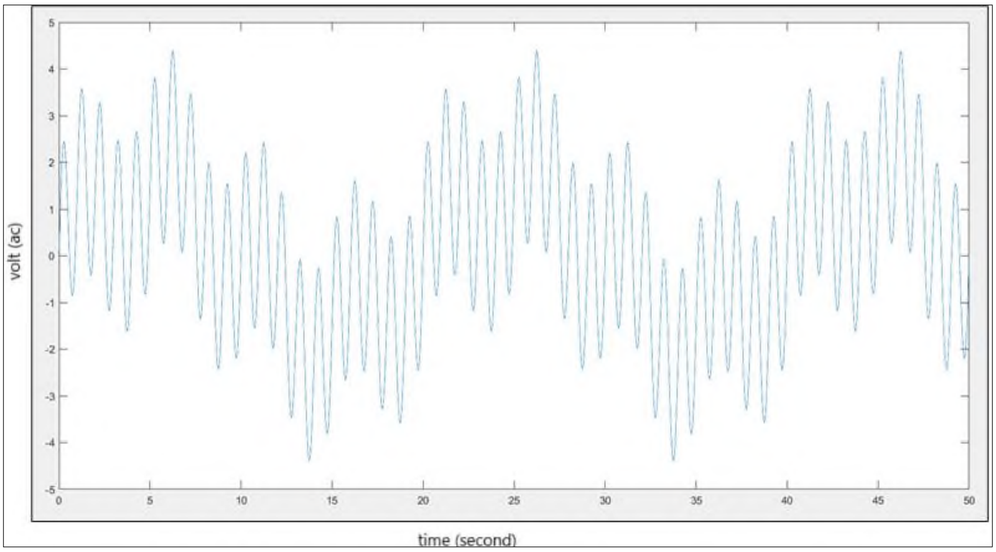

Figure 6. Stimulus signal

The obtained transfer function model has been transferred to the Matlab/Simulink software. The comparison graph in Figure 7 shows the 19-second (one period) comparison between the position information obtained from the transfer model using the same input signal and the position information obtained from the actual system. It is clearly evident that the hydraulic cylinder cannot exceed a maximum stroke value of 700 mm physically.

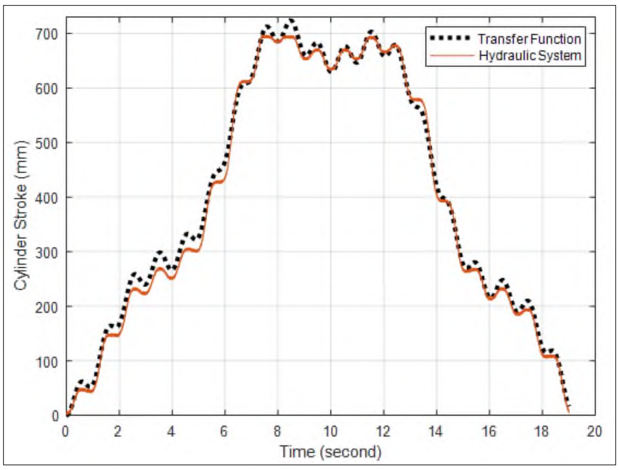

Figure 7. Transfer function output (black color), real system output (orange color)

2.2. Controller Design

PI control method is used as a controller for position control of the hydraulic cylinder. PI controller is a simple but effective control method. In order to control a system with a PID controller, first the control coefficients "K_p" and "K_i" are determined. There are many methods to determine these coefficients, the method used in this study is the Ziegler-Nichols method. In this method, the "K_i" term is first taken as "0" to determine these parameters. A step signal in terms of position is applied to the hydraulic cylinder. Then the "K_p" coefficient is increased until the smallest "K_p" coefficient is found at which the hydraulic cylinder oscillates in position. Once the "K_p" coefficient is determined, the "k_i" coefficient is calculated using the Table 2. "P" controller cannot provide zero steady state error and this can only be achieved with a "PI" controller. In addition, classical PD and PID controllers can lead to instability problems [24].

Table 2. Ziegler-Nichols Method Table [25]

Control Type	K_p	K_i	K_d
P	0.5Kcr	-	-
PI	0.55Kcr	(K_p*Tcr)/1.2	-
PID	0.6Kcr	(K_p*Pcr)/2	(K_p*Pcr)/8

The Ziegler-Nichols method was employed to determine the initial PI parameters of the hydraulic system, using the fundamental initial coefficients. The initial coefficient for K_p is found to be 0.2475 and the initial coefficient for Ki is found to be 0.14. Subsequently, a transition was made to the Matlab software and an appropriate block response was determined based on the initial coefficients found.

The transfer function model created in Simulink software and the complete model with the added PI block are depicted in Figure 8.

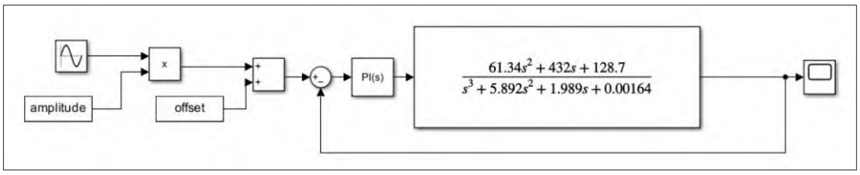

Figure 8. Matlab/Simulink hydraulic system model

The PI parameters have been calculated using the PID Tuner toolbox. According to this, the "K_p" coefficient has been obtained as 0.23023 and the "K_i" coefficient as 0.058609. The coefficient values were used in the LabVIEW software prepared for position control of the hydraulic system. The screenshot of the PID tuner with parameter adjustment is shown in Figure 9.

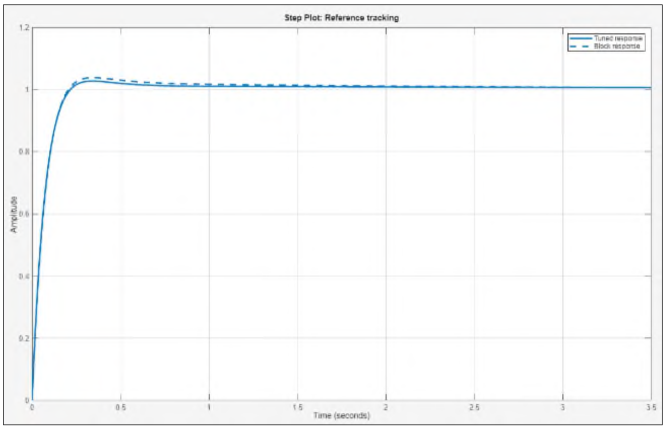

Figure 9. Matlab/Simulink PID Tuner

After determining the PI controller parameters using the Ziegler-Nichols and MATLAB/PID Tuner methods, a third approach, the meta-heuristic Genetic Algorithm (GA), was employed. The transfer function model was utilized in the MATLAB environment for determining the PI controller parameters using GA. For parameter optimization with GA, the following settings were used: population size of 50, generation count of 25, number of genes as 2, mutation rate of 0.01, crossover rate of 0.2, and ITAE as the fitness function. As a result of GA, the proportional gain k_p was determined to be 0.2989, and the integral gain ki was found to be 0.0023. The k_p and k_i values obtained using the three methods are presented in Table 3.

Table 3. PI Parameters

Method	K_p	K_i
Ziegler-Nichols	0.2475	0.14
Matlab/ PID Tuner	0.23023	0.058609
Genetic Algorithm	0.2989	0.0023

The stability analysis of the model, whose coefficients were determined and constructed in the Simulink environment, was performed using the Simulink software environment. The poles of the system have been determined as -5.5325, -0.3586, and -0.0008, and the stability of the system is depicted in Figure 10.

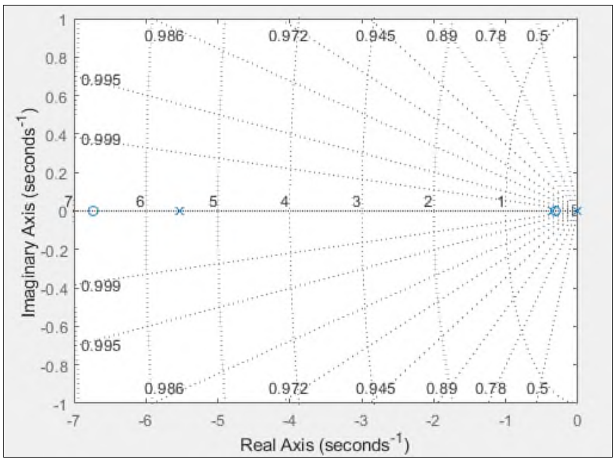

Figure 10. Stability analysis of transfer function

2.3. Position Control of Hydraulic System

The front panel for controlling the hydraulic cylinder at the desired frequency and voltage is provided in Figure 11. The user interface contains information about the frequency, amplitude, and offset of the sinusoidal signal to be applied to the hydraulic cylinder. There is a graphical monitoring screen available to display the applied reference signal and the obtained reference signal together. Furthermore, the user has the ability to select the data writing method for data recording.

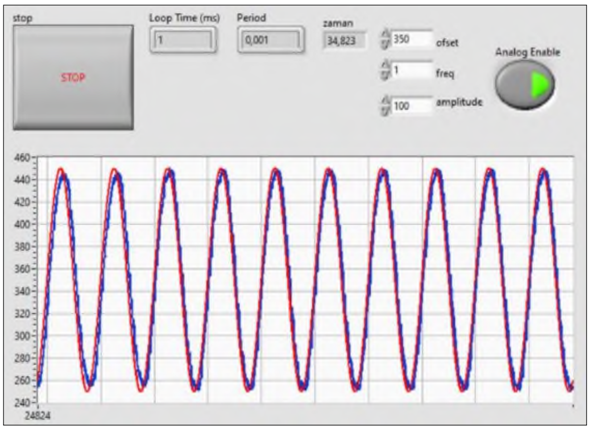

Figure 11. Developed a LabVIEW program for the front panel

The LabVIEW programming interface, which was created for the user, can be seen in Figure 12. The software loop speed has been set to 1 millisecond through the timed loop cycle. The developed software consists of four components. In the first section, a sinusoidal signal reference was generated as a function of time. The voltage signal obtained from the LVDT sensor integrated into the hydraulic cylinder was used to generate position information in the second section. The third section contains the PI block used for position control of the cylinder. A PI loop has been created in the LabVIEW software library without using the pre-built "PID" block. In the fourth section, the data has been transferred to a graphical interface for the user.

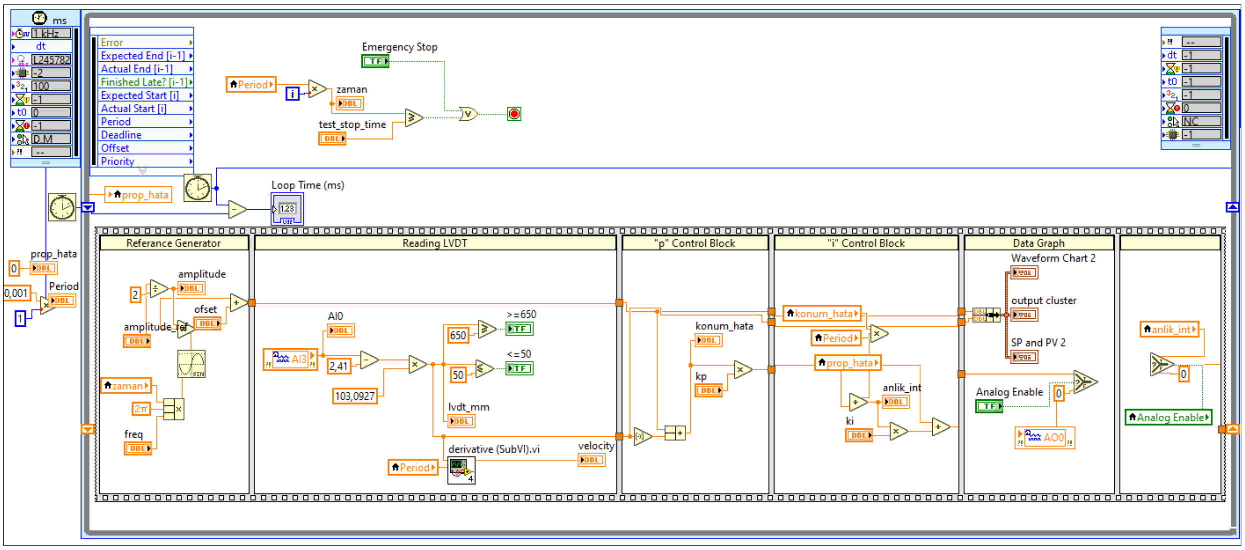

Figure 12. Developed a LabVIEW program for the back panel

2.4. Wave Generation

The flap-type wave generator, driven by a hydraulic cylinder located in the wave channel, has been operated at various water depths. A stimulating signal with a frequency of 0.8-1.0Hz has been sent to the hydraulic proportional valve. A program has been developed in LabVIEW software to enable real-time visualization and recording of waveforms resulting from this. This program records data from sensors at intervals of 32 milliseconds, which is the response time of the sensors. The front panel of the Labview program created for real-time wave measurement is provided in Figure 13. Three sensors are used for wave measurement in the wave channel.

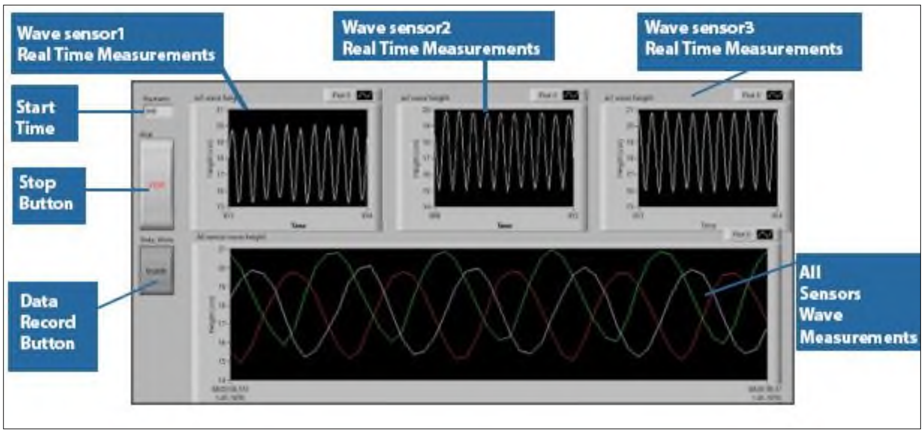

Figure 13. LABVIEW program front panel developed for real-time wave measurement

In the program structure given in Figure 14, both real-time measurement from three channels and recording of wave data in the desired file format are ensured.

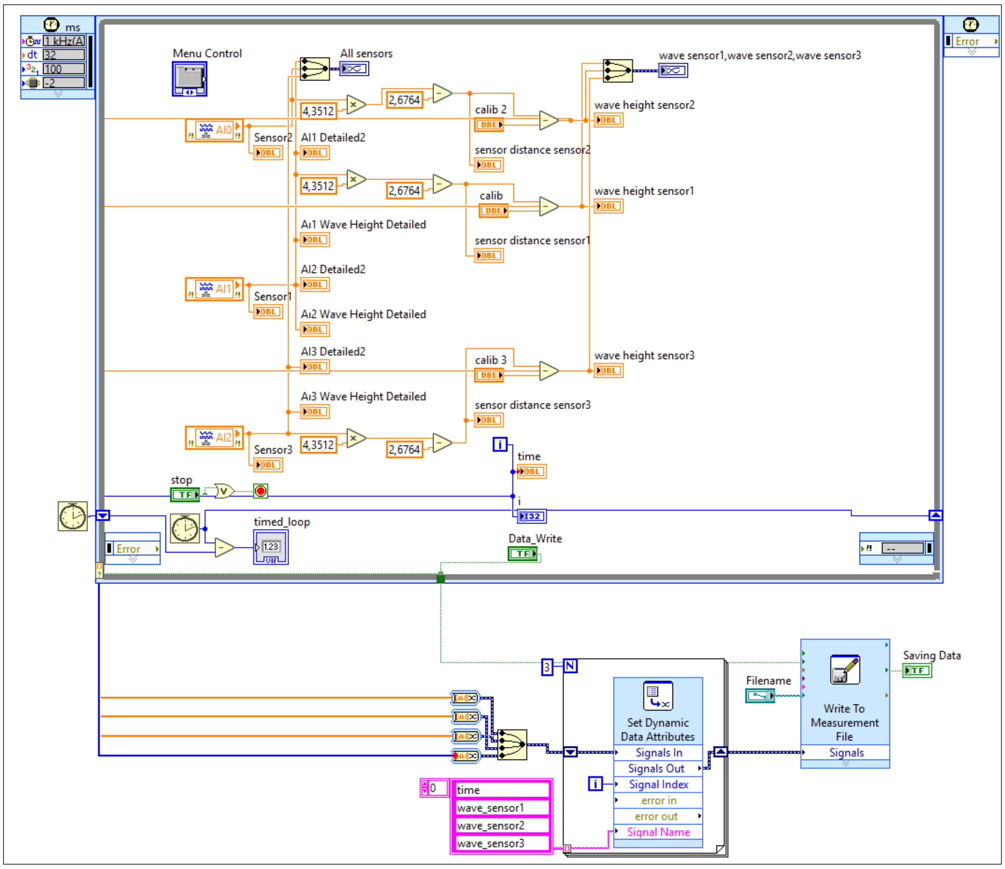

Figure 14. LABVIEW program back panel developed for real-time wave measurement

3. EXPERIMENTAL RESULTS

3.1. Step response analysis

The PI controller parameters determined using Ziegler-Nichols, MATLAB/PID Tuner, and Genetic Algorithm were implemented on the hydraulic system via LabVIEW software. The real-time measurement results obtained are shown in Figure 15.

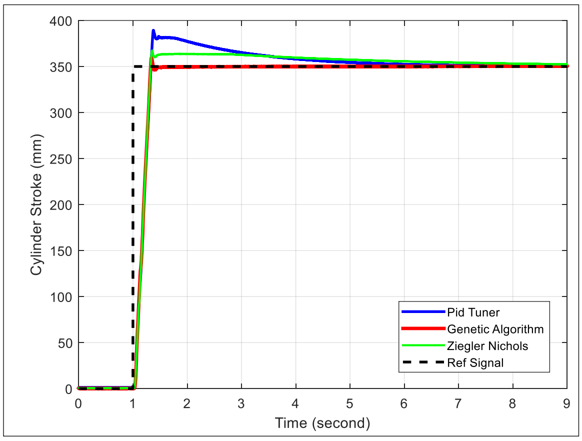

Figure 15. Step response

The controller parameters determined using Ziegler-Nichols, MATLAB/PID Tuner, and Genetic Algorithm were applied to the hydraulic cylinder system located in the wave channel, achieving position control of the cylinder. Based on real-time measurement results obtained from the hydraulic system with the applied controller parameters, the rise time was calculated to vary between 1.282 and 1.289 seconds, the settling time ranged from 1.626 to 8.508 seconds, the steady-state error was between 0.139 and 2.24 mm, and the overshoot ranged from 2.72% to 11.42%. Additionally, to demonstrate computational indicators of control performance, the root mean square error (RMSE), the mean absolute error (MAE), and the integral of time-weighted absolute error (ITAE) criteria are utilized as defined in Equation (3). A comparison of controller performance, calculated based on real-time measurement results obtained using the three methods, is presented in Table 4.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(e(t))^2}\ , \quad MAE = \frac{1}{N}\sum_{i=1}^{N}|e(t)|\ , \ ITAE = \int_0^T t\ |e|dt \tag{3}$$

Table 4. The controller performance comparison

Control Type	Rise Time(s)	Settling Time(s)	Steady-State Error (mm)	Over Shoot (%)	RMSE	MAE	ITAE
Ziegler-Nichols	1.282	8.508	2.240	4.97	0.4556	13.7029	34.765
Matlab/PID Tuner	1.289	6.704	0.13	11.42	0.4629	14.3182	28.705
Genetic Algorithm	1.285	1.626	0.464	2.74	**0.4458**	**7.2593**	**8.755**

The ITAE based results of Genetic Algorithm based PI showed an improvement of 74.82% and 69.50%, compared with Ziegler-Nichols and Matlab/PID Tuner, respectively. The RMSE based results of Genetic Algorithm based PI showed an improvement of 2.15% and 3.69%, compared with Ziegler-Nichols and Matlab/PID Tuner, respectively. The MAE based results of Genetic Algorithm based PI showed an improvement of 47.02% and 49.30%, compared with Ziegler-Nichols and Matlab/PID Tuner, respectively.

3.2. Sinus response analysis

The user controls the hydraulic system with a sinusoidal signal to generate regular-form waves in the wave channel. At this point, the parameters of the 'PI' controller, determined using the genetic algorithm, were applied to both the hydraulic system and the transfer function model in the MATLAB/Simulink environment. The position responses corresponding to the desired position control signal are shown in Figure 16.

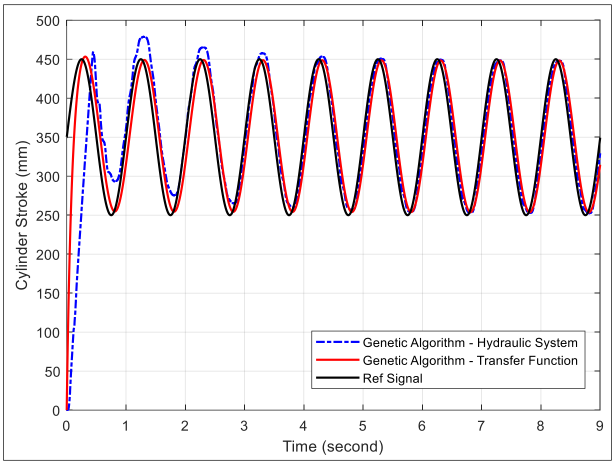

Figure 16. Transfer function output (red color), real system output (blue color), reference (black color)

Based on the calculations performed using the measurement results obtained from the control structure applied in real-time to the hydraulic system with the genetic algorithm, the ITAE was found to be 58.264, the MAE was 22.1941, and the RMSE was 0.5765.

3.3. Regular wave measurements

The hydraulic cylinder system and wave flap in the wave channel are controlled using the PI control method. The hydraulic cylinder system in the wave channel and the flap-type wave maker are controlled using the PI control method. According to the experiment presented in Table 5, the measurement results obtained from the sensor used for wave measurement, the stroke value of the hydraulic cylinder, and the constant water level data have been provided for a 1 Hz control signal.

Table 5. Wave Tank Experiment Results-I

Constant Water Level (h)	Hydraulic Cylinder Total Stroke	Wave Height (H), Hydraulic Cylinder Frequency
40 cm	50 mm	1 cm ,1 Hz
40 cm	100 mm	2 cm ,1 Hz
40 cm	150 mm	3 cm ,1 Hz
40 cm	200 mm	4 cm ,1 Hz
50 cm	50 mm	1 cm ,1 Hz
50 cm	100 mm	3 cm ,1 Hz
50 cm	150 mm	4 cm ,1 Hz
50 cm	200 mm	7 cm ,1 Hz
60 cm	50 mm	2 cm ,1 Hz
60 cm	100 mm	4 cm ,1 Hz
60 cm	150 mm	7 cm ,1 Hz
60 cm	200 mm	10 cm ,1 Hz

The hydraulic cylinder system in the wave channel and the flap-type wave maker are controlled using the PI control method. According to the experiment presented in Table 6, the measurement results obtained from the sensor used for wave measurement, the stroke value of the hydraulic cylinder, and the constant water level data have been provided for a 0.8 Hz control signal.

Table 6. Wave Tank Experiment Results-II

Constant Water Level (h)	Hydraulic Cylinder Total Stroke	Wave Height (H), Hydraulic Cylinder Frequency
40 cm	50 mm	1 cm, 0.8 Hz
40 cm	100 mm	1,6 cm, 0.8 Hz
40 cm	150 mm	2,4 cm, 0.8 Hz
40 cm	200 mm	3 cm, 0.8 Hz
50 cm	50 mm	1 cm, 0.8 Hz
50 cm	100 mm	2 cm, 0.8 Hz
50 cm	150 mm	3 cm, 0.8 Hz
50 cm	200 mm	5 cm, 0.8 Hz
60 cm	50 mm	1,5 cm, 0.8 Hz
60 cm	100 mm	3 cm, 0.8 Hz
60 cm	150 mm	5 cm, 0.8 Hz
60 cm	200 mm	7 cm, 0.8 Hz

4. CONCLUSIONS

In the conducted study, the position control of a hydraulic cylinder was utilized to generate a regular waveform in a wave channel. Water waves were created by a flap-type wave generator, which was fixed to the wave channel floor and driven by the hydraulic servo cylinder.

The parameters of the PI controller used in the position control of the hydraulic servo cylinder were determined using different methods. First, the Ziegler-Nichols method was experimentally applied directly to the hydraulic system. Second, using the model structure developed through the black-box approach, the parameters were determined via simulation in the MATLAB environment using MATLAB/PID Tuner and Genetic Algorithm. These parameters were then applied to the hydraulic system, and the accuracy of the developed model was validated.

The control signals applied to the wave channel were selected with frequencies of 0.8 Hz and 1 Hz, and the resulting wave data was recorded. The water level in the channel was maintained at a constant height of 40-50-60 cm for both signal structures, and the same control signal was applied in different frequencies. As a result, it has been determined that the effect of the generated water waveforms is dependent on the frequency of the applied control signal, even if all conditions are the same. It has been observed that as the frequency increases, the height of the water wave increases and directly affects the water level in the wave channel.

Furthermore, it has been determined that the difference between water waves generated at frequencies of 0.8 Hz and 1 Hz is at most 3 cm at water levels of 40-50-60 cm. Additionally, it has been established that a maximum wave height of 10 cm can be created with the control signal applied at a water level of 60 cm. In this study, the position control of a hydraulic servo cylinder was implemented using a PI controller to generate regular water waves in a wave channel. The position control of the hydraulic cylinder is performed in a closed loop, while the regular water wave control is performed in an open loop. In future studies, it has been evaluated that the position control of the cylinder and the wave control can be fully implemented in a closed-loop system, and the water level in the wave channel can be continuously measured and transferred to the controller as an input parameter for the wave. In this study, the application of black-box modeling and PI control methods was carried out on a physical wave channel for controlling wave generator systems, particularly in systems where control is provided by complex hydraulic structures.

Declaration of Ethical Standards

The authors declare that the study complies with all applicable laws and regulations and meets ethical standards.

Credit Authorship Contribution Statement

Autor 1: Writing, design, experiments, results analysis; Autor 2: Design, experiments, results analysis; Autor 3: Writing, design, editing, supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The findings from this study are available for use by other researchers.

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