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Fluid pressure optimization of a PID-controlled hydraulic jack for enhanced lifting efficiency and stability

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Abstract

Hydraulic and mechanical jacks are widely used for lifting applications but face limitations in efficiency and load handling. Despite being powerful, hydraulic jacks are prone to pressure loss and fluid leakage under static load, while mechanical systems lack automation and practicality. This research presents a hybrid hydraulic jack system integrating a Direct Current (DC) motor-driven screw actuator and Proportional Integral Derivative (PID) control for adaptive fluid pressure regulation. The purpose of this research is to develop an automatic hydraulic jack that integrates mechanical and hydraulic systems to improve the efficiency of load lifting time and reduce the risk of fluid leakage due to prolonged static pressure. The system was tested under three different loads: 90 kg, 110 kg, and 130 kg, with corresponding pressure setpoints of 170, 195, and 223 Pounds per square Inch (psi). Using the Ziegler–Nichols tuning method, the PID controller achieved high accuracy with error deviations of 1.1 psi, 0.1 psi, and 1.5 psi, respectively. These results represent a 95–99% precision rate in pressure regulation, compared to uncontrolled systems. The findings demonstrate the ability of the system to maintain pressure stability under varying load conditions, therefore reducing the risk of leakage and mechanical fatigue. This PID-based jack offers a cost-effective and efficient alternative to conventional power-pack hydraulic systems, particularly in mobile or resource-constrained applications.

Keywords:
PID control, hydraulic jack, push rod screw, fluid pressure

Nomenclature:

P	: Pressure, Pa, N
F	: Force, N
A	: Cross-sectional area, m^2
ω	: Angular motor speed, rad/s
τ	: Torque, Nm
K_u	: Ultimate gain value
T_u	: Ultimate periode, s
K_p	: Proportional gain
K_i	: Integral gain
K_d	: Derivative gain

Abbreviation:

PID	: Proportional Integral Derivative
psi	: Pounds per square inch
DC	: Direct Current
COG	: Centre of Gravity
MPC	: Model Predictive Control

1 Introduction

Lifting equipment plays a crucial role in transporting heavy objects, including goods, materials, and people. One such tool is the jack, which is commonly used to lift vehicles or other heavy loads [1]. In its application mechanism, the force changes according to the type of jacking system used. In general, jacks can work using a hydraulic system, which relies on Pascal's law to pump liquid, or a mechanical system by turning screws [2]. Hydraulic lifting systems rely on the force generated by the pressure generated by the liquid (generally a high-viscosity liquid) [3]. The way a hydraulic system works is that two connected cylinders receive the same pressure according to the principle of Pascal's Law. But since force is the result of pressure multiplied by cross-sectional area, the cylinder with the larger area will produce a greater force, with the same pressure on both cylinders. [4].

Examples of jack use can be found, such as in the automotive industry, where jacks are used to help lift cars so that car technicians and mechanics have more space to repair or have easy access to carry out various repair activities under the vehicle. In automotive, hydraulic jacks have the advantage of being more efficient in terms of power compared to mechanical jacks, but mechanical jacks have more long-term durability [5].

Although most commonly seen in the automotive world, jacks are also used in a variety of mechanical applications, such as industrial machinery (excavators, forklifts, etc.) or car washes that use hydraulic jacks to assist with maintenance and washing of the undercarriage. The types most commonly encountered in everyday life are scissor jacks (mechanical jack implementation) and bottle jacks (hydraulic jack implementation) [6]. Both of these methods have their disadvantages. Hydraulic systems, although capable of lifting heavier loads with less power, are prone to problems such as oil leakage, especially when the load is held for a long time [7, 8]. On the other hand, mechanical systems are less efficient as they require greater manual labor [9]. With the development of technology, innovations are needed that allow the jack to work automatically and efficiently, such as incorporating control algorithms to help the performance of the jack. In this case, the DC motor can be a medium for applying control methods such as PID, like the previous research [10, 11]. The selection of the PID control method in this study is because the results of PID implemented on DC motors have superior final results compared to other methods, such as fuzzy [12]. The DC motor, integrated with a PID controller, dynamically adjusts the fluid pressure to ensure stable and precise lifting performance [13].

By integrating hydraulic and mechanical work systems, this tool is expected to provide more precise control and reduce dependence on manual labor. The weight sensor (load cell) will detect the mass of the load to be lifted, while the oil pressure sensor will monitor the fluid pressure to keep it in line with the load requirements [14]. The DC motor actuator will control the single screw rod acting cylinder according to the required pressure, so that the load can be lifted with more precision and stability. Another advantage is that the controller used can also be used as a power pack for hydraulic jacks. This unit is generally used as a hydraulic pressure regulator that requires large electrical power [15]. The implementation of the PID control method in this system aims to improve the accuracy and stability of fluid pressure control, regulate pressure according to load variations, and minimize errors during the lifting process Through the integration of hydraulic and mechanical jacking systems, it is expected to improve process efficiency and extend the operational life of the device, by minimizing the potential for fluid leakage caused by long-term static pressure.

2 Research methodology

2.1 Methodology and implementation

The research method used in this research focuses on the development and testing of a fluid pressure control system on an automatic hydraulic jack using a push rod screw with the PID method. The size of the hydraulic cylinder used is an outer diameter of 7 cm with a hone tube length of 300 mm. Testing is carried out by lifting varying loads, such as 90 kg, 110 kg, and 130 kg, to observe the performance of the system in controlling fluid pressure. Each experiment is carried out twice to ensure replication and consistency of results. The control technique applied is PID, which is used to regulate fluid pressure in the system. PID parameter settings are done through programming in Arduino, which functions to control the DC motor connected to the screw rod based on feedback from the sensor. Data collected during testing is analyzed to evaluate the effectiveness of the control system. The test results are compared between the PID method and without PID to assess performance improvements. This study refers to several relevant sources [16] that discuss the design of electric vehicle steering using logic control, and also that develop a microcontroller-based unbalanced current monitoring system [17]

In the context of hydraulic system control, other relevant studies design PID controllers that are tuned for hydraulic systems [18, 19]. In addition, other studies that discuss the application of PID control in hydraulic systems can be found in articles that discuss hydraulic synchronous systems [20]. Thus, the method used in this study not only focuses on the development of tools, but also on the application of control techniques that have been proven effective in various industrial applications. The application of the research implementation flow is depicted in Fig. 1.

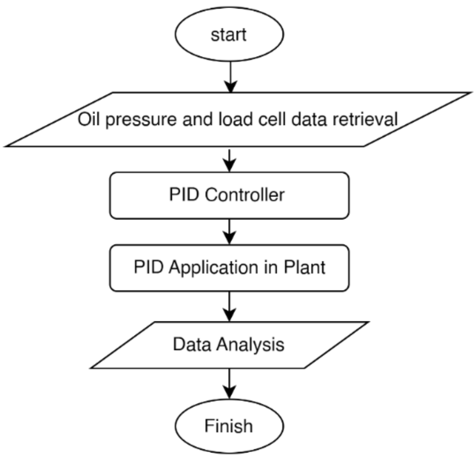

Fig. 1. Research method

2.2 PID

In this study, PID control is applied to control fluid pressure in an automatic hydraulic jack system [21]. PID control functions to minimize error, which is the difference between the actual output value and the desired set point value. Thus, PID control plays an important role in increasing system stability and reducing errors that occur. The PID control formula used in this study is stated in Eq. (1).

$$mv\ (t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) \tag{1}$$

Where $mv\ (t)$ is the PID control output, K_p is the proportional constant, T_i is the integral constant, T_d is the derivative constant, $e(t)$ is the error at time t. This equation can also be simplified to Eq. (2).

$$mv\ (t) = K_p\left(e(t) + K_i\int e(t)dt + K_d\frac{de(t)}{dt}\right) \tag{2}$$

Where $K_i = \frac{K_p}{T_i}$ and $K_i = T_d$. The implementation of PID control in this study aims to achieve stable fluid pressure in accordance with the specified set point [22, 23]. Adjustments to the parameters K_p, K_i, and K_d are made based on the results of testing and analysis to ensure optimal system performance.

2.3 PID tuning Ziegler Nichols

In this case, if analytical or computational methods are not possible, such as in some cases that do not have a mathematical model, for example, the plant system is very complex, where the mathematical model is not easy to obtain, then the Ziegler-Nichols tuning model can be used. In this study, a method was used to set the PID controller parameters using the Ziegler-Nichols tuning method [24]. This is beneficial for tuning the PID parameters because the Ziegler-Nichols model does not require a complicated mathematical model and is easy to apply. This method can be applied in two configurations: open loop and closed loop. In this study, we will focus on the closed-loop method. One of the steps in using this tuning approach is to configure the system by ensuring it operates in a closed-loop setup, with the PID controller initially set to default values (usually $K_i = 0$ and $K_d = 0$) [25]. The next step is to determine the Proportional Gain: Gradually increase the proportional gain value (K_p) until the system begins to oscillate stably. The point at which the system begins to oscillate is the ultimate gain value (K_u). Determining the Oscillation Period to measure the stable oscillation period, known as the ultimate period (T_u). This is the time required for one full oscillation cycle. And the last is to determine the PID Parameters at the K_u and T_u values to calculate the PID parameters using the formula specified in Table 1.

Table 1. PID tuning for a closed-loop system

Controller Type	K_p	K_i	K_d
P	K_u	0	0
PI	$0.9\ K_u$	$\frac{K_p}{T_u}$	0
PID	$0.6\ K_u$	$\frac{K_p}{2T_u}$	$\frac{K_p \times T_u}{8}$

2.4 Hydraulic

The use of the hydraulic system applied in this research is focused on controlling fluid pressure on automatic hydraulic jacks by utilizing the PID method as the controller [26]. This system utilizes Pascal's law, which states that the pressure applied to a fluid in a closed space will be transmitted evenly to all parts of the fluid. The pressure formula used to calculate pressure in the hydraulic system uses Eq. (3).

$$P = \frac{F}{A} \tag{3}$$

It is stated that: P is the pressure (in Pascals), F is the applied force (in Newtons), A is the cross-sectional area (in square meters). Hydraulic systems also utilize Pascal's law, which is expressed by Eq. (4).

$$P_1 = P_2\ or\ \frac{F_1}{A_1} = \frac{F_2}{A_2} \tag{4}$$

This implementation involves components such as hydraulic cylinders, pumps, and actuators (screw rods) that work in an integrated manner to produce the required force. In the control process, pressure sensors are used to monitor fluid pressure, and this data is compared with the desired set-point [27].

2.5 Hardware design

In the hardware design stage, a PID controller design is applied to the hydraulic jack. In addition, the implementation of the PID method uses the Arduino Nano Atmega328 microcontroller as a PID processor to regulate the pressure of the jack used. The description of the block diagram can be seen in Fig. 2. Description in Fig. 2 are the actuator is a DC motor that will regulate the rotation of the rod screw, the Plant is an area that will be controlled by PID, which in this case is a hydraulic jack, the sensor used is oil pressure to help read the pressure generated by the screw stem.

The hardware design used for the hydraulic system involves several key components that function to control and operate the hydraulic jack. Explanations regarding the hardware components used are presented in the following points. Linear Actuator Drive Application in the form of a DC Motor with specifications of 12 V and a maximum of 10 A. The screw pitch is 5 mm (0.005 m) and the motor speed is 500 rpm. The motor power is calculated (watts) with Eq. (5) [28].

$$P = V \times I \tag{5}$$

In equation (5) above, P is the symbol for power, V for voltage, and I for amperage. Meanwhile, regarding the angular speed of the motor ω [29], it is calculated by Eq. (6).

$$\omega = \frac{2\pi}{60} \times rpm \tag{6}$$

To calculate the torque generated when using a linear actuator using Eq. (7), and to calculate the force generated when using a linear actuator using Eq. (8).

$$\tau = \frac{P}{\omega} \tag{7}$$

$$F = \frac{\tau}{r} \tag{8}$$

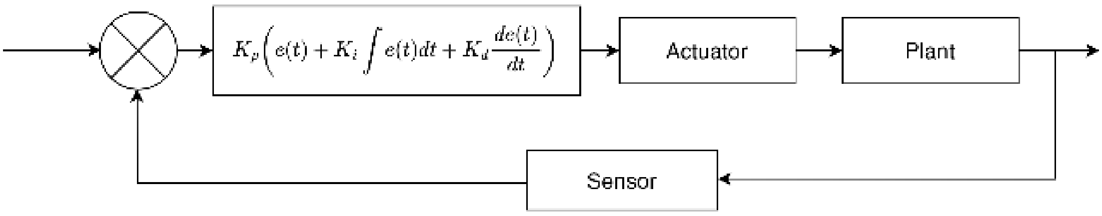

Fig. 2. Diagram block system

Another hardware used in the study is the Load Cell Sensor, which functions to measure the weight of the load above the jack cross-section. The Oil Pressure Sensor is used to measure fluid pressure in the hydraulic system. Arduino Uno R3: As the main controller that receives input from the sensor and provides output to the DC motor, and the BTS7960 Driver: as a controller of the speed and direction of rotation of the DC motor. Fig. 3 explains how the integration between the hardware implemented in this study.

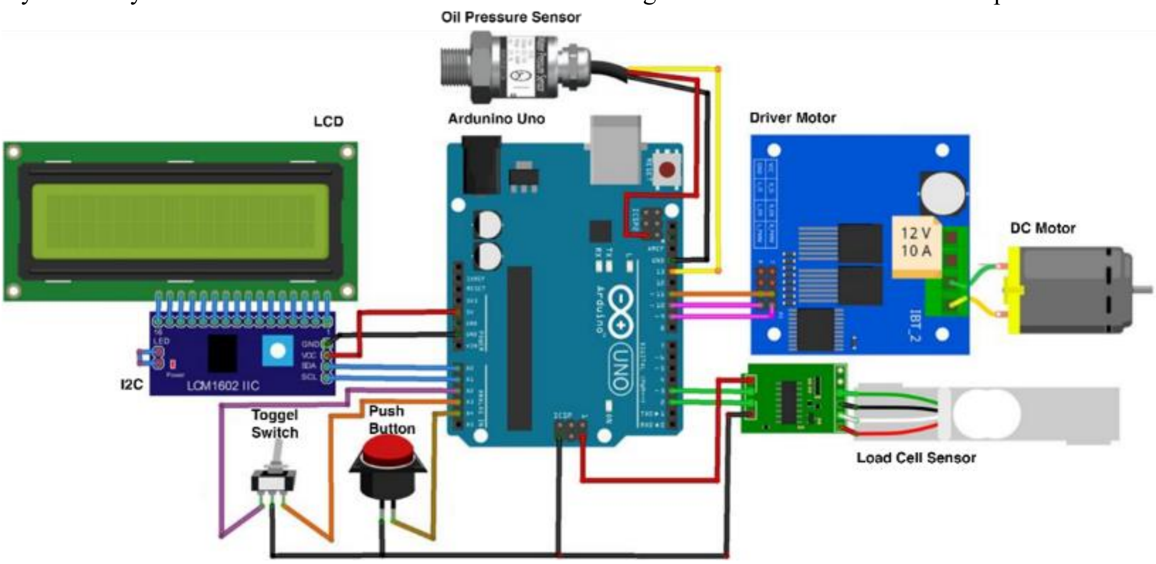

Fig. 3. Hardware design

2.6 Software design

The stage of research software design is done using the C++ programming language implemented through the Arduino Uno microcontroller. Fig. 4 shows the flowchart of the software algorithm that starts from several stages, namely setpoint value, control constant, and fluid pressure input from the oil pressure sensor and load weight through the load cell sensor, which then produces the expected output value using the PID control method.

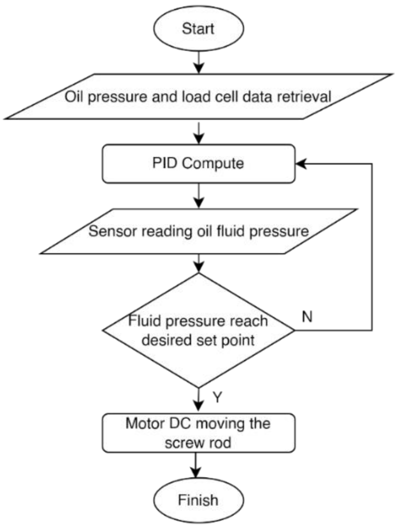

Fig. 4. Software design algorithm

The next step is calculating the control constant obtained from the tuning results using the Ziegler-Nichols method. The output generated from PID controller method is PWM value to control the screw rod using BTS9760 Driver, so that DC motor can move the screw rod on the hydraulic jack.

2.7 Material and equipment

The details of the components used in the pushrod-type automatic hydraulic jacks are described in this section. The following Table 2 shows the specifications of the fluid pressure regulator of the automatic hydraulic jack.

Table 2. Material and equipment

No	Equipment	Description
1	Motor DC	12 V
2	Od cylinder	Ø 7 cm
3	Oil pressure sensor	Max 30 MPa
4	Hose	R2AT ¼ - 6 mm x 100 cm
5	Od cylinder	Ø 4 cm
6	Load cell sensor	Max 200 kg
7	Frame	180 x 60 x 2 cm
8	Toggle switch	Activate the system
9	LCD	16x2 display
10	Microcontroller	Arduino Uno
11	Motor Driver	Driver BTS7960
12	Toggle switch	Reset the system
13	Toggle switch	Start the system
14	Power supply	12 V 10 A

3 Results and discussion.

In this work, we describe the results of designed prototype that was made and then installed on hydraulic jack system using an oil pressure sensor, load cell DC motor, pushrod screw, and Arduino microcontroller as the implementation of the PID system. An oil pressure sensor is installed on the prototype to detect the pressure that occurs in the fluid pressing the hydraulic jack. While the load cell is used to measure the load of objects in the ram. The value of the two sensors will determine the work of the PID system, when the load is detected by the load cell, the DC motor will move the push rod screw until the fluid pressure reaches the appropriate value, that is detected by the oil pressure sensor. All components of the closed-loop system are directly connected to the Atmega328 microcontroller as the data processing center to run the PID method.

Figs. 5 to 7 show the results of installing all aspects of the components on the hydraulic jack using the PID system. The load cell sensor is placed at the COG point of the frame so that the sensor can read more accurately, and the microcontroller can easily adjust the system input results.

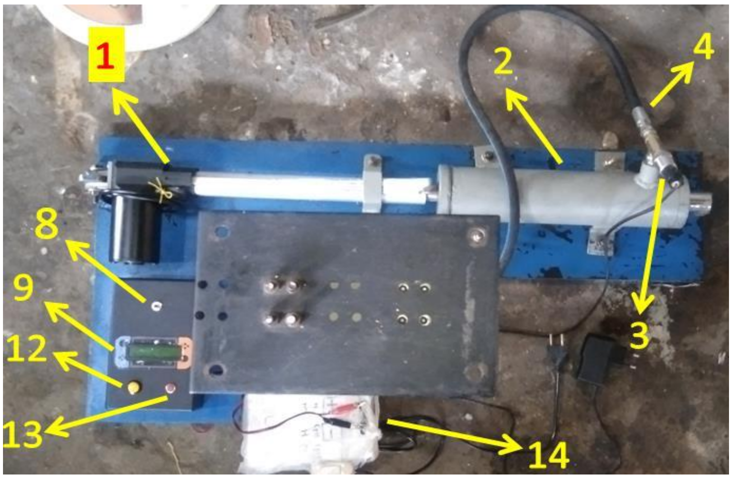

Fig. 5. Top-view mechanical system

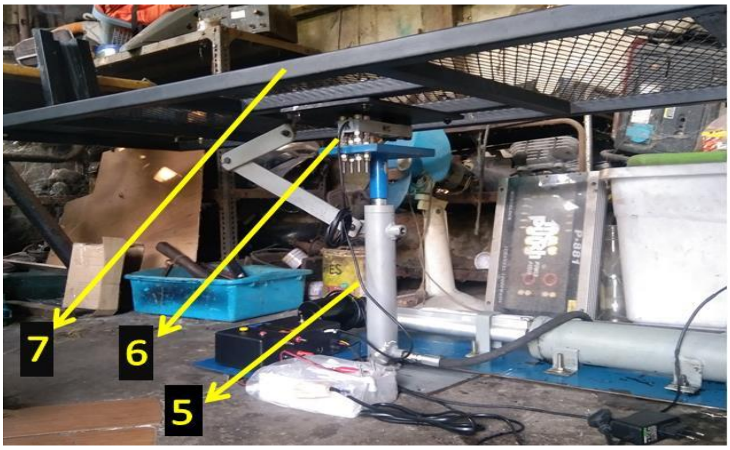

Fig. 6. Side view mechanical system

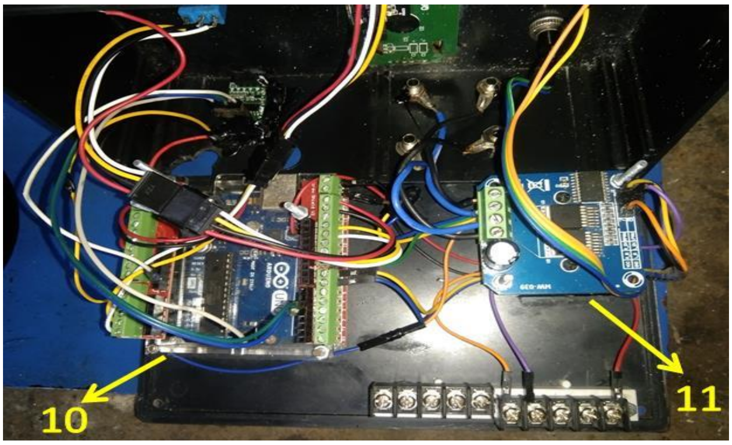

Fig. 7. Electrical component

The DC motor on the hydraulic jack is connected to the push rod bolts in the prototype component design. The numbering of components in Figs. 5 to 7 corresponds to Table 2.

3.1 Determining PID parameter

The PID controller uses Proportional (P), Integral (I), and Derivative (D) constants to control the dc motor as a rod screw pusher so that the system is able to reach a stable value according to the setpoint. This research applies the PID tuning process to determine the appropriate PID constant values for the hydraulic jack. In this study, the Ziegler-Nichols tuning method is used based on open-loop temperature data obtained from experiments. We use Ziegler-Nichols type tuning due to better performance than manual tuning; this has been proven in previous research using DC Motors as objects [30].

The fluid pressure data obtained from the sensors placed on the hydraulic jack is then converted into a graph in MATLAB so that the Ziegler-Nichols tuning process can be performed by giving the values of K_u and T_u, and generating a graph as shown in Fig. 8.

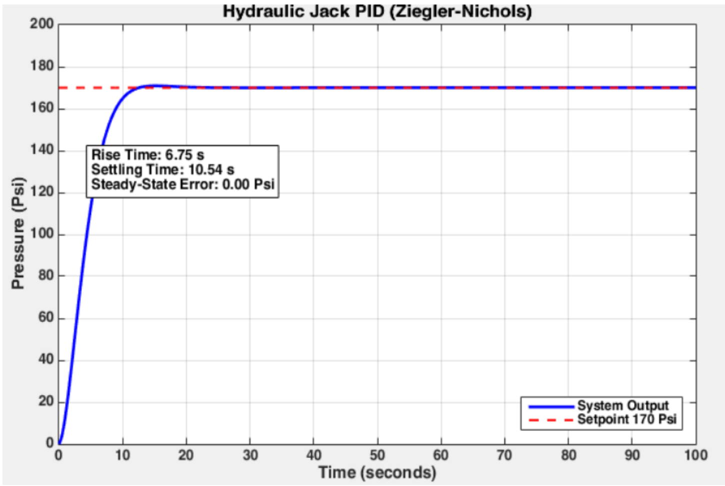

Fig. 8. Tuning the PID (Ziegler-Nichols) parameter in MATLAB

From the graph in Fig. 8, using the values K_u = 0.98 and T_u = 0.33. Using the types of PID controllers listed in Table 1, the appropriate PID controller parameters for the hydraulic jack system are obtained, namely $K_p = 0.6\,K_u$, $K_i = \frac{K_p}{2T_u}$, and $K_d = \frac{K_p}{2T_u}$. Through these values, a rise time of 6.75 seconds, a steady state time of 10.54 seconds, and a steady state error of 0.00 psi are obtained. Using these results as a reference, the proportional constant K_p = 11.59, the integral constant K_i = 0.98, and the derivative constant K_d = 0.8 are obtained, will be the values implemented on the Arduino Uno as the microcontroller of the PID controller system. Experiments using Matlab simulations, such as Fig. 8 using a 110 kg load, later several different loads will be used, namely 90 kg, 110 kg, and 130 kg, to distinguish how the results of this tuning work on a real plant hydraulic jack.

3.2 Result of the system test

The test is divided into two types of experiments to compare the performance of the PID controller in achieving predetermined set points. The first type of experiment is testing the lifting system using a hydraulic jack with a push rod screw without the PID method to control fluid pressure. In the experiment without using the controller method, there are 3 loads of different weights in each experiment (90 kg, 110 kg and 130 kg). The calculation of the F_2 variable used to control fluid pressure is entered into the Pascal formula, which can be seen in equation 3, which is derived into equation 4 as in the explanation of the previous section. Based on the results of the data obtained without the control method shows that the psi value of the resulting fluid pressure is quite far from the set point. Another thing that happens is that the unstable pressure causes an overshoot of the specified set point value.

In one example of an experiment, the fluid pressure setpoint value carried out in the first experiment with the use of a 90 kg load obtained the test data shown in Fig. 9, which obtained an average error value of 4.621 psi. The pressure value was obtained from an experiment conducted for ± 90 seconds as listed in Fig. 9.

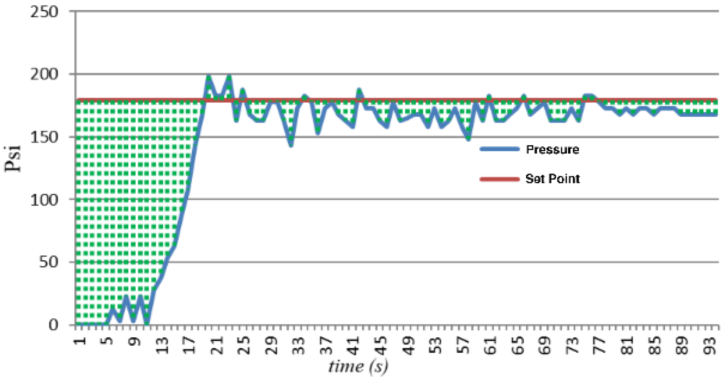

Fig. 9. Pressure with a load of 90 kg (no control method)

Fig. 10 shows the result of fluid pressure without the method in the second experiment using a load of 110 kg. The acquisition of test data shown in Fig. 10 has an average error value of -2.6 psi. Fig. 10 presents a graph of experimental data with a load of 110 kg without the PID control method, taken from data from one of the experiments.

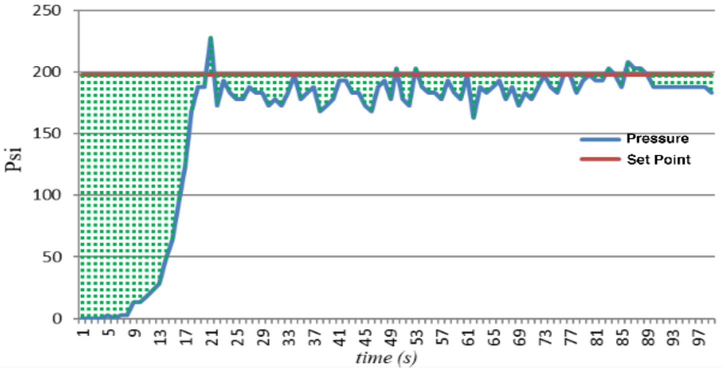

Fig. 10. Pressure with a load of 110 kg (no control method)

The last experiment was using a load of 130 kg, as shown in Fig. 11, which is a graph of the fluid pressure results without the method in the third experiment. The average error value of -9.8 psi in this experiment is the largest deviation from the predetermined set point. In Fig. 11 graph of 130 kg load data without PID control, the data taken shows that in achieving the specified pressure, the system is unable to reach the set point until the experiment ends.

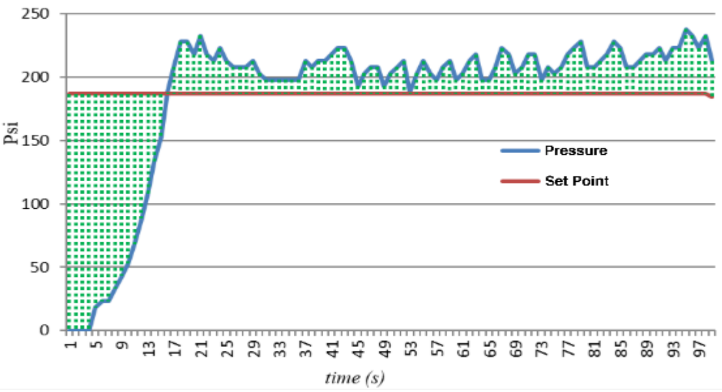

Fig. 11. Pressure with a load of 130 kg (no control method)

The PID method was previously tested on MATLAB, then validated through real-world tests; the results can be seen in Figs. 12 to 14. The PID test has a set point value of 170 psi for 90 kg, 195 psi for 110 kg, and 223 psi for 130 kg The test results of the average fluid pressure value in the 90 kg test, obtained the highest at a pressure of 178 psi and the lowest at a pressure of 169.2 psi with a lifting time range of 47 seconds. Based on experiments that use the parameters $K_p = 10.98$, $K_i = 2.73$, and $K_d = 1$get an average error value of 1.1 psi. The required fluid pressure value is obtained through Eq. 4, this result is a reference for experiments on loads of 90 kg, 110 kg, and 130 kg. Fig. 12 is a graph of the result data on one of the values of the 90 kg load PID experiment. One of the data taken shows that the value of accuracy in reaching the set point is quite long and difficult to reach the set point until the last second of lifting time.

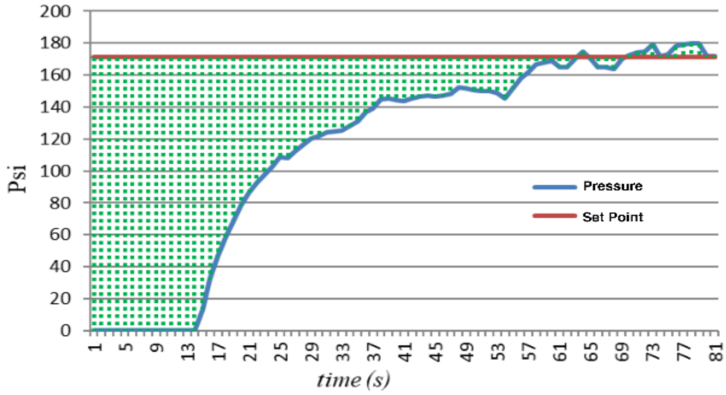

Fig. 12. Pressure with a load of 90 kg (PID)

With the same scheme through a 110 kg load with a fluid pressure set point of 195 psi, with input values of $K_p = 11.59$, $K_i = 0.98$, and $K_d = 0.8$, the average test results of the fluid pressure value obtained are highest at a pressure of 199.6 psi and lowest at a pressure of 192.1 psi, with a lifting time span of 100 seconds, the error obtained is 0.1 psi. The following is the result of the 110 kg PID experiment data shown in Fig. 13. In the figure, the increase experienced by fluid pressure does not experience significant oscillations, and it is easy to reach the required pressure value.

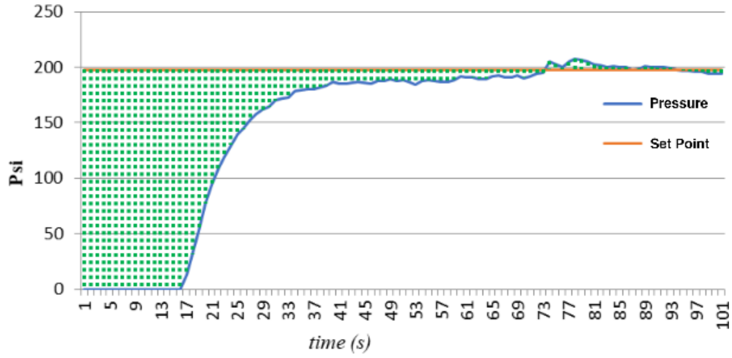

Fig. 13. Pressure with a load of 110 kg (PID)

The last test with the heaviest type of load, namely the weight value of 130 kg, with a fluid pressure set point of 223 psi, with input values $K_p = 8$, $K_p = 3$, and $K_p = 0.5$ has the average test results of the fluid pressure value obtained at the highest pressure of 230.4 psi, and the lowest is at a pressure of 215.5 psi with a lifting time span of 100 seconds. The following is the result of the 130 kg PID experiment data shown in Fig. 14. Based on the picture obtained with the use of parameters getting an average value of 1.5 psi error. Fig. 14 is a graph of PID experiment data with a 130 kg load, through one of the points taken showing the resulting pressure value has an oscillation value below the specified set point and does not experience overshoot.

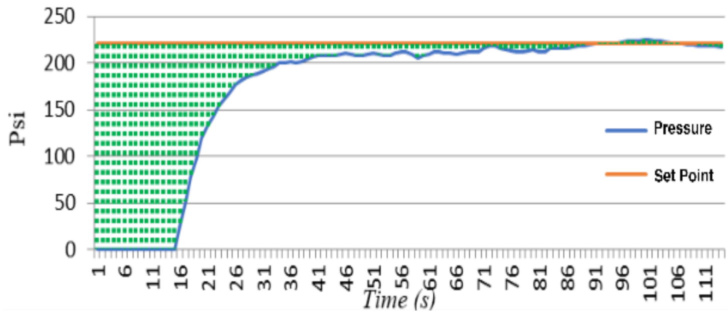

Fig. 14. Pressure with a load of 130 kg (PID)

To compare the performance between the use of PID and not in a clearer way, it can be seen in Figs. 15 to 17. It can be concluded that when using the PID method, the resulting graph has unstable oscillations, which is inversely proportional to the application of the use of the PID method. The overall oscillation is seen in the use of 90 kg, 110 kg, and 130 kg loads. But even though no oscillation occurs, the use of PID has a longer rise time compared to without the use of PID.

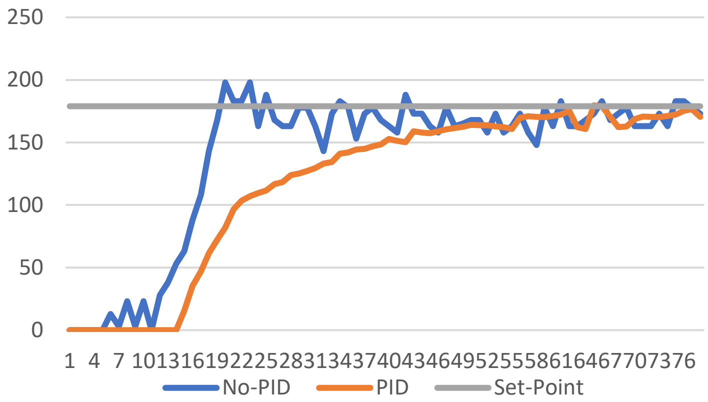

Fig. 15. 90 kg, Pressure PID and No-PID comparison

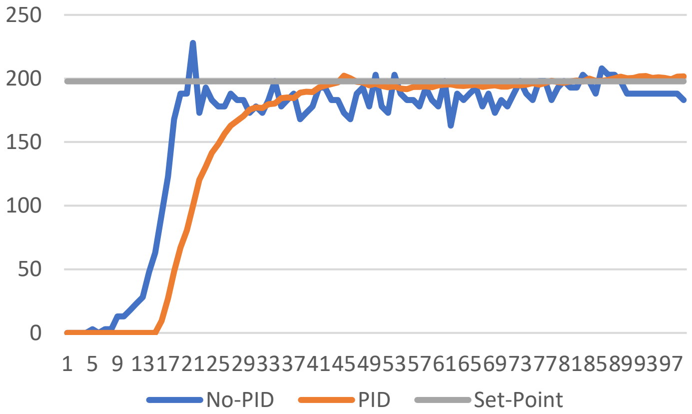

Fig. 16. 110 kg, Pressure PID and No-PID comparison

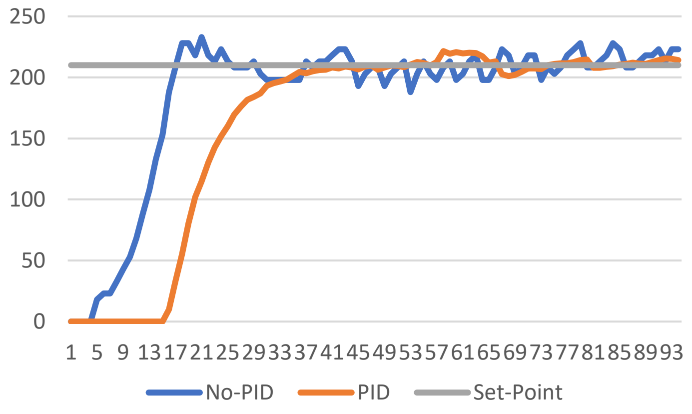

Fig. 17. 130 kg, Pressure PID and No-PID comparison

4 Conclusions

This study demonstrates the feasibility of a PID-controlled hydraulic jack system using a push-rod screw actuator and a 12V DC motor for lifting applications up to 130 kg. The integration of mechanical and hydraulic systems, guided by PID control, effectively regulates fluid pressure with high precision. Through experimental validation, pressure control errors were minimized to 1.1 psi (90 kg), 0.1 psi (110 kg), and 1.5 psi (130 kg), showing a significant improvement in pressure stability over conventional jacks without control systems. The use of Ziegler–Nichol's tuning provided an efficient means for determining optimal PID parameters. The consistent output temperatures and low-pressure deviation suggest robust operational reliability. For further research, enhancing lifting capacity and control performance should explore high-torque actuators and model-based PID tuning approaches such as MPC, Adaptive Control, or Internal Model Control (IMC).

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