JISSE

ISSN: 2636-4425

Journal of International Society for Science and Engineering

Vol. 5, No. 3, 73-82 (2023)

JISSE

E-ISSN:2682-3438

Modern Control Strategy Applied to Wave Power Hydraulic Simulator

Sara Fathy[1,*], Waleed abdel-Hady Oraby[2], Mohamed Hanafy[3]

[1] Teaching Assistant, Mechatronics Department, MTI University, Egypt
[2] Professor, Automotive & Tractors Department, Helwan University- Mataria Branch, Egypt t
[3] Assistant Professor, Mechanical Power Energy Department, Helwan University- Mataria Branch, Egypt

ARTICLE INFO

Article history:
Received:30-05-2023
Accepted:30-07-2023
Online:01-09-2023

Keywords:
Wave power
hydraulic simulator
renewable energy

ABSTRACT

The management of ocean Wave Energy Converters (WECs) controls what quantity of energy gets captured from waves. In order to improve the effectiveness and dependability of WECs and Power Take Off systems (PTOs), further research is required. WECs have the potential to become a substantial source of renewable energy. and to develop cost-effective solutions for commercial deployment. Throughout the past few decades, a spectrum of control techniques have been created and tested to maximize the gathered energy. In the current Paper, A wave power hydraulic model was created and compared to the existing test rig. to assess its validity to mimic the real system. Then a Modern control strategy was applied to the hydraulic simulator for maximum power harvesting. The maximum applied Pressure during the entire testing was 60 bars (the only change observed with higher pressure was accelerating the piston). In this research, an optimization technique is presented called A Particle Swarm Optimization (PSO), it is a Proportional-Integral-Derivative (PID) based method for optimizing the PID gain parameters while being applied to the model. The experimental results showed that the PSO-based optimization method did not improve the performance of the position control system in a significant manner.

Nomenclature:

Symbol	Description	Unit
α	Main spool angle	degree
A_a	valve throttling area (A to T)	m^2
A_b	valve throttling area (P to A)	m^2
A_c	valve throttling area (P to B)	m^2
A_d	valve throttling area (B to T)	m^2
A_P	Triangle throttling area	m^2
A_{tr}	Rectangular throttling area	m^2
$A(x)$	Valve Opening area	m^2
B	Bulk modulus	-
Cl	Radial clearance area	m^2
Clr	Radial clearance	M
C_d	Discharge coefficient	-
D	Spool throttling height	M

* Sara Fathy, Mechatronics Department, MTI University, Egypt, +201093281640, sara_bolarisso@hotmail.com

d_s	Main spool diameter	M
F_A	Force dependent on Solenoid A	N
F_B	Force dependent on Solenoid B	N
f_{ms}	Main spool friction coefficient	-
k_{ms}	Main spool spring stiffness = 22000 N/m [measured]	N/m
m_{ms}	Mass of the main spool= 0.0354 kg [measured]	Kg
P_A	Pressure on Port A	N/m^2
P_B	Pressure on Port B	N/m^2
P_T	Tank pressure	N/m^2
P_s	Supply pressure	N/m^2
ΔP	Pressure drop across the valve	Pa
Q	Port A flow rate to port T	m^3/s
Q_a	Port A flow rate to port T	m^3/s
Q_b	Port P flow rate to port A	m^3/s
Q_c	Port P flow rate to port B	m^3/s
Q_d	Port B flow rate to port T	m^3/s
X	Spool displacement	M
V_A	Oil volume in line A	m^3
V_B	Oil volume in line B	m^3
Y	Cylinder displacement	M
ρ	Oil density	kg/m^3

Abbreviation	Description
PTO	Power Take Off system
PSO	Particle Swarm Optimization
PID	Proportional-Integral-Derivative
EHSSV	Electrohydraulic Servo Solenoid Valve
FOFPID	Fractional Order Fuzzy Proportional Integral Derivative Controller
EHRA	Electro-Hydraulic Rotary Actuator
ID-BIABISMC	Incomplete Differentiation-Based Improved adaptive Back stepping Integral Sliding Mode Control
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
WECs	Wave Energy Converters
MPC	Model Predictive Control
LQR	Linear Quadratic Regulator
PDC3	Proportional-Derivative Complex Conjugate Control
SA	Singular Arc
PS	Pseudo-Spectral
ABC	Adaptive Back stepping Control
ARC	Adaptive Robust Control
IBHFLC	Improved Black Hole of Fuzzy Logic Controller
OWC	Oscillating Water Column
LVDT	Linear Variable Differential Transformer

1. Introduction

The increasing demand for renewable energy sources specially those last few decades has led to the exploration of several technologies, including wave energy converters (WECs) that can harness the power of ocean waves. WECs convert the kinetic energy of waves into electrical power. However, WEC efficiency and performance are profoundly affected by the type of power take-off (PTO) system used and the control method employed.

1.1. Wave Energy Converters (WECs):

WECs can be broadly categorized into two types: point absorber devices and oscillating water column (OWC) devices.

Point absorber devices use buoyant structures that move up and down with the waves, generating mechanical energy that can be converted into electricity. OWC devices, on the other hand, use a partially submerged chamber that captures the wave's energy as it enters and leaves the chamber, creating a pressure difference that drives a turbine to produce electricity.[2]

1.2. Power Take-Off Systems (PTOs):

Power Take-Off Systems are in charge of developing the WEC's mechanical energy into electrical power that can be delivered to the grid. The type of PTO system selected is determined by several criteria, including the type of WEC, wave conditions, and the required power generation. There are various types of WECs and PTO systems.[1]

The efficiency of WECs largely depends on the PTO system used. PTO systems can be broadly classified into four categories: hydraulic, pneumatic, mechanical, and electrical. Pressurized fluids are used in hydraulic systems to power a hydraulic motor, which in turn powers an electrical generator. Pneumatic systems use compressed air to drive a turbine, which generates electricity. Mechanical systems use gears or levers to convert the mechanical motion of the WEC into electrical power. Electrical systems use direct drive generators that convert mechanical energy into electrical energy.

Developing and testing of a large-scale wave simulator for point absorber PTO testing is less complicated than physical model of a system that behave similar to a wave while interacting with a particular PTO-system is difficult, especially when discrete type PTO-systems are taken into consideration. In addition to the high cost of constructing and examination PTO systems at sea.

The current paper focuses on the implementation of a wave simulator. Designing a system that behaves like a wave when it interacts with a certain PTO-system is problematic.

1.3. Methods for Modeling PTO systems:

-Analytical models: Analytical models are mathematical models that use equations to describe the behavior of the PTO system. These models can be simple or complex, depending on the level of detail required, and can provide useful insights into the behavior of the system.

-Numerical models: Numerical models use numerical methods to solve equations that describe the behavior of the PTO system. These models can be more accurate than analytical models and can provide detailed information about the system's behavior under different conditions.

-Finite element analysis (FEA): FEA is a numerical method used to simulate the behavior of complex structures. FEA is often used to model the mechanical components of a PTO system, such as the gears, bearings, and shafts.

-Computational fluid dynamics (CFD): CFD is a numerical method used to simulate the behavior of fluids. CFD can be used to simulate the flow of water around the wave energy converter and PTO system, which is crucial for understanding the system's behavior under numerous wave scenarios.

-Multi-body dynamics (MBD): MBD is a method used to simulate the motion of complex mechanical systems, such as the Power take off system. MBD could be used to mimic the motion of the PTO system's mechanical components, and how they interact with each other and the surrounding environment.

-Hybrid models: Hybrid models combine analytical and numerical methods to model the behavior of the PTO system. These models can be more accurate than analytical models while being less computationally expensive than numerical models.

These are several methods for modeling and simulating PTO systems, each with its advantages and disadvantages. The choice of method will depend on the complexity of the system and the level of detail required.[3], [4]

However, the effectiveness of wave energy converters (WECs) is influenced by the variable nature of the waves. Therefore, advanced control strategies are necessary to improve the efficiency and effectiveness of the WECs. Wave energy is an important source of renewable energy that is yet to be fully harnessed. Thus, efficient control strategies are required to improve their performance. In this paper, a hydraulic system Wave Power simulator was developed in order to determine the effectiveness of a modern control strategy applied on it. Her we present a model of the system and a suitable controller is developed.

The vast majority of wave energy converters are presently in the research and development stage. Some large-scale prototypes were developed and tested in real sea conditions, but there is yet no device that has reached commercial stage [5]

After we provide a detailed design, we carry out to the mathematical modeling and simulation part, results from the simulations generated very positive expectations.

The actual PTO dynamic performance then is verified through tests carried out on a test bench specifically designed for this purpose. Moreover, the validation tests results are used to verify the results of the simulations carried out with the MATLAB/Simulink model [6]

This paper proposes a model-based control strategy for a wave power hydraulic simulator that uses PSO to regulate the PID parameters for a better energy harvesting power take-off (PTO).

Wave power hydraulic simulator design and operation heavily rely on control strategy. Control strategies are employed in wave energy conversion systems to strengthen the wave energy converter's (WEC) capability and to guarantee dependable operation. The purpose of control strategies is to preserve the system's stability and dependability under a variety of operating situations while maximizing the energy harvested from the waves.

1.4. Control Strategies:

Modern control strategies have been widely studied and implemented in various renewable energy systems to improve their efficiency and reliability. In the case of wave power hydraulic simulators, advanced control strategies are crucial for ensuring accurate and efficient operation of the system. In this literature survey, we will review some of the recent research on modern control strategies applied to wave power hydraulic simulators.

-Model Predictive Control (MPC): is a well-known advanced control approach that has been extensively investigated for wave power hydraulic simulators. In a study by [7], an MPC-based control strategy was proposed for a wave energy converter (WEC) hydraulic simulator using AMESim which is a commercial software for modeling and analysis of multi-domain systems (SIEMENS)[7][8]. The proposed strategy was compared with some recently developed control methods as: proportional-derivative complex conjugate control (PDC3), and pseudo-spectral (PS) control, proportional-derivative (PD) and singular arc (SA), this has shown promising results by an efficiency of 72.58% compared to other controllers.

-Sliding mode control (SMC) : is another popular advanced control strategy that has been studied for wave power hydraulic simulators. In a study [9] , Adaptive robust control (ARC), adaptive backstepping control (ABC), disturbance-observer-based control, indirect adaptive backstepping control, Sliding mode control (SMC), and discrete sliding mode control have each been presented as multi-design controls. The (ID-BIABISMC) was then investigated, and the findings confirmed its effectiveness and superiority.

Also, a SMC-based control strategy was proposed in [10] for a hydraulic simulator of a wave energy converter for comparing the traditionally employed PI-based vector control with SMC which showed the superiority of SMC based strategy over outperformed traditional PI controller.

-Adaptive Control: This type of control strategy involves adjusting the control inputs according to the present operating conditions of the system as in [11] The adaptive sliding mode control strategy based on the back-stepping methodology was compared to the proportional integral derivative control strategy, and it was found that the adaptive back-stepping displacement can provide superior hydraulic cylinder displacement tracking control than the PID controller.

-Fuzzy control: is another modern control strategy that has been applied to wave power hydraulic simulators. Fuzzy control is a type of control strategy that uses fuzzy logic to create control rules that are based on imprecise or uncertain data. In the context of wave energy converters, fuzzy control can be used to optimize the control inputs based on various factors such as wave height, wave period, and power output.

One example of fuzzy control applied to wave power hydraulic simulators is the work by[1]. They proposed a Fuzzy controller optimized by the IBHFLC algorithm for a wave energy converter that utilized a fuzzy rule-based system to adjust the power take-off (PTO) conditions. When compared to alternative optimization approaches, such as PSO and conventional black hole algorithms, Fuzzy control was able to enhance performance. In general, as the reference speed changes, the applied fuzzy controller adapts to many reference speeds and becomes more robust, but the classic fuzzy controller is ineffective in speed tracking and power generation.

The work [8] is another example of fuzzy control. They suggested an approach for combining a fractional order PID (FOPID) controller and a fuzzy logic system, with the FOPID improving tracking, stability, and resilience of the system controlled by extending integral and derivative functions from integer order to non-integer order. The FOPID settings are adjusted using a fuzzy logic control system in response to time variant working conditions.

According to the comparison, the proposed controller produced a good tracking trajectory. When the rotary actuator changed direction, it could compensate for the altered external force and produce appropriate control signals at high cutoff frequencies. As a result, the suggested FOFPID controller has strong control competency not only for EHRA system applications but also for other complex requirement systems.

The author suggests that in case of future work, some adaptive laws will be investigated in order enhance performance even more and improve the system's applicability.

Overall, fuzzy control is a promising modern control strategy that can be applied to wave power hydraulic simulators to improve the efficiency and performance of wave energy converters by optimizing the control inputs based on imprecise or uncertain data.

-Linear Quadratic Regulator (LQR): is a popular control strategy that has been widely used to control the PTO system of point absorber WECs. LQR is an efficient optimum control method that involves adjusting the feedback gain to minimize the cost function. LQR is a state-space representation-based control method. of the system to design an optimal control law that minimizes a cost function. The cost function typically consists of a quadratic combination of the state variables and control inputs, and can be solved using the Riccati equation. LQR has been widely used in various control applications due to its simplicity, robustness, and ability to handle nonlinear systems. [12]

-Proportional-Integral-Derivative (PID): is widely utilized in control applications. The most frequent type of feedback is the proportional integral derivative (PID) controller. It was an indispensable part of early governors. Today, more than 95% of control loops in process control are PID, with the majority being

PI control. PID controllers are now found in almost every area where control is applied. PID controllers have seen significant technological advances, from mechanics and pneumatics to microprocessors via electronic tubes, transistors, and integrated circuits. The microprocessor has had a significant impact on the PID controller. Almost all PID controllers developed nowadays are based on microprocessors. This has created potential to provide new features such as automatic tuning, gain scheduling, and ongoing adaption.

-Particle Swarm Optimization (PSO):is a population-based optimization method inspired by bird flock social behavior. The algorithm is made up of a population of particles that travel across a search space in pursuit of the most efficient solution. Each particle's position and velocity are updated based on the best position determined by the particle and the best position found by the swarm.

The proposed method, PSO, is utilized to optimize the PID controller's parameters. In this research, we describe a PSO-based method for optimizing the PID parameters of a position control strategy.[13]

-Hybrid control strategies in my opinion are the future of control in general speaking, they utilize numerous control techniques to improve the system's overall performance. In the area of hydraulic wave power simulators and as the studies have shown us [7], [9], [11], [1] & [14] , hybrid control strategies can be applied to improve the effectiveness and power harvested from wave energy converters by combining different control techniques that are optimized for different operating conditions control. [15] & [16].

Overall, modern control strategies, such as MPC, SMC, Fuzzy, PSO, and hybrid control, have been widely studied and applied to wave power hydraulic simulators to improve their energy capture and stability. These advanced control strategies are crucial for ensuring the efficient and reliable operation of wave energy conversion systems.

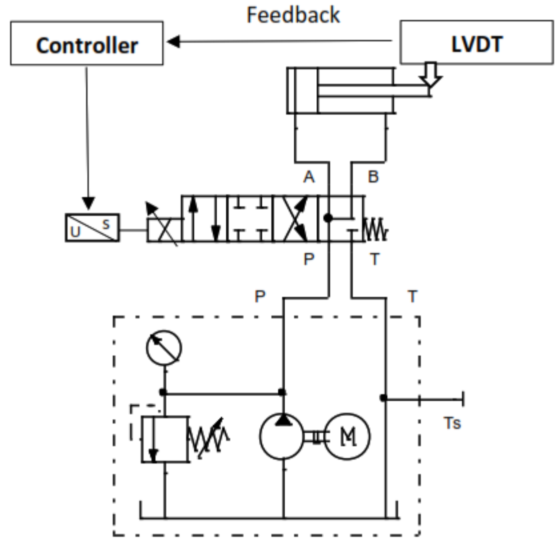

Figure 1: Schematic diagram that illustrates the Hydraulic system.

2. Mathematical Modeling and Simulation

The presented mathematical equations have been studied in order to describe the operation of an electrohydraulic wave power simulator. In SIMULINK software, these equations have been combined to create a computer program that simulates the electrohydraulic system. The various simulation parameters were achieved by experimentation and measurements.

For acquiring acceptable tracking performance from the electrohydraulic wave power simulator, we developed a mathematical model which is capable of describing the system dynamics.

2.1 System overview

The shown apparatus consists of a hydraulic cylinder connected with LVDT sensor, Controller, hydraulic servo solenoid valve integrated with an OBE (on-board electronics) amplifier, hydraulic unit. The hydraulic test rig in Figure.1 has been constructed to Investigate the valve spool displacement effect under various operating conditions, Study the valve response under different step input voltages & validate the simulation programs.

2.2 Equation of motion of the spool

Spool motion is governed by the solenoid force, the spring forces, the friction forces, the jet reaction forces and inertia forces. We found out that we can ignore The jet reaction forces in our current study. Therefore, the motion of the spool can be described as:

$$m_{ms}\ddot{x} + f_{ms}\dot{x} + k_{ms}x = F_A - F_B \tag{1}$$

2.3 Valve flow rate

The pressurized fluid flows through the valve due to spool displacement, the flow rate equation could be described as:

$$Q_a = C_d\, A_a \sqrt{\frac{2(P_A - P_T)}{\rho}} \qquad (2)$$

Where, Q_a is flow rate from port A to port T [m^3/s], C_d is discharging coefficient, A_a throttling area of the main valve (A to T) [m^2], P_A is Port A pressure [N/m^2], P_T tank pressure [N/m^2], ρ is oil density [kg/m^3],

$$Q_b = C_d\, A_b \sqrt{\frac{2(P_s - P_A)}{\rho}} \qquad (3)$$

Where, Q_b is flow rate from port P_s to port A [m^3/s], A_b throttling area of the main valve (P_s to A) [m^2], P_s is supply pressure [N/m^2].

$$Q_c = C_d\, A_c \sqrt{\frac{2(P_s - P_B)}{\rho}} \qquad (4)$$

Where, Q_c is flow rate from port P_s to port B [m^3/s], A_c throttling area of the main valve (P_s to B) [m^2], P_B port B pressure [N/m^2].

$$Q_d = C_d\, A_d \sqrt{\frac{2(P_B - P_T)}{\rho}} \qquad (5)$$

Where, Q_d is flow rate from port B to port T [m^3/s], A_d throttling area of the main valve (B to T) [m^2].

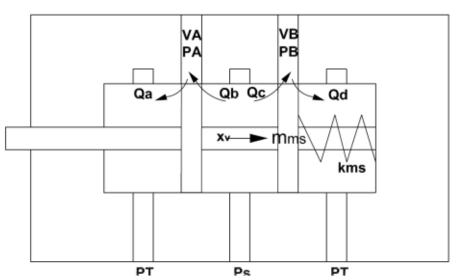

Figure 2: Valve functional scheme

2.4 Throttling area

The valve sleeve has a metering notch that provides a variety of flow rate profiles according to the given electrical command input to the valve as shown in Figure.3 (4WRP E H 6 C4 B 24 L-2X/G24 K0/A1 M)

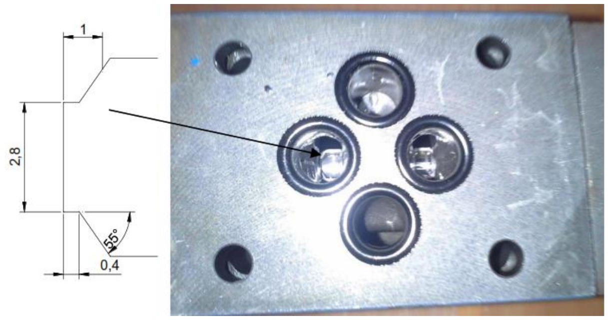

Figure 3: Valve throttling area for valve

$$A_a = A_c = \begin{pmatrix} x * 2.8 & 0 < x < .4 \\ x * 2.8 + x^2\ tan(55°) & .4 \le x < 1 \\ cl & x \le 0 \end{pmatrix} \qquad (6)$$

$$A_b = A_d = \begin{pmatrix} cl & x \ge 0 \\ x * 2.8 & 0 > x > -.4 \\ x * 2.8 + x^2\ tan(55°) & -.4 \ge x > -1 \end{pmatrix} \qquad (7)$$

$$cl = \pi d_s * clr \qquad (8)$$

Where, cl is radial clearance area [mm2], clr is radial clearance [mm] and ds is main spool diameter [mm].

2.5 Mathematical model of the hydraulic cylinder

The hydraulic cylinder is double acting double rode is divided into two chambers, each on connected to the EHSSV (port A and B) via pipes Figure.1 The modeling of the cylinder has been performed by considering the continuity equation applied to the flow, equation of motion of the piston and rod masses and the pressure force against the load.

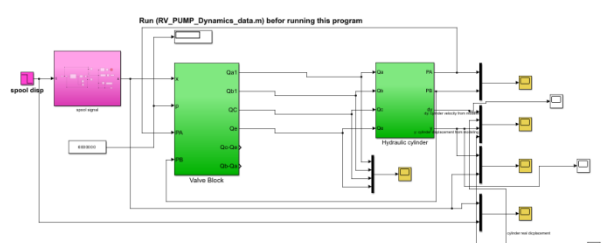

Figure 4 Simulink Block Diagram.

Applying the continuity equation to both chambers of the shown hydraulic cylinder V_A and V_B :

$$(Q_b - Q_a) - A_p \frac{dx}{dt} - Q_e = \frac{d}{dt}\left(\frac{V_A + A_p x}{\beta_e} P_A\right) \qquad (9)$$

$$A_p \frac{dx}{dt} + Q_e - (Q_c - Q_d) = \frac{d}{dt}\left(\frac{V_B - A_p x}{\beta_e} P_B\right) \qquad (10)$$

$$Q_e = C_t(P_A - P_B) \qquad (11)$$

Where, V_A is the oil volume in line A and the left side of the hydraulic cylinder [m^3], V_B is the oil volume in Line B and the right side of the hydraulic cylinder [m3], Qe is leakage flow rate [m3/s], Ct is total leakage coefficient and βe Is the bulk modulus of the hydraulic oil [N/m2].

The equation of motion applied for the piston and its rod could be described as follows:

$$m\ddot{x} - b\dot{x} = A_p P_L - F_d \qquad (12)$$

m is the total mass of the mechanism [kg], b is the viscous damping coefficient [N/(m/s)], P_L is the load pressure (P_L = P_A-P_B) [N/m^2] and F_d is the external forces acting on the steering mechanism due to tire-road interaction and other disturbances [N].

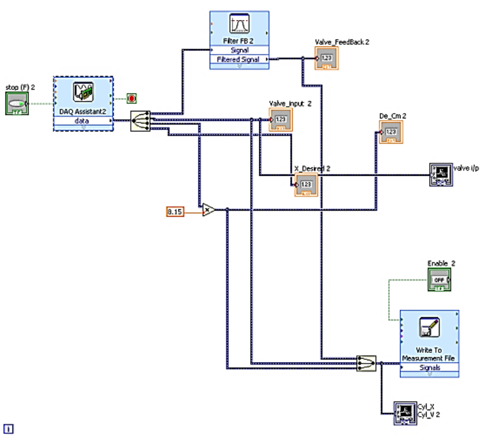

Figure 5: LabVIEW software for data acquiring.

Each element of the hydraulic circuit has been studied individually to obtain the mathematical equations describe its operation. These equations have been connected into SIMULINK software in order to obtain a computer program simulating the hydraulic circuit Figure.4 shows the SIMULINK model along with LabVIEW software to handle the data acquisition devices and for recording of date Figure.5

3. Experimental Work

3.1 System Description

Figure.1 shows a schematic diagram of the electrohydraulic wave power simulator. Here we have a hydraulic wave power simulator test rig constructed as shown, for a cylinder displacement to emulate the wave motion we designed a hydraulic circuit contains a hydraulic unit connected to a Servo Solenoid Valve (EHSSV) to control the amount of fluid required for the cylinder to move with a precise displacement.

We measured the cylinder displacement using LVDT connected to its rod, also NI-LABVIEW software connected to a DAQ system for acquiring of data & sending control signals

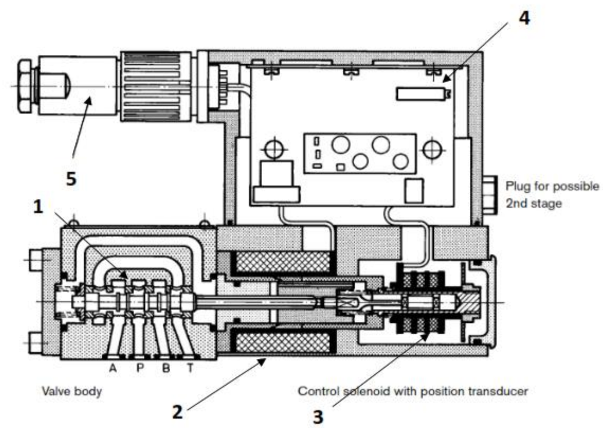

Figure 6: Electrohydraulic servo solenoid valve (EHSSV)

The NI-6220-PCI data acquisition is internally fitted in the host desktop computer and connected to the test rig through a SHC68-68-EPM shielded cable, NI-6063E card that provides input signal to the servo valve but we have also an internal LVDT in the selected servo valve that measures its spool displacement as a feedback signal.

There is another NI-6036 PCMCIA card installed in a notebook that has PCMCIA slot, Portable E series multifunction DAQ card of data acquisition and signal conditioning that is required to send control signals through analog output to the servo solenoid valve, which controls cylinder motion.

3.2. Description and Operation of (EHSSV)

Many applications in fluid power control field uses a variable orifice for controlling the fluid flow. A sliding spool can have numerous displacements that adjust flow. The spool moves through a bore (sleeve) with ports. its movement causes each displacement to alter the correspondent port area, thereby adjusting the flow-versus-pressure is dependent on the orifices. This is crucial for controlling hydraulic systems. It has four flow rates related to the orifice ports (Q_a ,Q_b ,Q_c , Q_d). The supply and return ports connect to the pump and tank lines, respectively. The orifice output port provides the regulated flow and usually connects to an actuator such as a hydraulic cylinder.

An electrohydraulic servo solenoid valve (EHSSV) is used to control the amount of flow passing through the circuit. Figure.6 shows the valve cross section. From this figure, it can be seen that the basic components of the valve are the valve body that contains a one-side solenoid Actuation, valve spool (1), Line socket(5) and Solenoid connected with the spool (2) with integral position feedback and on-board electronics (OBE) (4) Position feedback LVDT(3) (linear variable differential transformer) When the solenoid is energized, the control spool is operated directly and the LVDT starts to measure the spool displacement as a feedback to the OBE. The feedback signal is in the range of 0±10 voltage.

3.3. System identification

The mathematical model of the servo solenoid valve is difficult to be obtained, because of the following reasons:

1) Lack of information about the solenoid components (i.e. number of winding turns, permeability of core material, etc.).

2) No accurate mathematical model could simulate hysteresis in solenoid operation.

3) No mathematical model could simulate the friction losses during armature motion.

Therefore, the valve response being measured via the built in LVDT Feedback measuring, the excitation signal is step input 5-voltages, and the output signal is LVDT voltage.

In doing so, the total closed-loop transfer function of the servo-solenoid valve has the shape:

$$\frac{X(s)}{U(s)} = \frac{\omega_n^{\,2}}{s^2 + (2 * \xi * \omega_n)s + \omega_n^{\,2}} \qquad (13)$$

Where U(s) is the input voltage signal, X(s) is the system output, which is the spool displacement, ω_n is the natural frequency & ξ is Damping Ratio.

As shown in *Figure.7*. Delivering a step input (5 volts) to the valve then measuring its spool response based on the internal LVDT position feedback and comparing the resulted graph with the general equation (13) to acquire an equation represents the valve model (14). It became obvious that the representative equation of the servo solenoid valve is in good agreement with the experimental results so that now we can use it in our model.

According to experimental work, the transfer function is:

$$\frac{X(s)}{U(s)} = \frac{637.022^2}{s^2 + 564.0193s + 637.022^2} \qquad \textbf{(14)}$$

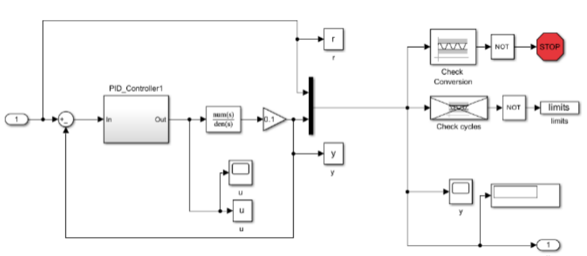

Figure 7: Step input (5 volts) to the valve and its spool response based on the internal LVDT position feedback

4. Results and Discussion

The servo-solenoid valve has a spool position feedback LVDT in the form of an electrical signal measured by a built-in sensor. Generally, based on this information and the experimental test done on the valve it was found that both the solenoid valve spool and the feedback sensor could be approximated as a Second order system equation (13,14).

4.1. Validation of the simulation program

In order to validate the wave power hydraulic simulator model, the computer program was run at various values of input voltage to the electro hydraulic servo solenoid valve and the transient spool displacement versus time has been compared with the experimentally measurement of transient state, figure.8 show the comparison between the simulated and the measured transient spool displacement and velocity. From this figure it can be seen that relatively small deviations in the transient period of these curves may be referred to ignoring the dynamic effect of the hydraulic oil in the simulation of connecting hoses, which may affect the transient state of the system.

By Tracking Cylinder displacement experimentally versus the model *Figure.8&9* the model works perfectly and its ready to apply a controller, as we can see the experimental cylinder displacement & velocity can relate to the modeled ones.

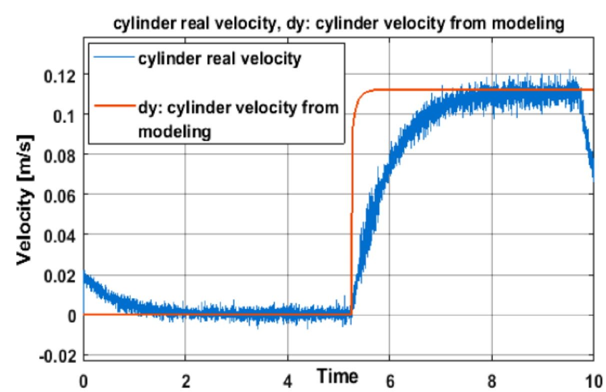

Figure 8: Cylinder displacement experimentally versus the model

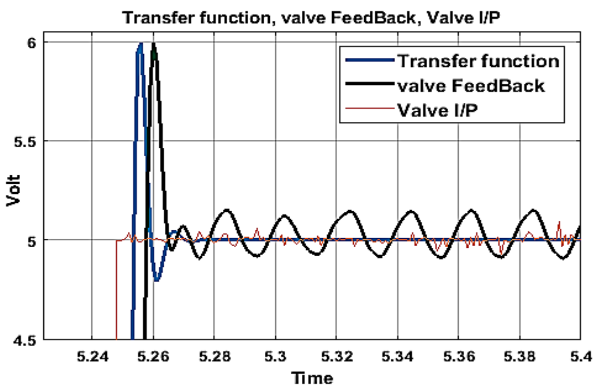

Figure 9: Cylinder Velocity experimentally versus the model without controller

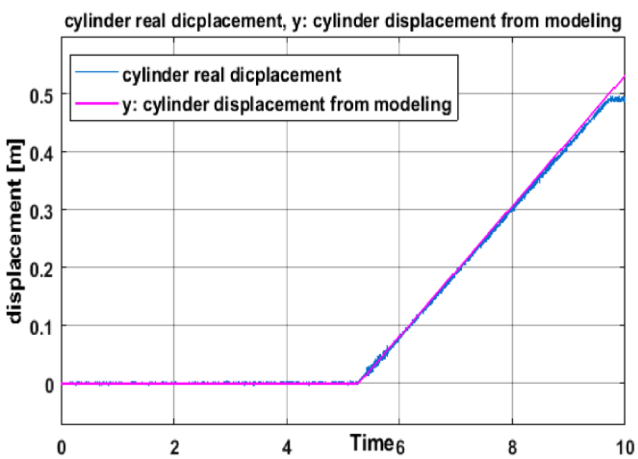

Figure 10: Cylinder displacement experimentally versus the model after controller adjustment

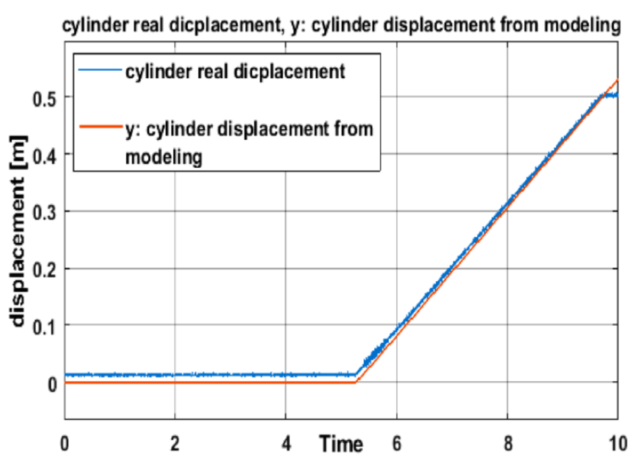

Figure 11: Cylinder Velocity experimentally versus the model after controller adjustment

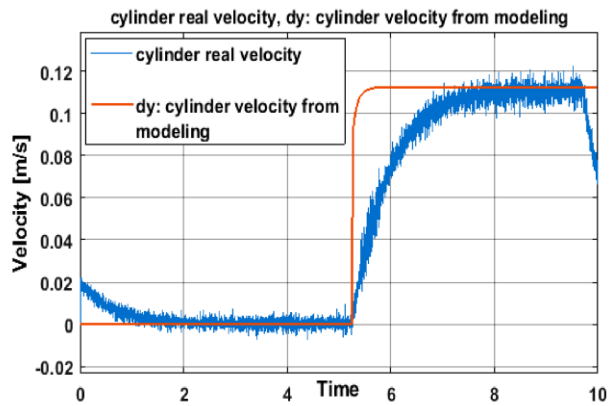

Figure 12 Using PSO to optimize the parameters of the PID controller.

5. Conclusion

In this paper, first the mathematical model of the system was developed based on linear control theory by using MATLAB SIMULINK software, it showed a reliable model. Then by using system identification techniques and based on comprehensive experimental tests the model parameters were determined then we presented a PSO-based method (Figure 12) for optimizing the PID parameters applied to a control strategy for position control for a simulated wave power hydraulic system. The experimental results Figure.10&11 showed that the PSO-based optimization method did not improve the performance of the position control system in a significant manner.

References

[1] M. Jalali, R. K. Moghaddam, and N. Pariz, "Tuning of Fuzzy Logic Controller Using an Improved Black Hole Algorithm for Maximizing Power Capture of Ocean Wave Energy Converters," *International Journal of Smart Electrical Engineering*, vol. 9, no. 1, 2020.

[2] M. A. Jusoh, M. Z. Ibrahim, M. Z. Daud, A. Albani, and Z. M. Yusop, "Hydraulic power take-off concepts for wave energy conversion system: a review," *Energies*, vol. 12, no. 23. MDPI AG, 2019. doi: 10.3390/en12234510.

[3] S. Johansson, "Modelling and Simulation of a Power Take-off in Connection with Multiple Wave Energy Converters," 2014.

[4] R. So, S. Casey, S. Kanner, A. Simmons, and T. K. A. Brekken, "PTO-Sim: Development of a Power Take Off Modeling Tool for Ocean Wave Energy Conversion."

[5] İ. Özer Erselcan and A. Kükner, "A REVIEW OF POWER TAKE-OFF SYSTEMS EMPLOYED IN WAVE ENERGY CONVERTERS," 2014.

[6] J. Lasa, J. C. Antolín, C. Angulo, P. Estensoro, M. Santos, and P. Ricci, "Design, construction and testing of a hydraulic power take-off for wave energy converters," *Energies (Basel)*, vol. 5, no. 6, pp. 2030–2052, Jun. 2012, doi: 10.3390/en5062030.

[7] S. Zou and O. Abdelkhalik, “Control of wave energy converters with discrete displacement hydraulic power take-off units,” *J Mar Sci Eng*, vol. 6, no. 2, Apr. 2018, doi: 10.3390/jmse6020031.

[8] T. C. Do, D. T. Tran, T. Q. Dinh, and K. K. Ahn, “Tracking control for an electro-hydraulic rotary actuator using fractional order fuzzy PID controller,” Electronics (Switzerland), vol. 9, no. 6, pp. 1–16, Jun. 2020, doi: 10.3390/electronics9060926.

[9] X. Dang, X. Zhao, C. Dang, H. Jiang, X. Wu, and L. Zha, “Incomplete differentiation-based improved adaptive backstepping integral sliding mode control for position control of hydraulic system,” ISA Trans, vol. 109, pp. 199–217, Mar. 2021, doi: 10.1016/j.isatra.2020.10.027.

[10] 2013 OCEANS - San Diego. IEEE, 2013.

[11] W. Zhang, S. Li, Y. Liu, D. Li, and Q. He, “Optimal control for hydraulic cylinder tracking displacement of wave energy experimental platform,” Energies (Basel), vol. 13, no. 11, Jun. 2020, doi: 10.3390/en13112876.

[12] H. C. Pedersen, R. H. Hansen, A. H. Hansen, T. O. Andersen, and M. M. Bech, “Design of full scale wave simulator for testing Power Take off systems for wave energy converters,” International Journal of Marine Energy, vol. 13, pp. 130–156, Apr. 2016, doi: 10.1016/j.ijome.2016.01.005.

[13] E. Sahin and I. H. Altas, “A PSO Tuned Fractional-Order PID Controlled Non-inverting Buck-Boost Converter for a Wave/UC Energy System,” 2016. [Online]. Available: www.ijisae.org

[14] S. Zou, “Optimal Control of Wave Energy Converters,” Michigan Technological University, Houghton, Michigan, 2018. doi: 10.37099/mtu.dc.etdr/702.

[15] N. E. Andersen et al., “energies Optimisation of Control Algorithm for Hydraulic Power Take-Off System in Wave Energy Converter,” pp. 1–18, 2022.

[16]M. Cylinder, “A Constant-Pressure Hydraulic PTO System for a Wave Energy,” 2022.