The Simulation and Experimental Study of Hydraulic Transmission with Constant-pressure Scheme for Wave Energy Converter Application

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Abstract. This paper presents the simulation and experimental results of the hydraulic system for wave energy converter application. The different input force applied from the pump unit will imitate the force of wave energy converter (WEC) produced by the ocean waves motion. The simulation conducted using the Hydraulic FluidSIM® 5th version, while the experiment was conducted at Festo-Hydraulic Laboratory. In FluidSIM®, the role of wave floater represented by a set of pump unit that will provide desired pressure to the hydraulic piston. The pump unit consists of a motor, pump, tank and pressure relief valve. The input pressure at the pump unit was adjusted in twelve different levels in the range of 5 Bar to 60 Bar. The different pressure will create a different oil velocity that caused the extension and retraction of the piston. The different pressure also will create a different speed (measured in RPM) of a hydraulic motor. An accumulator and four units of check valves used to drive the moving oil in unidirectional at a smooth flow rate. As a result, the rise of input pressure at the pump unit will increase the speed of a hydraulic motor. For this reason, to achieve the optimal electrical generation by a generator that mounted with hydraulic motor, the higher input pressure is needed. Furthermore, the simulation is validated by the physical experiment to determine the accuracy of generating data. The averaged accuracy of simulation data compared to experimental is 89.92%. After all, the finding from this study will be utilised as a reference in the estimation of the optimal dimension for the actual scale of a hydraulic system for application in the WEC.

1. Introduction
Nowadays, the main problem in the energy sector is the rapid depletion of non-renewable energy resources, such as coal and petroleum. Therefore, the exploration and exploitation of renewable energy resource are the solution to replace the dependent of the energy sector on conventional resource. By utilization of renewable energies such as ocean, wind, solar and other renewable energies will help in slowing the global warming, reducing the carbon emission and sustain the earth's ecosystem. In maritime countries such as Malaysia, that's surrounded by the ocean water, the wave energy is considered has potential for energy generation. This was confirmed by Loon and Koto (2016) that reported that the east coast of Peninsular Malaysia by South China Sea has enormous potential for wave energy exploitation in Malaysia [1].

This paper focuses on simulation and experimental study of hydraulic transmission based WEC system as depicted in Figure 1. In WEC, there are five different PTO configuration for wave energy to electricity conversion including: hydraulic system, air turbine, hydro turbine, direct mechanical drive system linked to rotary generator and direct electrical drive system with linear generator [2]. Although diverse PTO systems have been suggested by different wave energy researchers and developers,
hydraulic PTO transmission systems appear to be the choice of the vast majority of developers since there are many WEC device implement this technique [3]. The obtained simulation results were then compared with the experiment results. The experimental works of hydraulic power take-off (PTO) system were set up according to the laboratory scale test at Electro hydraulic laboratory facility.

**Figure 1.** Full conversion change stage in WEC with hydraulic PTO [4].

### 1.1. WEC device classification

WEC is the device system that harvests the wave energy to generate the electricity. The operating mechanisms of WEC depending on different area conditions; (i) onshore, (ii) shoreline and (iii) offshore conditions [2]. For onshore, the WEC was fixed structure and directly connected to the mainland, for example, the overtopping and oscillating water column. Nevertheless, for the shoreline area, the WEC captured the waves force based on the water depth of the ocean. In offshore area, the mechanism of the device is floater harvester [2]. There are several categories of WECs that differentiated based on their size and direction of elongation; (i) Oscillating Water Column, (ii) Wave Activated Body and (iii) Overtopping [2-3].

Wave activated body (WABs) is the most common and largest application that had been applied in WEC concept [2]. WAB can be classified into two categories; which are floating and submerge. For floating concept with approach of hydraulic PTO, the successive WEC device, Pelamis was mounted and connected with five joint tubes. The WEC was located in semi submerge on the ocean and while the waves come through the Pelamis, the hydraulic power take off used in the system to convert the kinetic energy from the waves force into mechanical energy then convert into electrical energy system [2]. Another floating device with direct mechanical drive as PTO system, UMT Eco Wave Power (UEWP) developed by Universiti Malaysia Terengganu (UMT), Malaysia [5]. The WEC device exploiting the fluctuated movement of floater that connected to the mechanical rack system. In the system, the mechanical rack moving the gear and pulley. The 10 kW generator that connected to the pulley belt will produce the electricity.

For the submerge category of WAB, the PowerBuoy that using a reference plate as a point of reference for the PTO. The device has applied the different solutions for PTO, including the using of oil hydraulics [2].

**Figure 2.** The P2 Pelamis (left) and PowerBuoy (right) with both use hydraulic PTO as working principle[2]
1.2 Hydraulic PTO in WEC system
In WEC, the Hydraulic PTO systems typically divided into two categories which are variable-pressure and constant-pressure system [4]. For variable-pressure configuration, the hydraulic motor is directly connected with the hydraulic cylinder without intervention of check valve arrangement between the line. The force control is applied directly to the system by means of hydraulic motor will functioned act as pressure regulation and the installation of accumulator will be helpful but are not essential. For constant-pressure system, accumulator implementation is essential to the system in providing smooth output due to highly variable power input. The multiple hydraulic cylinder implementation will affect much this configuration to feasible the force-control. For more details, Costello (2011) reports an analysis of both systems using conventional components [6]. In this paper the analysis will focuses on constant-pressure configuration.

![Figure 3](image3.png)

**Figure 3.** The scheme of a typical constant-pressure hydraulic transmission system [3].

![Figure 4](image4.png)

**Figure 4.** The scheme of a typical variable-pressure hydraulic transmission system [3].

2. Simulation and Experiment
The simulation of hydraulic PTO system was conducted by using the Hydraulic FluidSIM® 5th version. In the simulation set up, a pump unit imitates the designed floater that creates force which acts to the hydraulic double acting cylinder. Furthermore, the main didactic device that had been used for hydraulic
PTO comprises of; (i) coupled of two units of double acting hydraulic cylinders, (ii) a rectifier with the arrangement of four units of check valve, (iii) an accumulator and (iv) hydraulic motor. The components specification while conducting experiment as mentioned in the didactic components depicted in Table 1 and 2.

Table 1. Specification of the hydraulic transmission PTO parameters

| Parameter       | Value          |
|-----------------|----------------|
| Cylinder        |                |
| Bore diameter   | 16 mm          |
| Rod diameter    | 10 mm          |
| Stroke length   | 200 mm         |
| Accumulator     |                |
| Volume          | 0.32 cm³       |
| Pre charge pressure | 10 Bar     |
| Hydraulic motor |                |
| Displacement    | 8.2 CC/REV     |
| Fluid Oil       |                |
| Mineral oil     | Viscosity 22 cSt (mm²/s) |

Meanwhile, the Figure 5 shows the schematic of the designed WEC system in the simulation interface. The proposed electro-hydraulic system arrangement includes two units of a double acting hydraulic cylinder with both front-end linked together with the coupling nut. It is to allow the second unit of double acting hydraulic cylinder move synchronously when the first double acting hydraulic cylinder excites either extend or retract.

The experimental works have been set up identically with the simulation circuit design to allow the comparison study. The study on the effects of the hydraulic pressure to the rotational speed of the hydraulic motor was conducted by setting twelve different pressures from 5 Bar to 60 Bar, in the power pump unit of the system. By means of that, the pressure relief valve used in the experiment to allow manually control the input pressure with pressure gauge as an indicator.

The power pump unit as shown in Figure 6 will inject the oil pressure to move the piston inside the first double acting hydraulic cylinder. The power pump and the first double acting hydraulic cylinder will imitate the motions of the waves that move the floater of the system in the real application. The
second double acting hydraulic cylinder system acting as the hydraulic transmission PTO of the WEC device. The pressure gauges had been placed at the inlet and the outlet hydraulic cylinder to measure the force input and output of the system. The Digital Tachometer EM2236 was used to measure the rotation of the shaft on the hydraulic motor.

For the second hydraulic cylinder configuration, four units of check valve which assembled in rectified non-return valve and then delivered to the high-pressure accumulator [7]. The purpose of the accumulator is to store the hydraulic energy and deliver the oil flow to the fix displacement type of hydraulic motor and preserve the oil flow rate. The low pressure of oil being drawn after the hydraulic motor passes through the non-return check valve, then will retract hydraulic cylinder continuously. The hydraulic motor functioning to convert the hydraulic energy to kinetic energy and later will pass through the generator and electrical components to produce usable electrical energy.

![Figure 6. Hydraulic PTO Experiment at FESTO Lab](image)

**Table 2. Didactic components in the used in Hydraulic PTO**

| No | Parts | Symbols | Description |
|----|-------|---------|-------------|
|    | Coupling double acting cylinder | ![Coupling double acting cylinder](image) | Reacted as Hydraulic PTO connected to the system |
|    | Accumulator | ![Accumulator](image) | Storage energy for the oil flow |
|    | Non return valve | ![Non return valve](image) | Flow the oil inlet and outlet just in one direction |
A relief valve or pressure relief valve (PRV) is a type of safety valve used to control or limit the pressure in a system.

Connection of all components

Convert the hydraulic motion into rotational motion

This directional control valve comprises three switching positions for the control of flow rates and is directly actuated via DC solenoid coils.

To measure the rotational of the hydraulic motor speed in RPM

To measure the pressure at the hydraulic piston.

3. Simulation and Experiment

The physical model of hydraulic PTO system in FluidSIM® simulation is validated by comparing the measurements from the set-up hydraulic PTO test-rig. In this study, the hydraulic test circuit including of variable pump unit and hydraulic actuator represent as the ocean waves motion is utilized to reciprocating the hydraulic cylinder of PTO system. In addition, the hydrodynamics effects on the WEC device are ignored in this study. Therefore, the excitation force, $F_{exc}$ generated from the hydraulic test circuit is directly used as an input of the hydraulic PTO system. Since the $F_{exc}$ is proportional to the pressure setting of pump unit, the $F_{exc}$ is varied by adjusting the pressure of the pump unit from 5 Bar to 60 Bar.

Due to unavailability of force sensor in FluidSIM® software and experimental process, the forces are directly extracted from the pressure of the hydraulic cylinder chamber as illustrates in Figure 7 using equation (1) and (2), where, $F_1$ and $F_2$ are rod force and piston force (N), $d_2$ and $d_1$ are rod and piston diameter (m), $P_1$ and $P_2$ are pressure in the cylinder in the rod and piston side, respectively. Table illustrates the extracted $F_{exc}$ from the hydraulic cylinder of the hydraulic test rig. From the results, there are deviation between the $F_{exc}$ of simulation and experimental may be due to unexpected leakage of hydraulic oil during the experimental validation process. From the table, by adjusting hydraulic pump...
pressure from 5 Bar to 60 Bar in the simulation and experimental process, the $F_{\text{exc}}$ automatically varied from 20 N to 392.1 N and 20.1 N to 382 N, respectively.

Figure 7. Illustration of force extraction in hydraulic cylinder [8].

$$F_1 = P_1\left[\pi(d_2^2 - d_1^2)/4\right]$$

$$F_2 = P_2(\pi d_2^2/4)$$

Table 3. Extracted Excitation Force based on the hydraulic cylinder pressure

| Pressure setting of pump unit (Bar) | Excitation Force, $F_{\text{exc}}$ (N) |
|-------------------------------------|--------------------------------------|
|                                     | Simulation | Experiment |
| 5                                   | 20.0       | 20.1       |
| 10                                  | 40.2       | 40.2       |
| 15                                  | 140.0      | 100.5      |
| 20                                  | 201.0      | 180.9      |
| 25                                  | 261.3      | 221.1      |
| 30                                  | 291.5      | 261.3      |
| 35                                  | 311.6      | 301.5      |
| 40                                  | 321.6      | 321.6      |
| 45                                  | 331.7      | 321.6      |
| 50                                  | 341.8      | 341.8      |
| 55                                  | 361.9      | 361.9      |
| 60                                  | 392.1      | 382.0      |

Figure 8 presents the relationship between the excitation force, $F_{\text{exc}}$ and the hydraulic motor speed, $HM_ω$, both from simulation and experimental evaluation results. From the results, the $HM_ω$ is gradually increased proportional to the $F_{\text{exc}}$. However, started from 280 N of $F_{\text{exc}}$, the $HM_ω$ become constant due to maximum operation limit of hydraulic motor. Based on the results in the Figure 8, the averaged accuracy of simulation model of hydraulic PTO system compared to the experimental is calculated using equation (3), where the $HM_{ω,\text{sim}}$ and $HM_{ω,\text{exp}}$ are the hydraulic speed motor from the simulation and experimental results, respectively. From both analysis, the simulation accuracy is up to 89.92% compared with experiment. There are several factors that influenced the model accuracy during the experimental validation i.e., the pressure losses due to the leakage of hydraulic oil at components connection. In addition, the existence of friction in the piston and hydraulic motor also may be influenced. Apart from that, the inaccurate dynamic parameters setting of the hydraulic components in the simulation model set-up also may affected the performance of the simulation model.
Figure 8. Relationship of excitation force, $F_{exc}$ and the hydraulic motor speed, $H M_\omega$ from the simulation and experimental evaluation.

Model accuracy (%) = $1 - \frac{\left| \sum H M_\omega, sim - \sum H M_\omega, exp \right|}{\sum H M_\omega, exp} \times 100$ \hspace{1cm} (3)

4.0 Conclusion

In present study, the hydraulic PTO system is developed in high-fidelity FluidSIM® 5th version software. The developed model is then validated through experimental study conducted using hydraulic Festo Lab experimental test rig. The hydraulic test circuit includes of hydraulic pump and hydraulic actuator or cylinder is used to represent the reciprocation motion ocean waves. The pressure of hydraulic pump is adjusted from 5 Bar to 60 Bar to varied the excitation force input of hydraulic PTO system. The simulation and experimental results showed the hydraulic motor speed are recorded at 170 rpm and 160 rpm when the excitation forces are set to 392.1 N and 382 N, respectively. Apart from that, the validation result that obtained from the analysi showed the accuracy of developed simulation model is up to 89.92%.

The results shown significant accuracy between both analysis and lead to crucial outcome for future simulation analysis. Even though, the analysis is done in simulation the system is said capable to emulate the actual behaviour of hydraulic transmission system in real application. The next stage, the simulation analysis will be carried out by setting hydraulic components parameter according to the actual WEC device that currently developed. The hydraulic transmission system needs to properly designed and calculated to ensure the system able to cope the torque and speed rated from electrical generator to produce desired power. For future recommendation, it is also suggested to compare the hydraulic PTO system using Amesim software, which the most used of physical modelling and simulation software for mechatronic systems application.

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