Parameters estimation of hydraulic power take-off system for wave energy conversion system using genetic algorithm

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Abstract. This paper presents accurate control parameters estimation of the hydraulic Power Take-Off (PTO) model for the wave energy conversion system to maximise energy production. In general, the performance of the hydraulic PTO system depends on the parameters setting of hydraulic PTO system components such as hydraulic motor displacement setting, pre-charge of the hydraulic accumulator, and et cetera. Conventionally, it requires to manually obtain the optimal parameters of a hydraulic PTO system by repeating the simulation process. However, this estimation method exposed to human error and would easily be resulting in a non-optimal selection of hydraulic PTO parameters for the wave energy conversion system. Therefore, an easy and accurate approach of using the GA optimisation method for determining hydraulic PTO parameters was introduced in the present study. This approach is simple and more accurate compared to the conventional optimisation method. The hydraulic PTO model was developed in SIEMENS/Amesim environment using available components in the library. The specifications of the actual hydraulic PTO system components from the manufacturer were used during the simulation set-up. The complete hydraulic PTO system was optimised using a special genetic algorithm (GA) optimisation tools in the SIEMENS/Amesim software. The simulation results showed that GA was effective to determine the optimal configuration parameters of hydraulic PTO system. From the results, the optimal configuration parameters of hydraulic PTO system were successfully reduced about 38%. Consequently, the maximum force applied to the WEC devices was reduced up to 34%. This force reduction is important since it will enable the WECS to be operated during a smaller wave condition.

1. Introduction

Ocean waves is considered as one of the largest untapped and most promising renewable energy sources due to its natural characteristics of high-power density, cleanest, predictable, inexhaustible, safe and et cetera [1,2]. There are numerous wave energy conversion system (WECS) concepts that have been proposed and patented, which are capable of converting the energy from the ocean waves become usable electricity [3]. In general, these WECS concepts consist of three main subsystems, namely the wave energy converter (WEC) device, power take-off (PTO) system, and the control system. Recently, there are a variety of PTO concepts have been invented by researchers for the WECS application using different working principles such as air or water turbine-based, mechanical hydraulic-based, direct-
mechanical drive-based, and direct-electrical drive-based [4]. A mechanical hydraulic-based PTO is considered as the most promising PTO for wave-activated-body wave energy conversion system (WAB-WECs) due to its excellent features of higher efficiency, well-adapted to the low frequency and large power density waves, and also excellent controllability [5]. It was reported in the literature that the effectiveness of the mechanical hydraulic-based PTO system could be achieved up to 90% [6]. Due to such a promising characteristics, the mechanical hydraulic-based PTO system finds its application in WAB-WECs field.

There is a large volume of published studies presenting the applications of the mechanical hydraulic based-PTO system in WECS, for example, in [7–11]. From the preliminary study, most of the studies focused on the performance hydraulic PTO system performance without considering the optimal parameters setting of the PTO model. The optimal parameters setting of a mechanical hydraulic-based PTO system is a critical issue since it can influence the performance of the system and the amount of the output to be generated [9]. Only few studies considering this critical issue, for example, in [9–11]. However, in [9], the optimal parameters setting have been obtained through manually varying these parameters. Since a manual approach is used, this approach generally exposed to human error and easy to cause an inaccurate selection of parameters setting of mechanical hydraulic-based PTO system. Moreover, the manual approach also requires a long-time process in order to obtain accurate parameters setting. Therefore, the present study explores the optimisation of mechanical hydraulic-based PTO parameters setting using a genetic algorithm approach. The finding of this study will help the researchers and engineers to design high efficiency WECS.

The remainder of the paper is organised as follows. Section 2 presents the methodology of the studies includes theoretical descriptions of typical hydraulic PTO system (subsection 2.1), the important configuration parameters of hydraulic PTO system (subsection 2.2), and simulation set-up, optimisation and evaluation of hydraulic PTO system (subsection 2.3). Section 3 presents and discusses the results, while conclusions are drawn in Section 4.

2. Methodology

2.1. Technical descriptions of typical WEC with hydraulic PTO system

In general, the design of the WECS is dependent on location characteristics. In the present study, the concept of multi-point WEC with hydraulic PTO system which suitable for shoreline and nearshore location, as illustrated in Figure 1 is considered. This multi-point WEC concept is quite similar to the one used in several previous studies [12,13]. However, the difference in WEC shape design and the hydraulic configuration are proposed in this study. This concept has been specifically designed for nearshore application in Kuala Terengganu, Terengganu, Malaysia. The advantage of this concept is that only the WEC is placed in the water, whereas all the technical equipment operates on fixed-structure, thereby improving reliability and providing easy access for maintenance and repair. In this concept, the four parallel WEC devices, which includes uniquely shaped floaters, floaters arm, and floater level regulators are attached to the fixed-structure, as depicted in Figure 1. These WEC devices are connected to a single 10 kW hydraulic PTO system, which is located on the top of fixed-structure. A hydraulic PTO system includes a hydraulic double-acting cylinder, control manifold (set of check valves), accumulator, hydraulic motor, electrical generator, and et cetera, as presented in Figure 2.

According to Figure 1 and 2, the induced forces by the ocean wave against the floaters, namely an excitation forces, \( F_{ex} \) forced the floaters to swing upward and downward. The double-acting cylinder is attached to each floater’s arm to absorb the oscillating motion of WEC devices. The WEC devices motion push the double-acting cylinder rods at specified velocity \( \dot{x} \) relatively subjected to the PTO forces \( F_{pto} \). Then, the rod and piston exerted force the fluid in the hydraulic cylinder chamber through a controlled hydraulic manifold to a hydraulic motor. The produced torque from hydraulic motor \( \tau_C \) is used to drive the electrical generator at the specified rotation speed \( \omega_G \). The control manifold is utilised
to ensure that the hydraulic motor only rotating in a single direction. The accumulator also added to the PTO system, where the high-pressure accumulator (HPA) is placed on the inlet of the hydraulic motor. This accumulator is included to smooth out the supply of high-pressure fluid in the system by either providing or accumulating hydraulic energy when necessary.

2.2. Important parameters setting of hydraulic PTO system

The performance and behaviour of the hydraulic PTO system are influenced by parameters setting of hydraulic components. Based on the theoretical descriptions in [14], several influence parameters setting of hydraulic PTO system have been obtained for optimisation purpose as summarised in Table 1.

| No. | Parameters setting                      | Unit  |
|-----|----------------------------------------|-------|
| 1   | Diameter of piston, $D_{p,i}$          | mm    |
| 2   | Diameter of rod, $D_{r,i}$             | mm    |
| 3   | Accumulator capacity, $V_{HPC}$        | L     |
| 4   | Accumulator pre-charge gas pressure, $G_{pre,HPA}$ | bar |
| 5   | Hydraulic motor displacement, $D_M$    | cc/rev|
2.3. Simulation set-up, optimisation and evaluation of hydraulic PTO system

2.3.1. Simulation set-up of hydraulic PTO system

In this work, a simulation model of hydraulic PTO system model was built in Siemens Amesim software using available components in the hydraulic, mechanical and electrical libraries such as double hydraulic chamber single rod jack, hydraulic check valve with saturation, and et cetera. The parameters from the actual hydraulic PTO components were used to set-up the hydraulic model. Since the focus on the PTO system optimisation, the ideal WEC devices are considered in this study. The movement of WEC devices accurately follow the motion of the ocean wave is assumed. A sine signal source is used to generate an instantaneous regular ocean wave output for each hydraulic cylinder. The motion of hydraulic cylinders is assumed to extend and retract subjected to the ocean wave input. Apart from that, a simple rotational inertia component was used to represent a permanent magnet synchronous generator (PMSG) unit. In order to generate an accurate output power signal, actual data of speed, torque, and efficiency curve are used in the lookup table. In addition, the simulation time duration was set to 200 s. Consequently, the PTO force, motor torque, motor speed, and electrical power are the acquired outputs from the model.

2.3.2. Optimisation of configuration parameter of hydraulic PTO system

Since the optimal configuration parameters of the hydraulic PTO system are difficult to be obtained manually, the optimisation using a mathematical algorithm was considered in this study. In the optimisation process, five optimal parameters need to be obtained including of \( D_{p,i} \), \( D_{r,i} \), \( V_{HPA} \), \( G_{pre,HPA} \) and \( D_M \), as mentioned in the previous subsection. The objective of the optimisation problem is to maximise the energy production of the hydraulic PTO system. In this regard, the objective function \( (OF) \) was determined according to Eq. (4), where \( P_{set} \) and \( P_{actual} \) represent the desired and the actual electrical power output of the hydraulic PTO system, respectively. The optimisation problem was solved by one of the excellent mathematical algorithms, which is the genetic algorithm (GA). GA is an algorithm inspired by the process of natural evolution. GA has been effectively applied to a wide range of real-world problem of significant complexity. By using GA, the optimisation process is initially started with a randomly generated population (chromosomes) of five study parameters, as presented in Figure 3. Three main types of rules, i.e., selection, crossover and mutation, are used at each iteration to obtain a successor population. During selection rules, the parent chromosome that contributes to the population is selected for the next generation process. The selected parent chromosomes are recombined to produce child chromosomes. This process is iterated until the satisfactory fitness level is reached.

\[
OF(x) = \min \int \left( P_{\text{set}}(t) - P_{\text{actual}}(t) \right)^2 \, dt
\]

(1)
2.3.3. Evaluation of hydraulic PTO system performance

The evaluation of hydraulic PTO system was conducted at two different stages. For the first case, the evaluation was carried out to analyse the performance of hydraulic PTO system without proposed parameters optimisation approach. In this case, the hydraulic PTO system was simulated using manually defined of the configuration parameter. Meanwhile, for the second case, the evaluation was conducted on the hydraulic PTO system with the aim to evaluate the effectiveness of the parameters optimisation approach. In this case, the hydraulic PTO system was simulated using the optimal configuration parameter that have been obtained from the optimisation process. The evaluations of the hydraulic PTO system results are presented and discussed in the following section.

3. Results and discussion

Table 2 presents the optimal configuration parameters and the behaviour of hydraulic PTO system obtained using two different parameter estimation methods. For the manual case, the optimal configuration parameters of a hydraulic PTO system was estimated by repeatedly re-setting these parameters until the hydraulic PTO system can produce a maximum output power at the lowest PTO force. Based on Table 2, the optimal piston and rod diameter parameters \( D_{p,i} \) & \( D_{r,i} \) of the hydraulic cylinder were manually estimated to 65 mm and 50 mm, respectively. While the accumulator and hydraulic motor optimal configuration parameters including \( V_{HPA} \), \( G_{pre,HPA} \), and \( D_M \) were manually obtained to 35 L, 70 Bar, and 95 cc/rev, respectively. By using these configuration parameters setting, the hydraulic PTO system was able to generate a stable 10 kW electricity, as indicated in Table 2. Also, the maximum PTO force applied to the WEC devices was found can be reached up to 221 kN. However, the performance of the hydraulic PTO system was improved significantly by using the optimal configuration parameters, which obtained using the proposed optimisation, as demonstrated in Table 2 and Figure 4. Table 2 shows the optimal piston and rod diameter of the hydraulic cylinder were successfully reduced by 10% and 38%, from 65 mm to 58 mm and 50 mm to 31 mm, respectively. Besides that, from the data in Table 2, it is apparent that the proposed method was effective to reduce the accumulator capacity, accumulator precharge gas pressure and hydraulic motor displacement setting by 2.8%, 20% and 6.8%. As a result of the improved parameters, the overall cost of the hydraulic PTO system was reduced significantly.
Table 2: Optimal parameters setting and behaviour of hydraulic PTO system using two different parameter estimation method

| Hydraulic PTO Parameters                        | Parameter Estimation Method | Manually | GA Optimization |
|-------------------------------------------------|----------------------------|----------|-----------------|
| Diameter of piston, $D_{pi}$                    | mm                        | 65       | 58              |
| Diameter of rod, $D_{ri}$                       | mm                        | 50       | 31              |
| Accumulator capacity, $V_{HPA}$                 | L                         | 35       | 34              |
| Accumulator pre-charge gas pressure, $G_{pre,HPA}$ | Bar                      | 70       | 56              |
| Hydraulic motor displacement, $D_M$              | cc/rev                    | 95       | 88.5            |

Hydraulic PTO System Behaviour

| Parameter                          | Value     |
|------------------------------------|-----------|
| Average generator speed, $\omega_{G,ave}$ | rpm       | 250 | 250 |
| Average generator Torque, $\tau_{G,ave}$  | Nm        | 382 | 382 |
| Maximum hydraulic Cylinder force, $F_{pto,max}$ | kN       | 221 | 146 |
| Average electrical output power, $P_{e,ave}$    | kW        | 10  | 10  |

Furthermore, Figure 4 illustrates the complete hydraulic PTO system behaviour using optimal configuration parameters that were obtained using the proposed optimisation method. Figure 4(a) shows the obtained $x_{p,i}$ and $\dot{x}_{p,i}$ of piston motion profiles in order to generate 10 kW electricity. The patterns are similar for all hydraulic cylinders used since a similar ocean wave signal was applied to all hydraulic cylinders. The $x_{p,i}$ and $\dot{x}_{p,i}$ have a sinusoidal profile, where the highest $x_{p,i}$ and $\dot{x}_{p,i}$ are equal to 0.097 m/s and 0.109 m, respectively. Figure 4(b) illustrates the required forces profiles for pushing the hydraulic piston at the rated condition. A maximum of 146 kN PTO forces was applied to the WEC devices to push the hydraulic piston at the 0.097 m/s and resulted in 10 kW electricity was generated. This result was proven that the optimisation method was capable of reducing the PTO force applied to the WEC devices by 34% due to the reduction of configuration parameters, as mentioned previously. Apart from that, Figure 4(c) and (d) illustrates the performances of the hydraulic motor in terms of speed and torque. The hydraulic motor was required 150 s to operate at its rated condition (250 rpm and 382 Nm). Finally, Figure 4(e) shows the generated electrical output power profiles by the hydraulic PTO system at the optimal condition. As shown in the figure, the PMSG driven by the hydraulic motor was capable of generating the electricity of up to 10 kW.
4. Conclusion
The optimal parameters setting of a nonlinear hydraulic-based PTO system is a critical issue since it can influence the performance of the system and the amount of the output to be generated. Previously, only few studies concerning this critical issue. However, to the best of the authors’ knowledge, no report has been found so far using the intelligent mathematical algorithm to estimate the optimal configuration parameters for the wave energy conversion system. Therefore, this paper presents the development, optimisation and performance investigation of a 10 kW hydraulic PTO system for wave energy conversion system. The objective of this paper is to determine the optimal configuration parameters of a hydraulic PTO system. Initially, the concepts and the mathematical models of the hydraulic PTO system were described. Then, the important configuration parameters of hydraulic PTO system was discussed. Finally, the simulation model set-up and the evaluation of the hydraulic PTO system model in Siemen Amesim software were carried out.

The presented results in this study illustrate that GA was effective to determine the optimal configuration parameters of hydraulic PTO system. From the results, the optimal piston and rod
diameters of the hydraulic cylinder were successfully reduced by 10% and 38%, respectively. Besides that, the accumulator capacity, accumulator precharge gas pressure and hydraulic motor displacement setting also have been reduced by 2.8%, 20% and 6.8%, respectively. The significant reduction of the configuration parameters consequently reduces the overall operational cost of the hydraulic PTO system. In addition, the most important finding to emerge from this study is that GA was able to reduce the PTO force applied to the WEC devices by 34%, from 221 kN to 146 kN in order to generate 10 kW electricity. This finding is important since it will enable the WECS to be operated during a smaller wave condition.

5. Future Work
The study has gone some way towards enhancing the performance of the hydraulic PTO system using mathematical optimisation method. It is recommended that further research be undertaken in the following areas: Firstly, it would be interesting to obtain an optimal configuration parameters of hydraulic PTO system using different types of a mathematical optimisation algorithm such as particle swarm optimisation (PSO), gravitational search algorithm (GSA), genetic algorithm (GA), ant colony optimisation algorithm (ACO), and et cetera. Thus, the best optimisation algorithm for hydraulic PTO system case could be obtained. Secondly, further investigation and experimentation of optimal hydraulic PTO system are strongly recommended. Therefore, the effectiveness of the proposed parameters estimation method on the actual condition can be proved.

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