The 10th JFPS International Symposium on Fluid Power FUKUOKA 2017 Oct. 24-27, 2017 JFPS The Japan Fluid Power System Society

SPEED AND DAMPING CONTROL OF HYDRAULIC WAVE ENERGY CONVERTER

Rongyu ZHA, *Dr Andrew HILLIS, **Dr Jos Darling, ***Prof Andrew Plummer

Department of Mechanical Engineering, Faculty of Engineering
University of Bath
Claverton Down, Bath, BA2 7AY, United Kingdom
(E-mail: R.Zha@bath.ac.uk)
*Department of Mechanical Engineering, Faculty of Engineering
University of Bath
Claverton Down, Bath, BA2 7AY, United Kingdom
(E-mail: A.J.Hillis@bath.ac.uk
**Department of Mechanical Engineering, Faculty of Engineering
University of Bath
Claverton Down, Bath, BA2 7AY, United Kingdom
(E-mail: J.Darling@bath.ac.uk)
***Department of Mechanical Engineering, Faculty of Engineering
University of Bath
Claverton Down, Bath, BA2 7AY, United Kingdom
(E-mail: A.R.Plummer@bath.ac.uk)

Abstract: This paper introduces a hydraulic wave energy converter (WEC) system. This wave-to-wire system is established for the complete process from the original wave capture device to the final generated electricity supplied to the grid. The speed controller is designed to ensure the system operating with the constant speed, which is the criteria of the grid and the damping controller is to extract the maximum energy by applying the optimum damping ratio. The Energy Capture Device (ECD) is a point absorber based on the heaving theory, while hydraulic Power Take-Off (PTO) system is proposed as it well suited to the high force, low frequency input signals from waves. A synchronous generator is connected to provide actual electricity.

Keywords: Wave energy, Simulation work, Wave-to-Wire, Power take-off system, Control Strategy

INTRODUCTION

With the rapid increase energy demand energy and serious consequence caused by traditional energy-generating methods, the wave energy is recently proposed as a potential substitution to the other well-developed renewable energy sources, with the outstanding advantages of high power density, which is estimated to be 2TW worldwide [1], and unrestricted access all over the world.

The major challenge with the current wave energy conversion process is how to ensure the converter operating with high reliability to satisfy the grid requirements and high efficiency to generate the maximum electricity. Therefore, a thoughtful controller with both speed and damping control algorithms is critical. The controller is designed to be compatible with the wave-to-wire (W2W) system.

The W2W system is divided into three stages based on the working principle: absorption stage, transmission stage and generation stage. As the rotating component that drives the electricity generator through shaft is required to rotate within the speed tolerance range, the speed control is applied to transmission stage to maintain the rotational speed regardless of incoming wave conditions. By applying damping control to the generation stage, the damping component of the WEC system is tuned accordingly and hence to extract the maximum energy from the wave [2, 3]. Neither too high nor low damping is desirable, as the oscillating motion is either limited or free, both of which will result in less energy.

This paper presents the simulations of a WEC system as a Wave-to-Wire integrated unit together with controller, under different incoming wave conditions.

NOMENCLATURE

TABLE 1. System Parameter Definition and Value

Name & Explanation		Value
Absorption Stage:		
Buoy parameter:		
f_w	Total force from wave	
f_{PTO}	Mechanical force created by PTO	
f_e	Excitation force	
f_r	Radiation force	
f_s	Hydrostatic restoring force	
$x, \dot{x}, \ddot{x}$	Buoy Behavior	
m_{total}	Total mass	53 ton
m	Buoy mass	
m_{add}	Added mass	
K_e	Excitation force coefficient	9000 N/m
K_b	Hydrostatic stiffness force coefficient	126481N/m
D_b	Radiation force damping coefficient	
Transmission Stage:		
Cylinder parameter:		
Equaled bore area of the piston		0.007 m^2
Stroke of the cylinder		5 m
Columba friction		3500N
Viscous friction		100N/(m/s)
Working fluid &:Pipework parameter:		
Fluid type		Skydrol LD-4
Maximum pipeline relative pressure		350 bar
Internal diameter		0.05m
Accumulator parameter:		
Capacity		200L
Initial volume		40L
Motor parameter:		
D_m	Motor Capacity	0.1803 l/rev
x_m	Fraction of the swash plate	0.01-1 (1%-100%)
Coulomb friction		70 N*m
Viscous friction		0.6 N*m/(rad/s)
Generator Stage:		
Generator parameter:		
Nominal frequency, Nominal speed		50 Hz, 1500 rpm
Equivalent three-phase loading resistance		5 ohms in parallel
D_{PTO}	Overall damping of PTO	
T_e	Electromagnetic generator torque	
C_g	Equivalent generator damping	
ω_m	Angular velocity of the shaft	
V	Field excitation voltage supply	

MODELLING

Absorption Stage

The absorption stage includes a reciprocating mechanism designed to capture the motion together with the energy (either potential energy or kinetic energy) from the incoming waves and transform into a motion acceptable to the transmission system. There are several possible principles that have been proposed: point absorber [4, 5], attenuator [6, 7], terminator [8, 9], oscillating water column [10, 11] and overtopping devices [12].
Point absorber is used based on the theory of heaving as shown in Fig. 1. By applying linear wave assumptions, the upright motion is considered dominant.

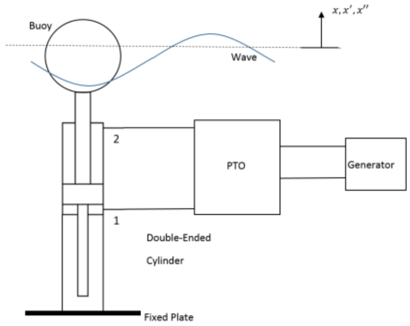

FIGURE 1. Sketch of WEC System

The behavior of buoy is described as below:

$$m\ddot{x} = f_w + f_{PTO} \tag{1}$$

$$f_w = f_e + f_r + f_s \tag{2}$$

The excitation force is proportional to the wave amplitude by a frequency-dependent coefficient. However, it's reasonable to simplify this gain to a constant value under non-extreme wave conditions. The value is dependent on the size and form of the buoy, together with the wave density.
The radiation force which is produced by an oscillating body creating waves on an otherwise calm sea. f_r consists of two terms: the first term is associated with the acceleration of the ECD and represented as an added mass m_{add} to the heave; the second term is associated with the velocity of the buoy and acts as a damper with damping coefficient D_b. D_b is a complex convolution integral, however it's used as a second order transfer function currently.

$$f_r = -m_{add}\ddot{x} - D_b\dot{x} \tag{3}$$

Hydrostatic force, also known as buoyancy force, is proportional to the displacement of buoy, and thus acts as a spring with hydrostatic stiffness coefficient K_b.

$$f_s = -K_b x \tag{4}$$

Transmission Stage

The PTO system is designed to complete the transmission from the waves surging to the generator rotating. The hydraulic PTO has its advantage to apply the accumulators to separate the energy capture process and power generation process. In this way, the surplus potential or kinetic energy from wave is stored as hydraulic energy in accumulators, and released when the original power supply is insufficient to maintain the energy feeding into motor and generator.
In the concept diagram of Fig. 2, a boost system including a boost pump and pressure relief valve, incorporated with two check vales connected with chambers, is added between actuator and rectified system to compensate the external leakage from motor to tank and hence avoid cavitation problem.
As the motor is driven by the pressure difference across, two accumulators are connected to smooth the flow and reduce the differential pressure fluctuation and maintain the motor speed. Another benefit of this W2W design is

the rectified system-direction valve, is applied before the operational fluid entering the hydraulic motor, to ensure the motor rotates in the same direction regardless of the wave conditions.
However, in order to maintain the motor speed accurately, the speed controller is necessary to ensure the shaft is rotating within the allowable range.

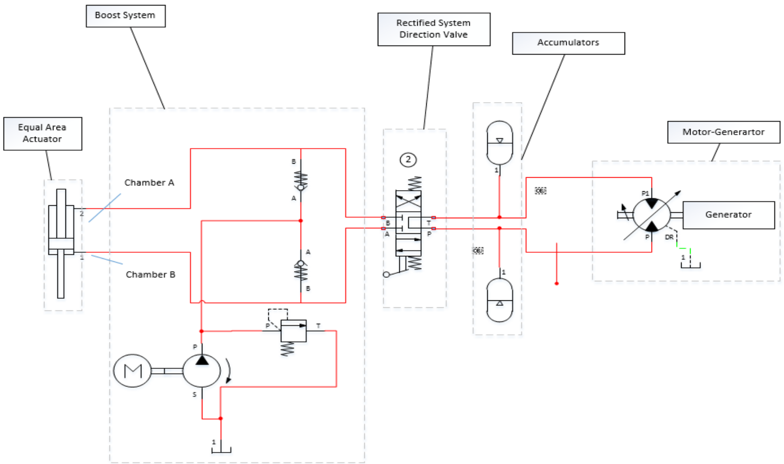

FIGURE 2. Rectified PTO Diagram

As shown in Fig.2, the G-spool, four-way, three-position directional control valve switches the position based the moving direction of actuator actively. The strategy applied here is the relaying control and control signal is the moving direction. As the buoy moves upwards with wave, the control signal is set to be 1, representing the valve fully open with B to T and P to A, while downwards with control signal -1, repressing A to T and P to B.
The relaying equations is shown as below:

$$\text{output} = \begin{cases} -1 \quad \text{upper position} \qquad \text{input} < -\text{deadband} \\ \;\;1 \quad \text{lower position} \qquad \text{input} > \text{deadband} \end{cases} \tag{5}$$

where the deadband is set to be 0.01 in this case.
The algorithm illustrates that when the input signal (velocity of buoy) is approaching the negative deadband, the output (opening of valve) stays with -1; when the input crosses the lower offset from negative values but still in the range of deadband, the output is -1 as well; while, on the other hand, when the input exceeds the upper offset, the output is set to1 and when it goes back into the deadband zone from positive values, the output sticks with 1. Similarly, the direction of fluid is rectified as uni-directional: upward buoy motion determines the flow in the path of B-T-P-A; downward A-T-P-B.

Generation Stage

For the generation stage, a three-phase synchronous generator is chosen. The generator in Fig.3 [13] is a 'wound-rotor' machine including stator and rotor. Based on the construction of the generator, the stator is fixed in the frame while rotor rotating with shaft. In order to maximize the output power, the loading is crucial, therefore the damping controller is built to modulate the electromagnetic torque.
An external DC voltage supply is applied to the field winding. The voltage used as the control signal to output the optimum electromagnetic torque with respect to the current sea state and motor displacement value. The electromagnetic torque is dependent on the filed current from field voltage supply, with a constant shaft velocity.

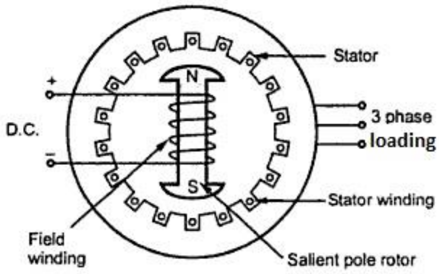

FIGURE 3. Construction of Generator

4

CONTROL ALGORITHM

Speed Control

Even though the accumulators are used to keep the differential pressure across the motor steady, it's still necessary to implement a PID feedback speed controller to reduce the error between the output and the required velocity under all wave conditions, just in case the accumulators are not sufficient. In Fig. 4, the fraction of motor displacement (X_m) is chosen to be the control signal, thus a variable displacement motor is required.
The feedforward path is the calculation process of the desired fraction with respect to the inlet flow rate and desired speed.
The closed loop of PID controller is capable to generate an offset value to the desired fraction. This offset value stops the amendment when the velocity achieves the requirements.
There is a saturation filter applied to motor capacity fraction from 1% to 100% for reliability. The first order delay D(s) is used to imitate the fundamental dynamics of the swash for non- instantaneous motion.

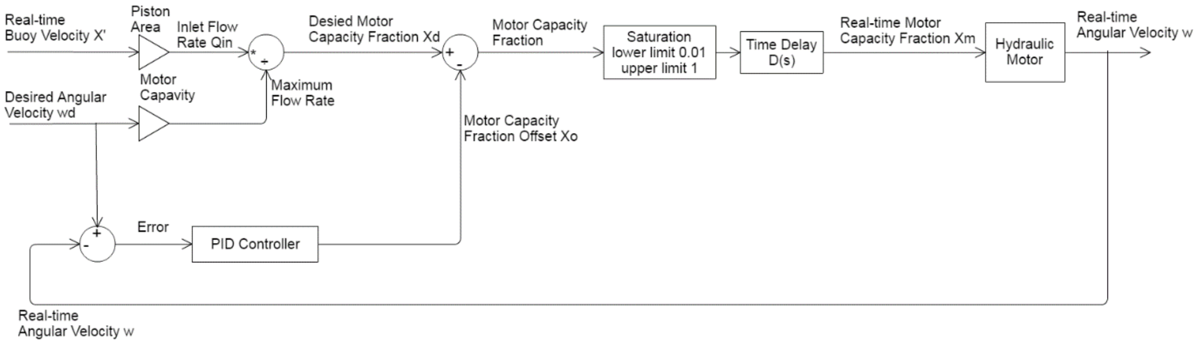

FIGURE 4. Speed Control Block Diagram

Damping Control

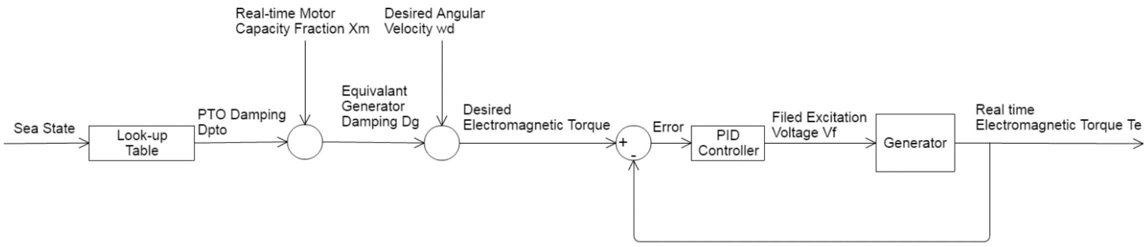

FIGURE 5. Damping Control Block Diagram

The damping coefficient of hydraulic PTO system is the critical parameter to achieve the optimum operating condition. Based on research in [14,15], the optimum value of D_{pto} is basically irrelevant with the height of incoming waves, whereas highly relevant with wave period. Therefore, in Fig. 6, a look-up table is built to find the optimum damping.

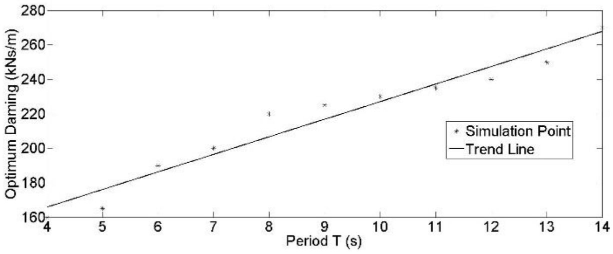

Figure 6. OPTIMUM DAMPING VS WAVE PERIODS WITH H=2m

The overall damping confident of the system is denoted as D_{pto} as below:

$$D_{PTO} = \left(\frac{A}{x_m D_m} \right)^2 \times C_g \tag{6}$$

$$T_e = \omega_m \times C_g \tag{7}$$

In order to achieve the optimum system damping, the field voltage is actively modulated by the error between the calculated result and feedback value of electromagnetic torque via another controller. Then the error is minimized to make the torque achieve the optimum value.

RESULTS

Speed Control

Regular Incoming Waves

The monochromatic waves behave as a sinusoidal wave, as shown in Fig. 7 (a), with Height 2m and period 8s. In Fig. 7 (b) and (c), the motor shaft is rotating with a stabilized speed around required 1500 rpm, and the fraction of motor displacement is oscillating from 33% to 38%.

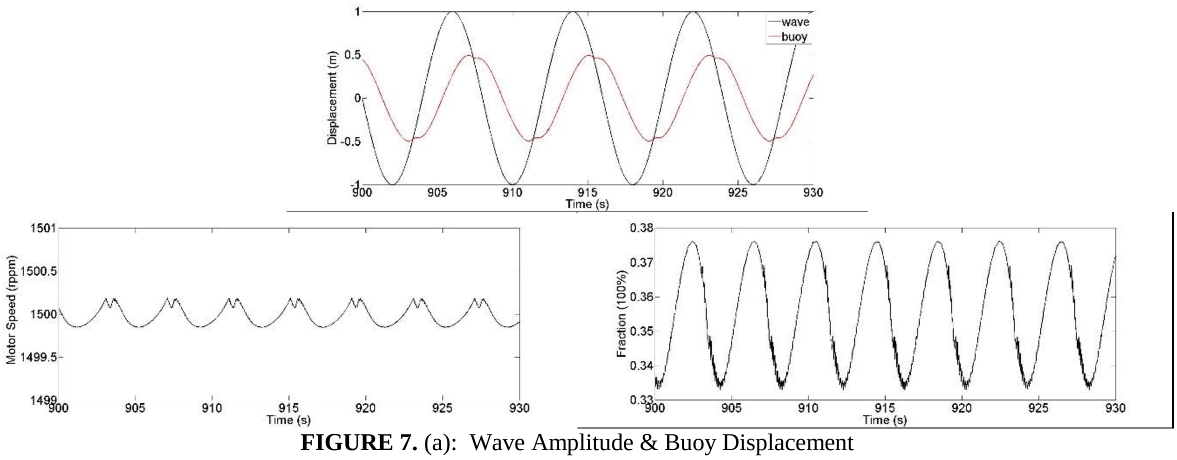

FIGURE 7. (a): Wave Amplitude & Buoy Displacement
(b): Motor Speed; (c): Motor Capacity Fraction

Irregular Incoming Waves

With respect of irregular waves, different from regular sinusoidal waves, the wave exciting conditions are far more complicated as in Fig. 8 (a). Nevertheless, in Fig. 8 (b) and (c), it illustrates that the system is capable to cope with these incoming conditions with tiny changed motor speed and allowable motor swash fraction.

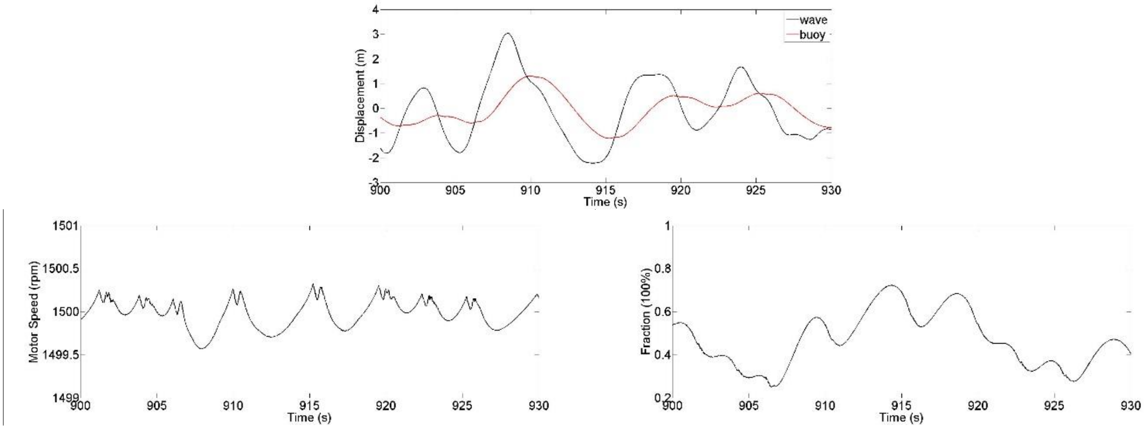

FIGURE 8. (a): Wave Amplitude & Buoy Displacement
(b): Motor Speed; (c): Motor Capacity Fraction

Damping Control

From the look-up table, for the wave condition of 2m height and 8s period, the optimum value of PTO damping for waves is 220 kN/(m/s). Both the relative demand electromagnetic torque based on the optimum damping in green colour and the real-time torque output signal in red colour are shown in Fig. 9 (a). It clearly shows that the output torque signal follows the demand signal well with the negligible difference. Therefore, the generator outputs the optimum torque and hence as in Fig. 9 (b), WEC converts the maximum electricity of 6.4 kW with the current integrated design.

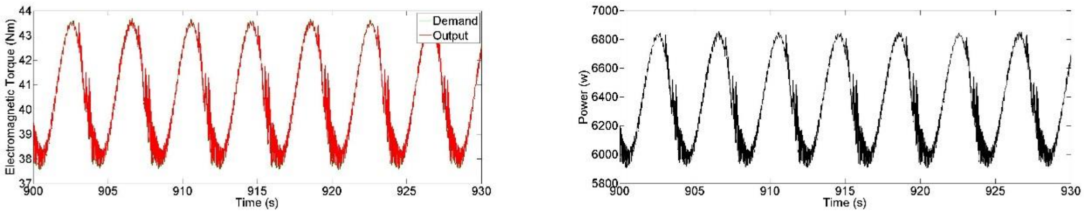

FIGURE 9. (a) Demand & Output Torque (b) GENERATED POWER

CONCLUSIONS

In order to design a wave energy converter from wave to wire for practical application, the controller is established primarily on both prospects- speed and damping.
In aspect of speed, the closed loop control strategy is built to the transmission stage. By cooperating with the appropriate accumulators, adjusting the motor displacement according to the wave conditions is used to maintain the speed of motor-generator shaft roughly constant, which has been investigated in both the regular and irregular wave condition.
As for the damping control that is applied to the generation stage, the electricity output is generated controllably via a look-up table for the optimum system damping factor under different wave conditions. The filed excitation voltage applying across the generator rotor is capable to alter the electromagnetic torque based on the demand value, hence the power is converted from wave to grid subsequently.

REFERENCES

1. T. Thorpe, "An overview of wave energy technologies," Future Energy Solutions, 1998.
2. U. Korde, "Efficient primary energy conversion in irregular waves," Ocean engineering, vol. 26, pp. 625-651, 1999.
3. K. Budar and J. Falnes, "A resonant point absorber of ocean-wave power," Nature, vol. 256, pp. 478-479, 1975.
4. K. Schlemmer, F. Fuchshumer, N. Böhmer, R. Costello, and C. Villegas, "Design and control of a hydraulic power take-off for an axi-symmetric heaving point absorber," in Proceedings of the Nineth European Wave and Tidal Energy Conference, Southampton, 2011.
5. N. Baker and M. Mueller, "Direct drive wave energy converters," Rev. Energ. Ren.: Power Engineering, pp. 1-7, 2001.

6. R. Henderson, "Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter," Renew. Energy, vol. 31, pp. 271-283, 2006.
7. J. Brooke, Wave energy conversion: Elsevier, 2003.
8. Masuda Y, Kuboki T, Xianguang L, Peiya S. Development of a terminator type BBDB. 3rd EWEC, Patras, Greece, 2000.
9. Yemm R, Pizer D, Retzler C. The WPT-375-a near-shore wave energy converter submitted to Scottish renewables obligation 3, 1998. Third European wave power conference 1998, In: Dr.-Ing, editor. Proceedings of an International Conference held in Patras, Greece, 30 September–2 October 1998, Wilhelm Dursthoff, University of Hannover, Germany, 2000, Vol. 2, p. 243–9.
10. M. Mueller, H. Polinder, and N. Baker, "Current and novel electrical generator technology for wave energy converters," in Electric Machines & Drives Conference, 2007. IEMDC'07. IEEE International, 2007, pp. 1401-1406.
11. J. Ringwood, G. Bacelli, and F. Fusco, "Energy-Maximizing Control of Wave-Energy Converters THE DEVELOPMENT OF CONTROL SYSTEM TECHNOLOGY TO OPTIMIZE THEIR OPERATION," IEEE Control Syst. Mag., vol. 34, pp. 30-55, 2014.
12. J. P. Kofoed, "Wave Overtopping of Marine Structures: utilization of wave energy," Videnbasen for Aalborg UniversitetVBN, Aalborg UniversitetAalborg University, Det Teknisk-Naturvidenskabelige FakultetThe Faculty of Engineering and Science, Institut for Vand, Jord og MiljøteknikDepartment of Civil Engineering, 2002.
13. (2017, 22/03). Construction of Three Phase Synchronous Motor.
14. Antonio, F. de O. "Modelling and control of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator." Ocean engineering 34.14 (2007): 2021-2032.
15. Ricci, P., et al. "Control strategies for a simple point-absorber connected to a hydraulic power take-off." Proceedings of 8th European Wave and Tidal Energy Conference, Uppsala, Sweden. 2009.