19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

Ocean Wave Energy Converter Performance at a Specific Geographical Location

S. J. Illesinghe[1], **R. Manasseh**[2], **R. Dargaville**[3] **and A.Ooi** [1]

[1]Department of Mechanical Engineering
University of Melbourne, VIC 3010, Melbourne, Australia

[2]Faculty of Engineering and Industrial Sciences
Swinburne Univeristy of Technology, VIC 3122, Melbourne, Australia

[3]School of Earth Sciences, The University of Melbourne, Victoria 3010 Australia.

Abstract

Ocean Wave Energy Converters (WEC) attempt to convert energy from ocean waves to useful electrical energy. This sustainable energy resource is available across the Australian continental shelf and has potential to contribute to the total electrical supply. Although pilot scale projects on wave energy extraction approaches are currently underway, there is limited knowledge on the optimum characteristics of generic WEC devices for any given location. The performance characteristics of a generic WEC are presented. A generic WEC is modelled by a linear oscillator equation. This can be derived considering the Euler equations for sea-surface flow and the fluid flow induced by the device motion, together with additional parameterisations. Data used to analyse the potential wave energy resource is generated from the AUSWAVE model. The AUSWAVE model is developed by the Bureau of Meteorology, based on the WAVEWATCH III model and the Australian Community Climate and Earth-System Simulator weather model for Australia (ACCESS-A). These data are also used to analyse the potential wave energy resource. This data will be utilized to analyse the performance of the generic WEC technology at various locations across the Australian continental shelf. The power output of the WEC was determined on monthly and yearly basis. Additionally, the performance of the WEC was further analysed to identify energy contributions from ocean swell and the wind waves. A decomposition of the WEC performance into the component due to the ocean swell and the component due to wind waves reveals that the approach to considers in extracting the largest quantity of wave power from a specific location.

Introduction

Ocean Wave Energy Converters (WEC) attempt to generate useful electricity from ocean waves. These ocean waves carry both potential energy and kinetic energy [6]. Some ocean waves travel vast distances to reach a location with minimum energy loss, which are known as ocean swell while other ocean waves are locally generated by local winds and are known as wind-sea [3]. Therefore multiple wave systems operate at any given location. The identification of optimal machine parameters for a WEC technology at a specific location provides WEC technology developers useful information prior to large scale infrastructure development at that specific location.

There are many WEC approaches [5] to generate ocean wave energy into useful power, with each approach having varied benefits in efficiency, longevity, and commercial viability. WEC technologies have been deployed with varying success levels across the globe over the last few decades [8, 2]. A common WEC approach is the oscillating buoy [5]. Oscillating buoys are WEC devices which operate fully submerged or semi-submerged in the ocean, and are anchored to sea floors or other marine structures. The WEC buoy is excited by incoming waves, when it oscillates. These oscillations of the buoy are converted to electricity by a power take off device [3]. The WEC buoy is likely to operate differently when it is excited by various wave systems. The present paper aims to provide a methodology to identify optimal machine parameters of a generic WEC buoy which operates at a location with multiple wave systems.

In this paper, we will provide wave property estimates for the various wave systems operating at a specific location. The wave energy resource variability at a specific location will be estimated on a monthly basis. Euler equations for fluid mechanics will be utilized to develop a model to estimate the sea-surface flow and the fluid flow induced by the WEC buoy motion. Then the effect of machine parameters such as the damping parameter and non-dimensional natural period of oscillation of the device will be varied to estimate the annual, and monthly WEC performance to identify optimal machine parameters which generate power at that specific location.

Methodology

The model developed by Australian Bureau of Meteorology was used to estimate ocean wave properties at a given location. The AUSWAVE model uses version 3.14 of WAVEWATCH III and surface wind data from the Australian Community Climate and Earth-System Simulator for the Australia region (ACCESS-A) to generate oceanographic data [4]. The oceanographic data generated for the various wave systems by AUSWAVE, utilizes the spectral partitioning schemas as detailed in Durrant *et al.* [4]. Hourly data for 2011 were utilized in this study. As southern coastal regions in Australia have abundant wave energy [7] , a location near Port Fairy was considered as a potential location for the installation of the WEC device. The wave properties at this location are detailed in Table 1. The table shows annual averages for the wave periods and wave heights of the primary swell system, secondary swell system and the wind-sea system. The table also shows the standard errors in brackets. As expected the primary swell system period is greater than the secondary swell system period which is followed by the wind-sea system period. The average wave heights are greater for the primary swell system compared to the secondary swell system and the wind-sea system at this Port Fairy location.

Wave energy resource estimation

To estimate the wave energy resource, the energy flux in deep water is assumed, and the linear water wave theory was adopted in the usual way,

$$E_{flux} = \frac{\rho g^2}{64\pi} T_e H_{sig}^2, \tag{1}$$

where ρ is the density of liquid, g gravity and T_e the wave en-

Wave systems	Period (sec)	Wave height (m)
Peak wave	13.1 (0.0)	2.6 (0.0)
Primary swell	11.9 (0.0)	1.9 (0.0)
Secondary swell	6.3 (0.1)	0.4 (0.1)
Wind-sea	3.14 (0.1)	0.8 (0.0)

Table 1: Annual wave property statistics for the Port Fairy site location. The standard errors of the wave property statistics are shown in brackets.

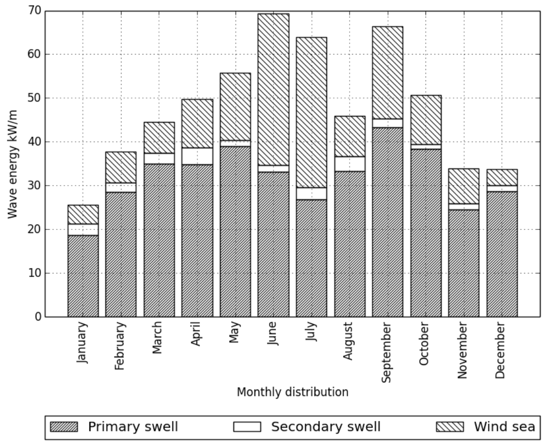

Figure 1: Monthly wave energy distribution by various wave systems at the Port Fairy site location.

ergy period and H_{sig} the significant height of the wave [6]. The wave energy period T_e is approximated as $T_e = 0.86T_p$, where T_p is the peak wave period, similar to Behrens *et al.* [1] and Saulnier *et al.* [9]. The energy fluxes resulting from the primary swell, secondary swell and the wind-sea were calculated. Each wave system contribution on an monthly basis is shown in Figure 1.

The monthly distribution of the wave energy resource at the Port Fairy location shows that the average monthly wave energy is largest in June and smallest in January. The difference between the largest and the smallest monthly averages is about 50 kW/m. Figure 1 shows the contribution by each wave system on the overall wave energy system. At this location the primary swell system contribution is larger than the wind-sea system contribution for most months except for June. The secondary swell system contribution to the overall wave system is significantly minimal compared to the wind-sea system and the primary swell system. The wind-sea system contribution is significantly large in June and July when compared to other months of the year. Greater variation in wave energy due to the wind-sea system is evident at this location. Such variation was also observed at other locations in the southern oceans of Australia. In analysing the wave system distribution at this location the greatest portion of power is generated by WEC if it is designed to extract energy from the primary swell system. If the WEC is designed only to extract wave energy from the primary swell system, in June 52.4 % of available wave energy would not be utilized to generate power. WEC developers would benefit if their technology operates with multiple wave systems rather than with a single wave system. Therefore, to determine the effect of multiple wave systems on power generation, a generic WEC model is developed.

Formulation of the WEC device model

A generic WEC buoy device which oscillates in the vertical direction was considered. The WEC buoy is excited by an incoming wave having significant height H_{sig} and an oscillating frequency ω. This incoming wave applies pressure on the WEC buoy body, forcing the buoy to oscillate. The motion of the WEC buoy displaces a liquid mass. It is assumed that this liquid mass is significantly smaller than the WEC body mass and the WEC body is fully submerged. Relating this displaced liquid mass to its density and volume allows the equation of motion of the generic WEC device to be simplified as,

$$\ddot{\hat{z}} + 2\delta\omega_0\dot{\hat{z}} + \omega_o^2\hat{z} = \frac{gH_{sig}}{L}\sin\omega t, \qquad (2)$$

where ω_o is the natural frequency of the WEC device and δ is the damping parameter of the device. The vertical oscillatory motion is denoted by $\hat{z}$. Eq.(2) is driven by the incoming wave with a significant height H_{sig} and period ω. The length of the WEC buoy body is denoted as L. Most prior formulations of the WEC models have been dimensional. As there could be multiple combinations of device geometrical lengths, natural frequencies and damping parameters, a non-dimensional scheme with scaling parameters is utilized to effectively analyse the oscillatory motion of the WEC buoy body. Scaling parameters used in the non-dimensionalization scheme are,

$$\begin{aligned} t &= \omega_o\hat{t}, \text{ and} \\ z &= \frac{\hat{z}}{L}. \end{aligned} \qquad (3)$$

Applying scaling parameters defined by Eq.(3) into Eq.(2) gives,

$$\ddot{z} + 2\delta\dot{z} + z = \frac{1}{Fr}\frac{H_{sig}}{L}\sin\left(\frac{\omega}{\omega_0}t\right), \qquad (4)$$

where Fr is a class of Froude number with the form $Fr = \frac{\omega_0^2 L}{g}$. The motion of the generic WEC device identified in Eq.(4) has a number of parameters. These parameters include the damping parameter δ, the constant Fr, the ratio of significant height to the length of the body (i.e. $\frac{H_{sig}}{L}$) and the frequency of the incoming wave ω and the natural frequency of oscillation ω_0 of the device. In identifying the non-dimensional equation of motion, the magnitude of real power of the system was formulated as,

$$P_{real} = \delta|\dot{z}|^2. \qquad (5)$$

The real power of the system is the power which is transferred from the WEC device.

The non-dimensional velocity $\dot{z}$ was identified by solving Eq. (4) in the usual way, and was used to identify the magnitude of real power or the time-averaged transferred power by the WEC device in Eq (5). Therefore, the non-dimensional real power is the power generated by the WEC device. The machine parameters which determine the power generated, include the length L of the body, damping parameter δ and the natural frequency ω_0. The WEC device length acts to increase or decrease the gravitational acceleration which excites the device. If a WEC buoy has a smaller length it would be excited by a larger frequency range and would oscillate with greater magnitude of amplification. Therefore a comparable device length is required. As large scale pilot projects currently under construction have WEC devices having lengths between about $20-30$ m, a device length of 30 m was considered for this analysis. Also, WEC developers typically limit the displacement of the WEC device by a mooring system or an inherent feature of the device design. Therefore in the present study, WEC device displacement was limited to the amplitude of the incoming wave. The real power estimated for the generic WEC device in Eq.(5) was evaluated with multiple wave systems at the specific site location. The damping parameter, and the natural period of oscillation of the WEC device was varied.

Results and Discussion

Annual distribution

Figure 2 shows the mean annual non-dimensional power generated by the generic WEC device for a range of damping parameters varying from 0.05 to 1.0 with specific non-dimensional natural period of oscillation ranging from 0.0 to 1.0. T is the non-dimensional natural period of oscillation, where the natural period of oscillation is normalized by a reference period of 12.0 sec. Figure 2 shows that the largest mean non-dimensional power is generated for the non-dimensional natural period of oscillation of 1.0, while the smallest non-dimensional power is generated for the non-dimensional natural period of oscillation of 0.33. Figure 2 also shows an optimal damping parameter exists for each mean non-dimensional natural period of oscillation. As the non-dimensional natural period of oscillation increases the optimal damping parameter increases for the non-dimensional natural period of oscillation range of 0.33 to 1.0. The maximum non-dimensional power estimated as shown in Figure 2 is for the non-dimensional natural period of oscillation of 1.0, while the minimal non-dimensional power is observed for the natural period of oscillation of 0.33. A difference of about 870.6 mean non-dimensional power units is evident between the optimal damping parameter for the non-dimensional period of oscillation of 0.33 and 1.0. This shows that a optimal damping parameter can be identified for the various wave systems operating at the Port Fairy location. If the non-dimensional natural period of oscillation is not appropriate for the location the magnitude of mean non-dimensional power generated is suboptimal. Therefore, an optimal non-dimensional natural period of oscillation is further considered.

Figure 3 shows the mean annual non-dimensional power generated by the generic WEC device for a range of non-dimensional natural periods of oscillation varying from 0.33 to 2.5 for specific damping parameters. An optimal natural period of oscillation exists within the range of non-dimensional natural periods of oscillations of 1.58 and 1.83 for the damping parameter range of 0.1 to 0.9. The minimal annual non-dimensional power is evident for a damping parameter 0.1. Similarly, Figure 3 shows that the mean annual non-dimensional power generated is largest for the 0.9 damping parameter.

The optimal mean non-dimensional power changes with the damping parameter, similar to Figure 2. A difference of about 2031.8 in mean non-dimensional power is observed between damping parameters 0.1 and 0.9. Therefore, at this location, the optimal annual mean non-dimensional wave power is generated with a non-dimensional natural period of oscillation of about 1.67 and a damping parameter of 0.9. These optimal parameters provide useful information to WEC developers to consider

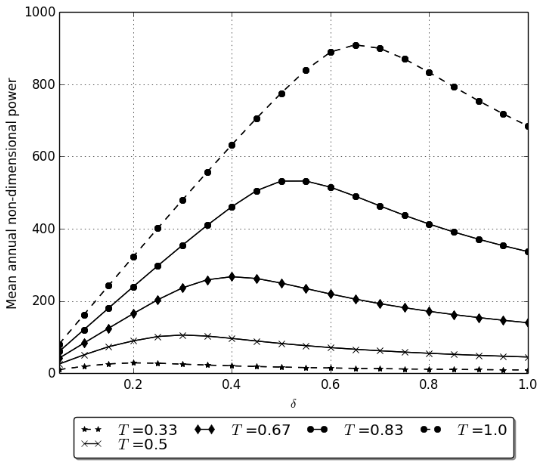

Figure 2: Annual mean non-dimensional power generated for various damping parameters and a non-dimensional natural period of oscillation varying from 0.33 to 1.0.

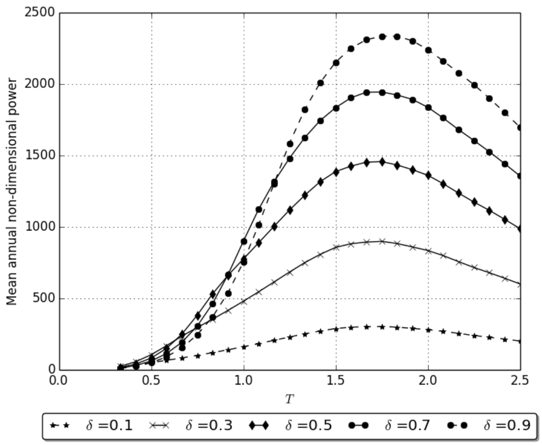

Figure 3: Annual mean non-dimensional power generated for various non-dimensional natural periods of oscillation and damping parameters varying from 0.1 to 0.9.

prior to large scale infrastructure developments at the Port Fairy location. As wave energy is variable across various months as shown in Figure 1, the optimal annual parameters may not be appropriate on a month by month basis. Accordingly, a monthly analysis is also considered here onwards.

Monthly distribution

Figure 4 shows the monthly distribution of the mean non-dimensional power generated with a non-dimensional natural period of oscillation of 0.83. The largest mean non-dimensional power is generated in June for the damping parameter range of 0.10 to 0.95. The smallest mean non-dimensional power is generated in January for the same damping parameter range. A difference of about 456.2 non-dimensional power units, is observed between the maximum power generated in June and the maximum power generated in January. The mean non-dimensional power increases from January till June. The mean non-dimensional power decreases from June to December with a increase from July to September at this location. An optimal damping parameter is evident for each month similar to the annual results as shown in Figure 3. The optimal damping parameter varies between 0.5 and 0.6. There is minimal difference between the annual optimal damping parameter and the

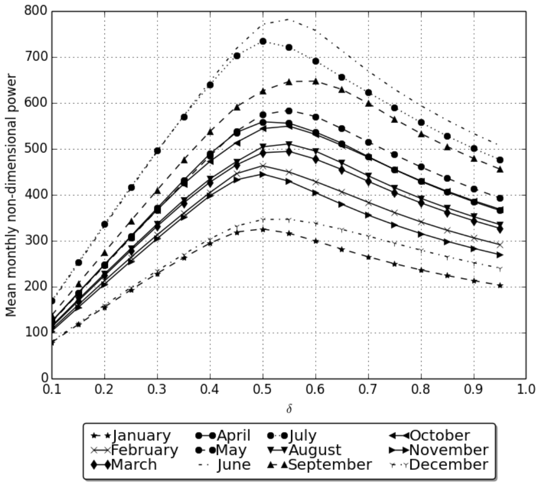

Figure 4: Monthly mean non-dimensional power generated with a varying damping parameter and a non-dimensional natural period of oscillation of 0.83.

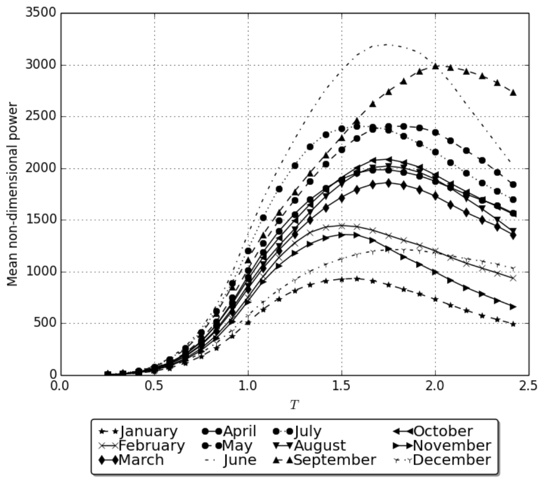

Figure 5: Monthly mean non-dimensional power generated with varying natural period of oscillation and a damping parameter of 0.7

monthly optimal damping parameters.

For further analysis, the mean monthly non-dimensional power for a range of natural period of oscillations and a damping parameter of 0.7 were analysed and the results are shown in Figure 5. Similar to Figure 4, the largest mean non-dimensional power was evident in June for the non-dimensional natural period of oscillation range of 0.42 to 2.42. The smallest mean non-dimensional power was generated in January while largest mean non-dimensional power was generated in June. A difference of 2260.2 mean non-dimensional power units, exists between the optimal non-dimensional natural period of oscillation in June and the optimal non-dimensional natural period of oscillation in January. Increases in the mean non-dimensional power is only evident for months ranging from January to June similar to that shown in Figure 4. Similar to Figure 4, the mean non-dimensional power decreases from June to December, however there is an increase in the mean non-dimensional power from August to September at this location.

An optimal natural period of oscillation appears to exist for all months similar to that shown in Figure 3. The optimal non-dimensional natural period of oscillation varies between 1.5 and 2.0. Compared to the annual non-dimensional optimal natural period of oscillation of 1.67, as shown in Figure 3 there is variation between the optimal natural period of oscillation for each month.

Conclusion

The wave energy resource available at the Port Fairy location showed that there are multiple wave systems operating at this location and they contribute differently for each month to the overall wave energy system. The effect of multiple wave systems on the power generated by a WEC model was explored on an annual basis for varying natural periods of oscillation and damping parameters. The results showed that there exists an optimal non-dimensional natural period of oscillation and a damping parameter combination for the Port Fairy location. The analysis was extended to consider whether the optimal annual non-dimensional natural period of oscillation and damping parameter combination would be appropriate on a month by month basis. For this location the optimal annual non-dimensional natural period of oscillation and damping parameter ranges did not change significantly compared to the optimal monthly non-dimensional natural period of oscillation and damping parameter ranges. The methodology in the present paper shows that the WEC developers could identify optimal natural period of oscillation and damping parameters for any geographical location where there are multiple wave systems operating at that location. The results also showed that an optimal non-dimensional natural period of oscillation and damping parameter range ideally maximizes the power generated by the generic WEC technology at a particular location.

References

[1] Behrens, S., Hayward, J., Hemer, M. and Osman, P., Assessing the wave energy converter potential for australian coastal regions, *Renewable Energy*, **43**, 2012, 210–217.

[2] Budar, K. and Falnes, J., A resonant point absorber of ocean wave power, *Nature*, **256**, 1975, 720–724.

[3] Cruz, J., *Ocean wave energy*, Springer-Verlag Berlin Heidelberg, Berlin Germany, 2008.

[4] Durrant, T. and Greenslade, D., Evaluation and implementation of auswave, Technical report, The centre for Australian weather and climate research, 2011.

[5] Falcão, A. F. O., Wave energy utilization: A review of the technologies, *Renewable and Sustainable Energy Reviews*, **14**, 2010, 899 – 918.

[6] Falnes, J., *Ocean waves and oscillating systems*, Cambridge University Press, Cambridge United Kingdom, 2008.

[7] Hemer, M. A., Church, J. A. and Hunter, J. R., Waves and climate change on the australian coast, *Journal of coastal research*, **50**, 2007, 432–437.

[8] Salter, S. H., Wave power, *Nature*, **249**, 1974, 720–724.

[9] Saulnier, J., Prevosto, M. and Maisondieu, C., Refinements of sea state statistics for marine renewables: A case study from simultaneous buoy measurements in portugal, *Renewable Energy*, **36**, 2011, 2853–2865.