Accelerating the Adoption of Renewable Energy as We Strive for Net Zero 2050 – a Breakthrough in Wave Energy Conversion – Phase 1

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Abstract

Wave energy has a huge potential in complementing existing renewable power grids. It has a high energy density, is more predictable than wind, and is readily available across the other 50% of the planet – oceans with water depths greater than 50m. However, no wave power generator has emerged as a commercially viable proposition, as existing solutions face design, operational, and financial challenges. WaveX is a renewable energy technology developer, with a breakthrough system which addresses these existing challenges and can help accelerate ocean communities towards Net Zero 2050. The D-Spar Wave Power Generator adapts an already proven technology from a parallel industry, for the purposes of wave energy conversion. It delivers a durable, environmentally sustainable, efficient, and easy to maintain device that transforms the vertical motion of ocean waves, directly into green electricity. This project aims to develop a numerical model for the D-Spar with improved accuracy and flexibility for design. At this nascent stage of development it was found that the D-Spar can generate up to 372 kW per year with a capture width ratio of 19.5% with identification of significant improvements and future works to further augment these metrics.

1. Introduction

Renewable energy is becoming vital in achieving net zero by 2050. However, with the rapidly growing energy demand, an alternative is needed to complement the existing wind and solar energy systems. Wave energy has huge potential, as it is more predictable than wind energy, less intermittent, and has a high energy density (Ilyas et al., 2014). The coastline at the 50 m depth along South Western Australia alone can theoretically produce 1,095,000 GWh a year (Hermer et al., 2016), which is a significant addition to Australia's renewable energy mix.

Despite the countless wave power generators (WPG) invented over the past few decades, only a few have progressed into commercialisation. The design itself is always a challenge, particularly for far offshore sites where large waves are encountered. Moreover, survivability under harsh conditions such as storms, hurricanes, and corrosive seawater need to be considered (Aderinto & Li, 2018). Operation and maintenance cost greatly affect its ability to be commercialised. Another important consideration is its impact on the environment.

To address all the hurdles encountered from past inventions, WaveX has developed its breakthrough wave power generator called the D-Spar. Using a proven technology, the D-Spar consists of an inner spar and an outer spar of different lengths, moving relatively in the vertical direction to generate power. Generation 1 of the device is comprised of a single pair of inner spar and outer spar, whereas Generation 2 utilises three pairs of inner and outer spars connected by bracing. However, unlike usual offshore structures, the D-Spar WPG is designed to resonate with ocean waves period. Figure 1 displays the most recent version of the D-Spar wave power generator (Generation 2).

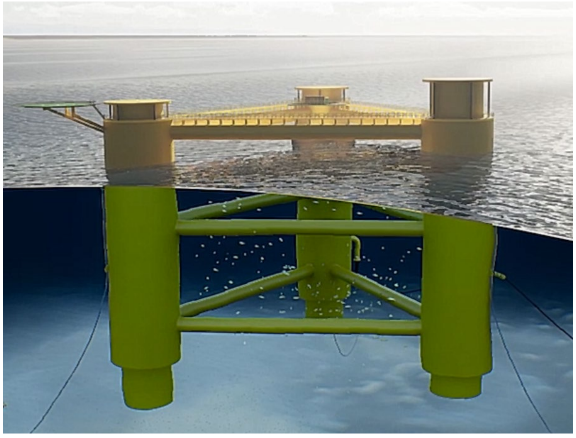

Figure 1 Generation 2 model of D-Spar wave power generator.

Given its design, Generation 1 can be classified as a self-reacting two-body heaving system, which is a point absorber. Generation 2 can be classified as a multi-body point absorber. A number of studies have focused on self-reacting bodies. An experimental study was conducted for a two-body WPG consisting of a streamlined conical outer buoy that surrounds an elongated inner buoy, and it was found that the device possessed stability and survivability, which enhanced energy capture (Li et al., 2023). A floating conical body with a central vertical tube was investigated and it was found out that gradually increasing the tube diameter results in a higher power capture relative to the size of the device (Kurniawan et al., 2019). The main objective of this project is to develop numerical models for Generation 1 and then Generation 2 devices in increasing levels of complexity, then conduct parametric studies, and present a simple optimisation of the WPG to further these previous works specific to the D-Spar.

2. Numerical Model Development

The numerical model assumes linear theory under the frequency domain, where due to harmonic oscillation, time dependence is factored out. Generalised modes of motion (Falnes & Kurniawan, 2020) are used to model the D-Spar. The equation of motion can be expressed in a standard frequency domain form as:

$$\left\{i\omega(\boldsymbol{M}+\boldsymbol{A})+\boldsymbol{B}+\boldsymbol{B_{PTO}}+\boldsymbol{B_{loss}}+\frac{1}{i\omega}\boldsymbol{C}\right\}\boldsymbol{U}=\boldsymbol{F} \quad [1]$$

M is mass matrix, **A** is added mass matrix, **B** is radiation damping matrix, $\mathbf{B_{PTO}}$ is diagonal power take-off (PTO) damping matrix, $\mathbf{B_{loss}}$ is diagonal loss damping matrix, **C** is stiffness matrix (includes hydrostatic **K** and gravity contribution), **U** is velocity vector, and **F** is excitation force vector.

For Generation 1, the system can be described in two modes, a combined heave mode and a relative heave mode. Other modes such as pitch and roll are not taken into account as they do not affect the resulting relative heave motion. Modes other than heave have to be considered in Generation 2, requiring the model to have nine modes. The first six modes correspond to the combined rigid body motions (surge, sway, heave, roll, pitch, and yaw). The subsequent three modes (due to three inner spars) correspond to relative heave motion between the combined rigid body and each inner spar. Figure 2 depicts sketches of the D-Spar.

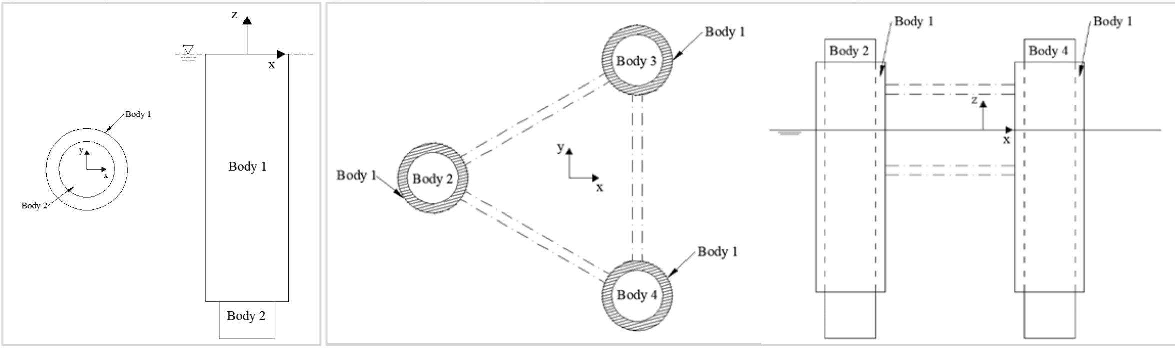

Figure 2 Generation 1 (Left) and 2 (Right) of the D-Spar sketches.

The components of the mass matrix **M** can be described as:

$$M_{ij} = \iiint_V \rho_m S_i^T S_j \, dV \qquad [2]$$

The elements of the hydrostatic restoring force matrix **K** can be expressed as:

$$K_{ij} = -\rho g \iint_{S_B} n_j (S_{iz} + z D_i) \, dS \qquad [3]$$

S_i and S_j are shape function of the body, ρ_m is mass density of the body, ρ is the mass density of seawater, n is normal component of shape function S, S_{iz} is the z-component of shape function S_i, D_i is divergence of S_i, V is volume of the body, and S_B is mean wetted body surface. Combining hydrostatic force and gravity contributions, **C** matrix is obtained. **A** and **B** matrices are obtained from NEMOH (boundary element method code).

The mooring system and rigid frames connecting multiple spars are not modelled. PTO damping is assumed to behave linearly and is optimised for each sea state. The vertical coordinate of the centre of gravity is assumed to be a multiple of that of the centre of buoyancy. To ensure the survivability of the D-Spar, a locking mechanism based on wave height limits are imposed which are consistent with the intended operation of the D-Spar at industrial scale. For the sake of brevity, only a wave incident angle of 0° is used. The WPG is analysed using Torbay, Albany wave data (Cuttler et al., 2017).

3. Results and Discussion

3.1 Parametric Study

The base dimensions of Generation 1 and Generation 2 are determined based on the previous numerical model (Kurniawan et al., 2023) and RiverLab prototype, respectively. Parameters are then modified to measure the effect on the mean annual power. Wetted area is used to normalise the mean annual power. Table 1 presents the dimensions used as the base model.

For the sake of brevity, abbreviations are used to describe the parameters, which are OSD for outer spar draft, ISB for inner spar draft, OSD for outer spar diameter, ISD for inner spar diameter, SSD for spar-to-spar distance, COGM for centre of gravity multiplier (obtained by multiplying centre of buoyancy by a factor).

Gen.	OSD [m]	ISD [m]	OSB [m]	ISB [m]	SSD [m]	COGM
1	11	7.5	33	38	-	-
2	12.6	9	32	38	50	1.5

Table 1 Base dimensions of Generation 1 and 2.

Figure 3 presents the resulting parametric studies. Increasing inner spar draft yields higher power per wetted area for both generations due to a longer natural period, which coincides more with the wave period, hence producing resonance. Increasing the outer spar draft reduces power per wetted area for both generations. In terms of increasing the outer spar diameter, Generation 1 power output per wetted area increases almost linearly as the waterplane area increases, whereas Generation 2 power per wetted area appears to peak at 15.2 m. Increasing the inner spar diameter proves to be inefficient for Generation 1. For Generation 2, an increase in inner spar diameter generates higher power up to a diameter of 10 m.

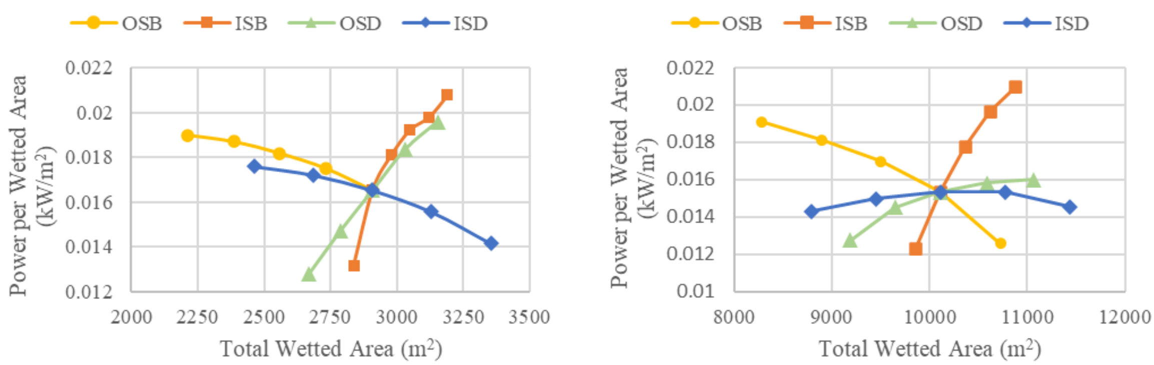

Figure 3 Normalised power of core dimension parametric studies for Generation 1 (Left) and 2 (Right).

Figure 4 shows spar distance and centre of gravity parametric studies, which are only applicable to Generation 2. In general, reducing spar-to-spar distance may prove to be cost effective, as the power yield does not change significantly. On the other hand, designing the centre of gravity to be closer to the water surface reduces the power per wetted area.

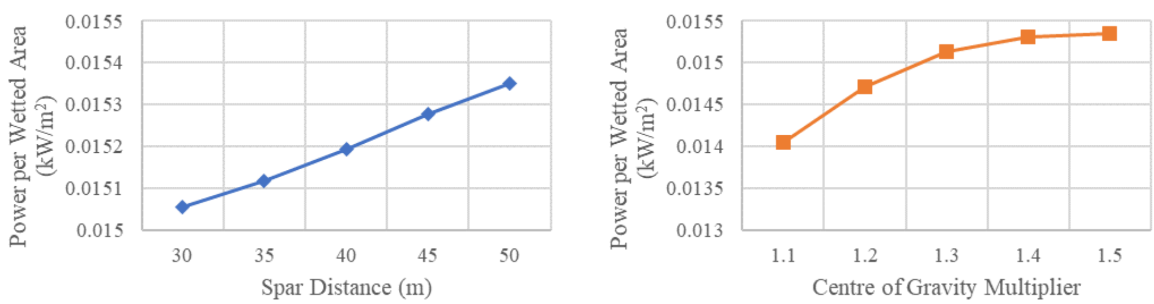

Figure 4 Normalised power of spar distance (Left) and centre of gravity (Right) parametric studies for Generation 2.

3.2 Sponson and Heave Plate

In order to boost the D-Spar performance further, sponsons and heave plates are tested for the Generation 1 model. Sponsons enlarge the waterplane area, increasing the radiation damping and force excitation. Heave plate addition increases the added mass, shifting the natural period to a longer period, which may coincide with the wave period. Figure 5 shows sponsons and heave plate parametric studies.

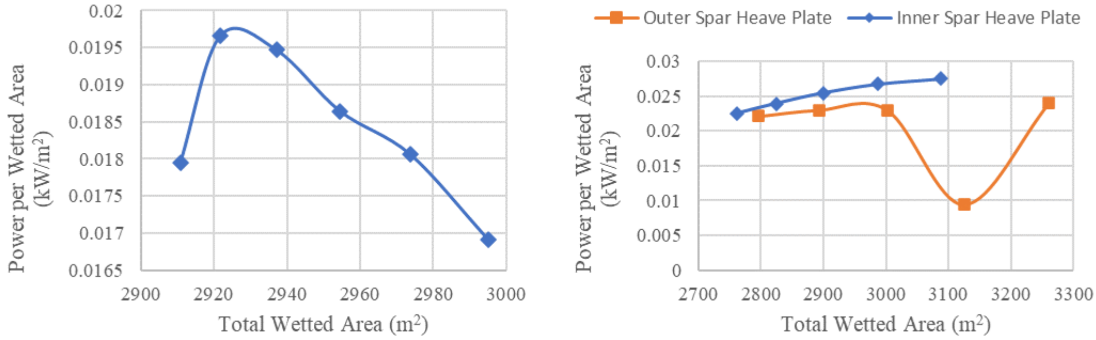

Figure 5 Normalised power of sponsons width (Left) and heave plate (Right) parametric studies for Generation 1.

A peak for sponsons width is observed at 0.5 m. Modifying it lowers the power as less cancellation of incident waves occur due to changes in radiation damping, excitation force, and natural period. For heave plate models, both show a better performance than the base case of 0.0165 kW/m^2. However, a significant depression is observed, which may be caused by the force excitation cancellation.

3.3 Optimisation

Based on the parametric studies, optimised dimensions are proposed in Table 2. Additional abbreviations used are SW for sponsons width and HPW for heave plate width. Figure 6 depicts the meshes used for the optimised models.

Gen.	OSD [m]	ISD [m]	OSB [m]	ISB [m]	SW [m]	HPW [m]	SSD [m]	COGM
1	12	6.5	30	41	0.5	5	-	-
2	15.2	9	32	47	-	3	40	1.5

Table 2 Optimised dimensions of Generation 1 and 2.

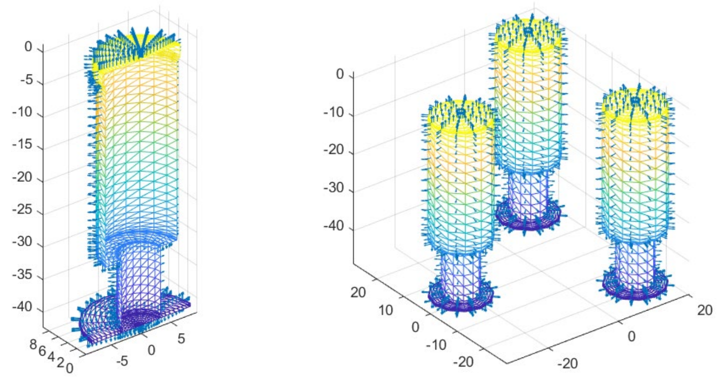

Figure 6 Optimised meshes for Generation 1 (Left) and 2 (Right).

From the optimised dimensions, Generation 1 produces 100kW annually with a capture width ratio of 18.6%. On the other hand, Generation 2 produces 372kW annually with a capture width ratio of 19.5%.

4. Conclusions and Future Work

The D-Spar Generation 1 and 2 have been successfully modelled and analysed. Increasing the outer spar diameter and inner spar draft are the most efficient method to scale the power up. Reducing spar distance in the Generation 2 model may tremendously lower the construction and operation costs without affecting performance heavily. As the addition of heave plates increases added mass, it is a great alternative to increasing draft to tune the natural period with a resulting reduction in steel for fabrication.

While sponsons provide a huge leap in power generation, further study in time domain is essential to understand the effects of varying water plane area due to the sponson, as well as the hydrodynamic loss associated with the heave plate. Additionally, research into analysing the D-Spar as a whole, along with its mooring system and complete structures, is essential to obtain a more accurate picture of Levelized Cost of Energy (LCOE). Implementing an active control may also improve the performance of the D-Spar.

5. Acknowledgements

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