Accelerating the Adoption of Renewable Energy as We Strive for Net Zero 2050 – a Breakthrough in Wave Energy Conversion – Phase 2 (Time Domain Analysis)

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Abstract

Depleting conventional energy sources and impending global warming threats necessitates a sustainable approach to energy production. WaveX has developed a wave powered generator to harness the energy from ocean waves, initially on the southern coastline of Australia, but also applicable globally. These devices are designed to interact with harsh ocean environments and convert the wave's energy into electrical energy. As part of a previous CEED project, numerical modelling in the frequency domain was adopted to optimize the device. This model is based on linear theory, assuming motions and incident waves are small. While suitable for investigating linear effects and optimizations, a time domain model is required to investigate larger motions and more complex D-Spar geometries.

This project aims to develop a time-domain model to extend its applicability to cases where non-linearities play a significant role. MATLAB and output from the boundary element solver NEMOH are utilized in this project. A linear time-domain model was developed for Generation 1 wave powered generator and is in the process of adding non-linear parameters. Random wave conditions were simulated using the JONSWAP spectrum to utilize the model's full potential. Following this work, the model will be augmented to consider the Generation 2 device.

1. Introduction

As the world moves towards an energy-intensive future, along with the depletion of conventional energy sources and emerging challenges due to global warming, a more sustainable approach to energy production is needed. Australia is considered home to one of the most enormous wave energy resources due to the Southern Ocean swell, and harnessing this energy could accelerate the transition to Net Zero. Despite its abundance and high-power density compared to other renewable resources, wave energy is one of the most underutilized renewable energy sources (Hemer et al., 2017).

In harvesting this energy source, WaveX has collaborated with The University of Western Australia to develop a wave powered generator to generate power from offshore ocean waves.

In December 2021, a scaled model of Generation 1 wave powered generator (D-Spar) was built and tested at the UWA's Coastal and Offshore Engineering Laboratory (Kurniawan et al., 2022). After further testing, the Generation 2 wave powered generator was developed in April 2023 with modifications to the initial design. A frequency-domain numerical model based on linear theory was built as a first step in numerical modelling in August 2023. This model can predict the motion of the Generation 1 wave powered generator and predict the mean power output of the device (Kurniawan et al., 2023). The revised model uses the boundary element solver NEMOH (Kurnia & Ducrozet, 2022) to calculate hydrodynamic coefficients and improve accuracy. Even with this, the frequency-domain model has some limitations. Since it is based on linear theory, the validity of the results diverges as wave amplitudes or motion responses increase or in situations where drag force is significant (Folley, 2016). There is a need for an approach to deal with such conditions more accurately. In this project, a time-domain numerical model of Generation 1 and Generation 2 wave powered generators is developed to tackle these limitations. Using this model, the existing wave powered generator is analyzed to study the effects of geometrical modifications on efficiency and power absorption. This model could be used as an accurate tool to explore the design space and validate physical model tests.

1.1 Background Information

Wave powered generators convert wave energy into another useful form of energy. Wave powered generators take various forms depending on the mechanism of energy absorption, location, and mechanism used for power take-off. The WaveX's D-Spar is a point absorber and is further classified as "self-reacting" - two floating bodies react against each other rather than against the seabed. The D-Spar is unique because it can adapt to many different power take-off types. Currently, work is advancing with direct-drive linear generators.

The D-Spar consists of an outer and inner floating spar buoy with different hull lengths. The inner spar and outer spar are allowed to oscillate based on the wave motion, and this relative motion between the inner and outer spar is utilized to harvest energy with the help of a linear electrical generator made up of a coil magnet assembly. The system is kept stationary with the help of 3 mooring lines connected between the seabed and the outer spar. Physical model testing was conducted in the wave flume at the Coastal and Offshore Research Lab at UWA. The model testing was carried out on a 1:100 scale to match the wave conditions of the test site in Albany, Western Australia (Kurniawan et al., 2022). To explore further improvements to the performance of the wave powered generator, a series of tests would be required to explore the parameter space, which would be both time consuming and expensive. The preferred alternative is to develop a numerical model based on the device's existing dimension and conduct further numerical optimization.

1.1.1 Numerical Modelling

A frequency-domain model of the system was developed in MATLAB in August 2023. This model is based on linear theory (Kurniawan et al., 2023). Since the actual hydrodynamic coefficients were unavailable, the values used in the model were the coefficients of a simple cylinder obtained using the eigenfunction expansion method (Yeung, 1981). The calculated results were comparable to the physical testing. However, the motion in the physical testing was significantly damped. Due to the inaccuracy in the existing numerical model, further work was carried out. Currently, the frequency-domain model uses the boundary element solver NEMOH to calculate the hydrodynamic coefficients. However, since the frequency-domain model is based on linear theory, the result would not be accurate in nonlinear conditions. Although the time-domain model also employs linear potential flow theory, it could accommodate nonlinear effects due to the body motions, such as enabling the calculation of the buoyancy force based on the body's instantaneous position. Even if such usage is not strictly correct according to linear theory, it can improve the model's accuracy in predicting nonlinear response, making the time-domain model necessary for further development (Folley, 2016).

2. Process

Time-domain numerical models of Generation 1 and Generation 2 systems will be created during the project. Even though Generation 1 and Generation 2 wave powered generator differ in geometrical aspects, the same procedure will be followed to develop both numerical models. Understanding the existing frequency-domain model and boundary element solver NEMOH is a crucial stage. The predictions from the frequency-domain model will act as the reference for verifying the time-domain model. For the Generation 1 wave powered generator, the degrees of freedom will be assumed to be two, as the motion in all degrees of freedom other than heave is neglected. For the Generation 2 wave powered generator, all six rigid-body degrees of freedom will be needed, plus three additional modes for the motion of the inner spars. Once the modelling of the linear time domain model is completed, nonlinear terms will be added to the model. In addition, the device's performance in random wave conditions based on a desired wave powered generator deployment location will be simulated.

2.1 Equations of Motion

The numerical modelling is carried out using the assumption of linear theory. The generalized equation of motion in the frequency domain model is represented as follows:

$$\left\{i\omega(\boldsymbol{M}+\boldsymbol{A})+\boldsymbol{B}+\boldsymbol{B}_{PTO}+\boldsymbol{B}_{loss}+\frac{1}{i\omega}\boldsymbol{C}\right\}\boldsymbol{U}=\boldsymbol{F} \tag{1}$$

Where $\boldsymbol{M}$, $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{B}_{PTO}$, $\boldsymbol{B}_{loss}$, $\boldsymbol{C}$, $\boldsymbol{U}$, and $\boldsymbol{F}$ are the mass matrix, added mass matrix, radiation damping matrix, power take-off damping matrix, loss damping matrix, stiffness matrix, velocity vector and excitation force vector respectively. The generalized equation of motion of the time domain model can be represented using Cummins equation as:

$$\sum_{j=1}^{n}\left\{\left[M_{ij}+A_{ij}^{\infty}\right]\ddot{x}_j(t)+\int_{-\infty}^{t}R_{ij}(t-\tau)\dot{x}_j(\tau)d\tau\right\}=F_i \tag{2}$$

$\ddot{x}, \dot{x}, x, t, \boldsymbol{A}^{\infty}$, $\boldsymbol{R}$, and $\boldsymbol{F}$ indicate the acceleration, velocity, displacement, time, infinite-frequency added mass matrix, radiation impulse response function, and external force respectively. Various forces acting on the body are represented below in table 1.

Symbol	Force
$\boldsymbol{F}_{exictation}$	Wave excitation force
$\boldsymbol{F}_{restoring}$	Buoyancy restoring force
$\boldsymbol{F}_{PTO}$	Power take-off force
$\boldsymbol{F}_{friction}$	Friction force
$\boldsymbol{F}_{drag}$	Drag force
$\boldsymbol{F}_{mooring}$	Mooring force

Table 1 Forces acting on the device

All forces acting on the system could be added as a part of the external force $\boldsymbol{F}$:

$$\boldsymbol{F} = \boldsymbol{F}_{excitation} + \boldsymbol{F}_{restoring} + \boldsymbol{F}_{PTO} + \boldsymbol{F}_{friction} + \boldsymbol{F}_{drag} + \boldsymbol{F}_{mooring} \tag{3}$$

The radiation impulse response function is computed using the equation:

$$R_{ij}(t) = \frac{2}{\pi}\int_0^{\infty} B_{ij}(\omega)\cos(\omega t)d\omega \tag{4}$$

The power absorbed by the power take-off system can be calculated using the equation:

$$P(t) = b_{PTO}u_r^2(t) \tag{5}$$

b_{PTO} *and* u_r represent damping coefficient of power take-off and relative velocity between the two bodies.

3. Results and Discussion

A linear time-domain model of the Generation 1 wave powered generators was created using MATLAB, and the model's prediction is compared with that of the frequency-domain model. Following the notations in the frequency-domain model, the time-domain model consists of 2 modes: heave of the combined body and relative heave. The combined heave represents the motion of the outer spar, and the relative heave is the heave motion of the inner spar relative to the outer spar. For the linear model, the forces taken into consideration are wave excitation, damping force due to power take-off, linear friction force, and linear restoring forces. The nonlinear time domain model replaces the linear restoring force with a nonlinear restoring force. To verify the results of the nonlinear time domain model, simulation was carried out for the scaled version of the D-Spar. As expected for the given geometry type, the linear and nonlinear time domain model yielded a similar prediction, as shown in figure 1. Throughout the simulations, the damping coefficient for power take-off is set to 100,000 kg/s, and linear friction coefficient is set as 20% of the maximum value of the hydrodynamic damping coefficient.

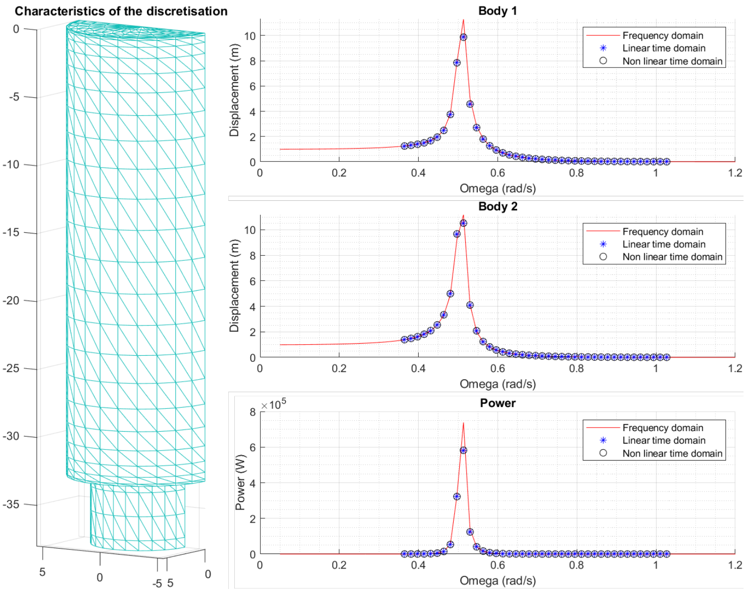

Figure 1 Mesh of D-spar and comparison of frequency domain model, linear and nonlinear time domain model for incident wave of 1 m amplitude.

The comparison of frequency-domain prediction with the prediction of the linear and nonlinear time-domain model for geometry with the addition of semi submerged sponsons is shown in figure 2. As expected, there is a variation from the linear model due to the sudden change in the shape of the device near the mean water level, which is not accounted for in the linear model.

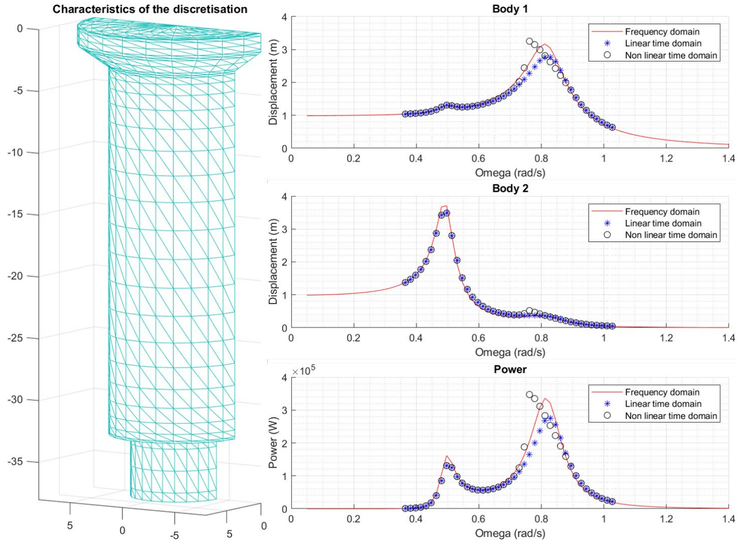

Figure 2 Mesh of D-spar with semi submerged sponsons and comparison result of frequency domain model, linear and nonlinear time domain model for incident wave of 1 m amplitude.

The response to random waves was then simulated in the time and frequency domain for regular D-spar without any sponsons. The results are shown in figure 3 and figure 4. The frequency domain and linear time domain model are used to simulate and compare results.

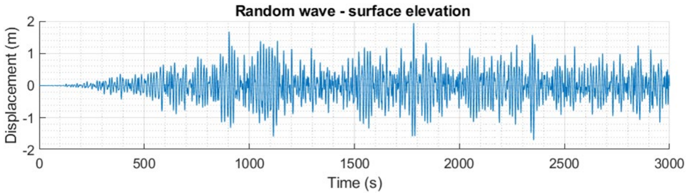

Figure 3 Surface elevation of random wave based on the JONSWAP spectrum.

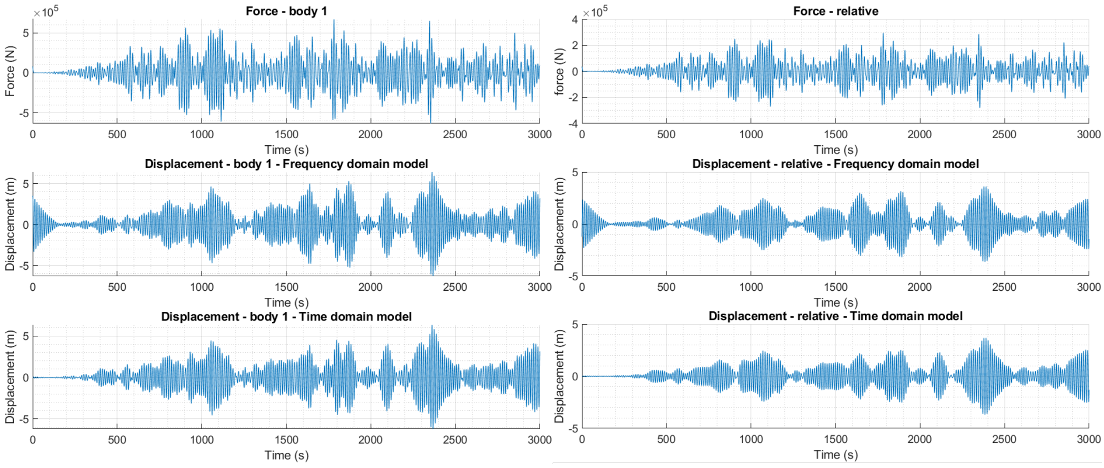

Figure 4 Force and predicted displacement of the Generation – 1 wave powered generator based on random wave.

The random wave was generated using the JONSWAP spectrum, assuming the wave's peak period and significant height are 14 seconds and 2 meters, respectively. The peak gamma for the JONSWAP spectrum is assumed to be 3.3. A sinusoidal ramp is provided to the random wave in the first 1000 seconds.

4. Conclusions and Future Work

A linear time-domain model for the Generation 1 wave powered generator was created using MATLAB, which successfully predicted the device's response. The hydrodynamic coefficients used for the model were imported from the boundary element solver NEMOH. The predictions from the time-domain model are compared with those from the frequency domain model and indicate good agreement. In the following stage, the linear buoyancy force was replaced with a nonlinear buoyancy force, and the results were analyzed. The prediction from the nonlinear model significantly deviates from the linear model's predictions for the structures with a significant change in the cross-sectional area near the mean water level. Therefore, linear and nonlinear time domain model's predictions were the same for d-spar without sponsons as the cross-sectional area is uniform. The time domain model further included the capability to generate random waves for a given location based on the wave spectrum, significant height and time-period, enabling it to predict the device's motion in a way that is similar to that of a device deployed in the ocean. For more accurate predictions, the remaining nonlinear forces, such as drag and mooring force, need to be added to the device prior to conducting the parametric study, which is still to be completed. After the completion of the time domain model for the Generation 1 wave powered generator model, a similar model will be created for the Generation 2 wave powered generator.

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