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Author: Mukther Raowf Abdul Maria	**Student No:** 273776
Supervisor: Professor Yihan Xing **Co-supervisor:** Chao Ren, Post Doc Research	
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Master's Thesis
on

Reactive control system for Swell Wave Energy Convertor

Mukther Raowf Abdul Maria
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Abstract

Wave energy converters are devices designed to harness the power of ocean waves and convert it into usable electricity. These converters are essential because they provide a reliable and consistent source of renewable energy, unlike some other renewable sources like solar or wind, which can be intermittent. This predictability makes wave energy converters a reliable source of power generation, providing stability to the energy grid.

Wave energy from swell waves has garnered significant attention as a promising source of renewable energy. Swell waves are ocean wave that originates from distant storms and carries a substantial amount of energy. The potential of wave energy from swell waves lies in its consistency and capability to generate power regardless of the weather conditions. This sets it apart from other renewable sources and makes it a valuable addition to the renewable energy mix.

A patented swell wave energy converter Power take off (SWEC PTO) by Ocean Energies AS holds great promise in harnessing the energy of swell waves. With its innovative design, this converter has the potential to revolutionize the wave energy industry by efficiently capturing the power of swell waves.

The objective of this thesis is to define a model for 30-meter diameter floater and investigate the hydrodynamic forces acting on it under swell waves of defined wave height and time period. These forces are intended to be utilized as a driving mechanism for the SWEC PTO. Subsequently, a reactive control strategy will be formulated using a flywheel with twin clutch system to enable efficient transmission of power from the floater to the tri-crank system of the PTO and further to a Generator input.

Declaration:

This Thesis work leverages a patented SWEC technology, which, due to non-disclosure agreements, necessitates some limitations on the information presented.

While specific details regarding the PTO design parameters, control logic, control algorithm MATLAB codes and precise physical characteristics of the WEC cannot be openly disclosed, it is emphasized that these proprietary elements were rigorously incorporated into the dynamic simulations and the development of the reactive control strategy presented in this work.

Acknowledgment

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I am extremely grateful to Lyder Moen, Oceanenergies AS for providing me with this exciting opportunity to collaborate on challenging and promising study.

Finally, I am eternally thankful to my colleagues, whose unfailing encouragement and support have been essential sources for inspiring me throughout the course.

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1. Introduction to Wave Energy Convertors

Renewable energy sources are crucial in addressing the growing global demand for clean and sustainable energy. (Sun et al., 2018). One of the prominent renewable energy sources is wave energy, which has the potential to play a significant role in expanding renewable energy capacity. Wave energy converters, specifically those designed to capture energy from swell waves, hold great potential in tackling the needs of renewable energy production (Catalbas & Çatalbaş, 2020).

Wave energy potential is determined by the physical characteristics of ocean waves, such as wave height, wavelength, and frequency. Swell waves, which are long and rolling waves that travel across the ocean surface, have been recognized as a significant source of wave energy. Studies have shown that swell waves possess immense energy potential, and their global distribution makes them a viable resource for wave energy generation. (Shabara & Abdelkhalik, 2023) It's estimated that swell waves could potentially provide over 200 terawatt-hours of electricity per year globally.

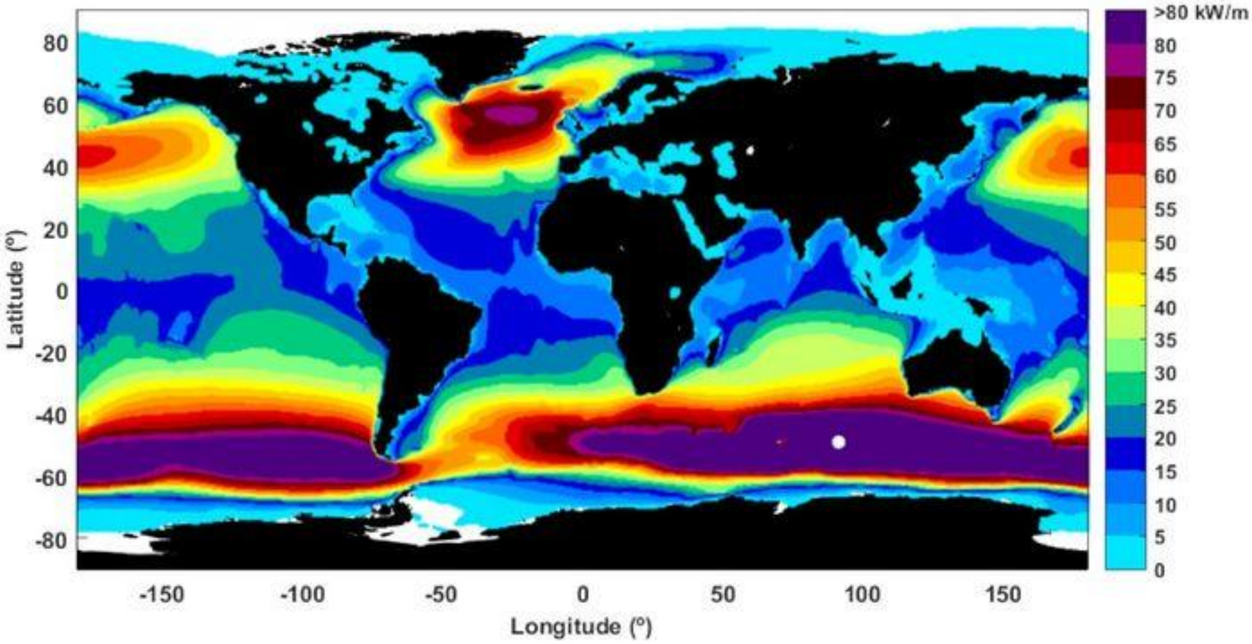

Figure 1. Mean wave power over the 30-year time interval considered (1989–2018) Evaluation of the Worldwide Wave Energy Distribution Based on ERA5 Data and Altimeter Measurements (Rusu and Rusu) (Liang et al.).

1.1 Types of Wave Energy Convertors

There are various types of wave energy converters, each employing different mechanisms to harness wave energy. These include oscillating water columns, point absorbers, attenuators, and oscillating surge converters (Zhang et al., 2021).

1.1.1 Oscillating Water Columns

Oscillating water columns are partially submerged structures that utilize the fluctuating water level inside an enclosed chamber to drive a turbine. As waves pass by, they force air upward through a turbine located at the top of the chamber. This turbine, often a Wells turbine, is specially designed to rotate in the same direction regardless of the airflow direction, allowing it to generate electricity from both the upward and downward movement of the waves. OWCs are advantageous as they have relatively few moving parts, reducing maintenance requirements, and can be integrated into existing coastal structures like breakwaters (Falcão & Henriques, 2016).

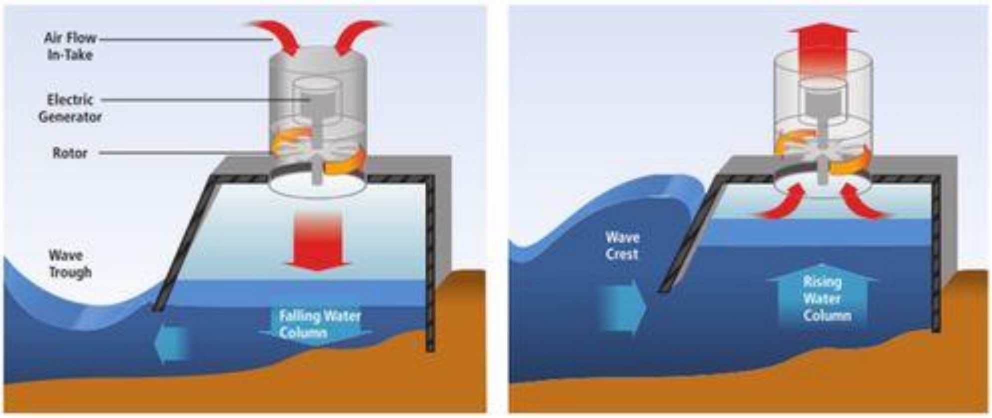

Figure 2.Working principles of Oscillating water column (https://www.ipcc.ch/report/renewable-energy-sources-and-climate-change-mitigation/ocean-energy)

1.1.2 Point Absorbers

Point absorbers are floating devices that capture energy from the vertical motion of waves. These devices are typically small in size compared to the wavelength and can be deployed individually or in arrays. (Sharma et al., 2017) As the waves pass, the buoy-like structure moves up and down, driving a generator or hydraulic system to produce electricity. Point absorbers are known for their simplicity in design and their ability to adapt to varying wave conditions (Shabara & Abdelkhalik, 2023) (Vo et al., 2021).

There are different types of point absorbers:

Heaving one-body PA: The entire device moves up and down with the waves, and the relative motion between the floater and a fixed reference point is used to generate power.

Self-reacting two-body PA: This type consists of two bodies, with one body (e.g., a submerged cylinder) acting as a reference against which the motion of the other body (e.g., a floating buoy) is measured to generate power.

Self-containing two-body PA: Similar to the self-reacting type, but the PTO system is located within one of the bodies, simplifying the design and reducing potential environmental impacts.

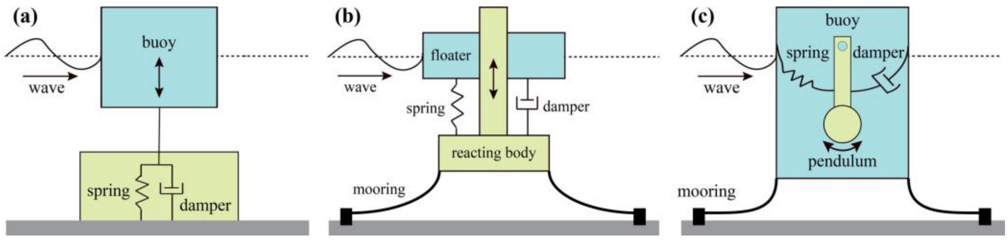

Figure 3.Working principles of Heaving Point Absorbers (Guo et al., 2022)

(a) One body Point Absorber (b) Self Reacting Two body Point Absorber
(b) Self containing Two body Point Absorber (Guo et al., 2022).

1.1.3 Attenuators

Attenuators are long, interconnected structures that are normally aligned parallel to the direction of wave propagation. As waves pass along the length of the device, the relative motion between the different sections is used to drive hydraulic motors or other power take-off mechanisms. Attenuators can capture energy from both the vertical and horizontal motion of waves, making them efficient in converting wave energy into electricity. (Beam et al., 2013)

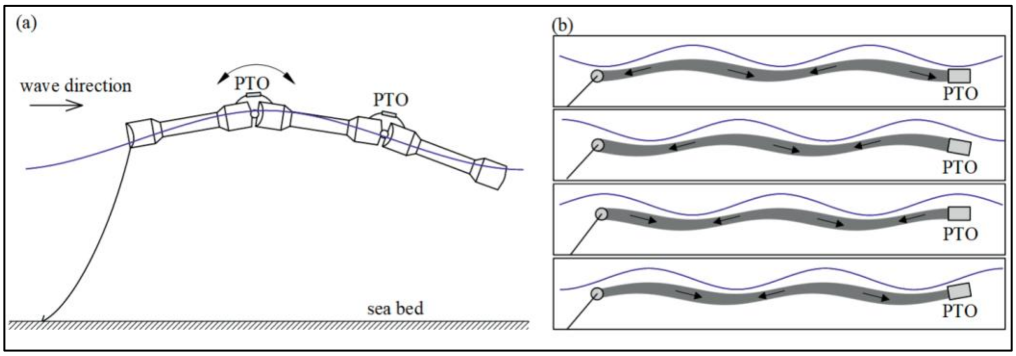

Figure 4.Working principles of attenuator devices

(a) Hinged Type (b) Flexible Tube type
(Zheng, Siming)

An attenuator moves together with the waves and their operation is mostly parallel to the wave direction. The relative velocity of the two arms as the wave passes them is used to power these converters.

These converters absorb energy primarily from surge, sway, and heave motions.
The wavelength under which these types of converters operate is crucial in determining their operational efficiency.

1.1.4 Oscillating Surge convertors

Oscillating surge converters are devices that utilize the horizontal motion of waves to generate power. These devices are typically positioned perpendicular to the wave direction, with a hinged flap or other oscillating mechanism that moves back and forth as waves pass. The oscillating motion is then used to drive a generator or hydraulic system to produce electricity. Oscillating surge converters are particularly well-suited for near-shore locations where the wave climate is dominated by surging waves (Chen & DelBalzo, 2015).

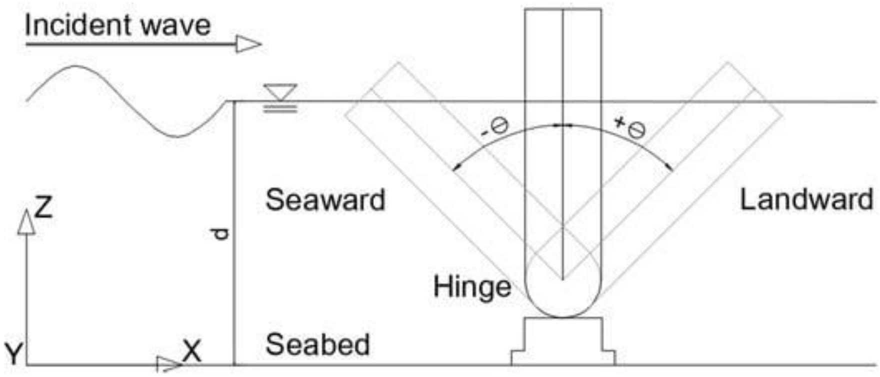

Figure 5.Schematic drawing of an Oscillating Surge Converter.
(Benites-Munoz et al., 2020)

One advantage of oscillating surge converters is their suitability for shallower water depths compared to some other types of wave energy converters.

However, they can potentially impact marine life, particularly if located in areas with high fish or marine mammal activity. Careful design considerations are essential to minimize these potential impacts.

1.2 Efficiency and Power Performance of Wave Energy Converters

The efficiency and power performance of wave energy converters are crucial factors in determining their viability as a renewable energy source. Research has shown that different types of wave energy converters exhibit varying levels of efficiency and power output.

Factors such as the design of the device and the of the wave parameters mainly, wave height, frequency, and angle on incidence, significantly affect their performance (Aderinto & Li, 2019).

Various techniques have been employed to improve the efficiency and power performance of wave energy converters, such as the use of advanced control systems to optimize the device's response to varying wave conditions (Drew et al., 2009) and the integration of different energy capture mechanisms, like combined oscillating water column and point absorber designs.

To compare the efficiencies of different wave energy converter technologies, research have focused on determining the hydrodynamic efficiency, mainly with respect to the characteristic length of the wave energy converters and the wave source potential. This allows for a standardized assessment of how effectively different converter designs capture energy from the available wave resource (Babarit, 2015).

By optimizing designs and selecting suitable locations with favorable wave climates, the efficiency and power output of wave energy converters can be maximized, paving the way for their wider adoption as a sustainable and reliable source of renewable energy.(Zhang et al., 2021)

1.3 Power Take Off

The power take-off system is a very important component of a wave energy converter, acting as the interface between the captured energy from waves, the force transmitting links and electrical power generation unit. This system typically comprises hydraulic or mechanical components that efficiently transfer the energy from the wave-induced motion of the WEC to a generator or turbine. (Aderinto & Li, 2018) (Czech & Bauer, 2012) (Amir et al., 2016), (Drew et al., 2009) (Sheng & Lewis, 2016) (Wang et al., 2020).

The PTO system plays a critical role in defining the overall performance and economic viability of a WEC. Its efficiency directly impacts the amount of wave energy that can be converted into electricity, ultimately influencing the cost-effectiveness of wave energy as a renewable energy source.

The PTO system is the core of a WEC, and has following functions:

1. Energy Conversion: The primary function of the PTO is to convert the mechanical power derived from the WEC's movement (e.g., the oscillating motion of a buoy or the pressure fluctuations in an oscillating water column) into electrical energy.

2. Hydrodynamic Efficiency Enhancement: The PTO system can be designed to optimize the interaction between the WEC and the incoming waves, maximizing the amount of energy absorbed from the wave. This is often achieved through control strategies that adjust the load on the WEC in response to changing wave conditions.
3. Safe Operation: The PTO system must be robust enough to withstand the harsh marine environment, including corrosive saltwater, storms, and biological fouling. It also plays a role in protecting the WEC from excessive loads and potential damage during extreme wave events.
4. Reliability and Maintenance: The PTO system should be designed to minimize the need for frequent maintenance and ensure reliable operation over the WEC's lifespan.

As the key component linking the wave energy converter to the electrical grid, the PTO system's efficiency, reliability, and cost-effectiveness are essential factors in determining the overall viability and widespread adoption of wave energy technology (Wan et al., 2020) (Czech & Bauer, 2012) (Handoko & Mukhtasor, 2021).

The specific design and configuration of the power takeoff system can vary depending on the type of wave energy converter and the characteristics of the waves.

1.4 Power Take Off Control Strategies

The motion transmitted within a wave energy converter should be controlled, aiming to maximize the energy absorption as well as efficient transmission to electrical generation unit. This should also consider the constraints of the equipment’s operating limits and their mechanical capabilities.

Hence, the control strategy employed by the PTO system is crucial for maximizing energy capture, ensuring the safe operation of the WEC, and extending the lifespan of the PTO components. The control system continuously monitors the WEC's motion and adjusts the load on the PTO to optimize power output while staying within safe operating limits. (Beam et al., 2013)

Elaborating on this, the control strategies for the PTO depends on parameters as follows:

(i) PTO Capabilities: The type of PTO system (hydraulic, pneumatic, mechanical) and its operational characteristics (response time, force limitations) influence the control strategies that can be implemented (Handoko & Mukhtasor, 2021).

(ii) System Model Availability and Complexity: A detailed mathematical model of the

WEC and PTO system can aid in developing and optimizing control strategies. However, the complexity of the model and the availability of accurate system parameters can influence the feasibility and effectiveness of model-based control approaches (Coe et al., 2017).

(iii) Wave Field Information: Real-time measurements or predictions of wave characteristics, such as wave height, period, and direction, can be used to adapt the control strategy to changing wave conditions, improving energy capture.Number of controlled variables (Coe et al., 2017).

(iv) Number of Controlled Variables: The number of variables being controlled (e.g., position, velocity, force) and the desired level of control complexity (single or multiple inputs/outputs/actions) influence the choice of control algorithm (Coe et al., 2017).

(v) Environmental Conditions: The wave climate and other environmental factors, such as currents and storms, impact the control requirements to ensure safe and reliable operation (Têtu, 2016).

(vi) Economic Considerations: The control strategy must balance energy capture, system complexity, and maintenance requirements to achieve the desired cost-effectiveness (Elizondo et al., 2006).

Classification of control algorithms based on the above is shown in Figure 6

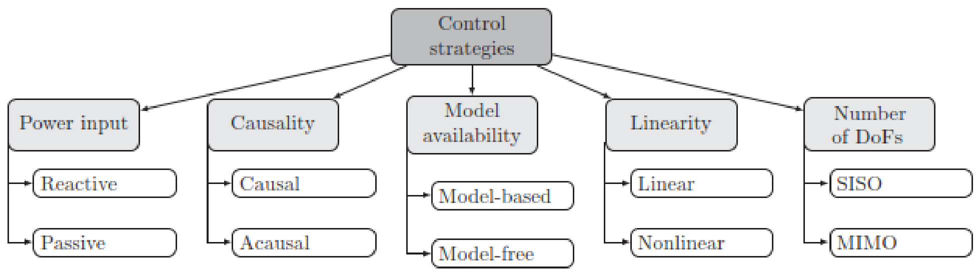

Figure 6. Overview: Wave energy converter control strategies (Têtu, 2016).

Control strategies, such as passive control, active control, reactive control, latching control, and model predictive control, have been explored to enhance the performance of wave energy converters. These control methods aim to match the PTO's impedance to the optimal impedance of the WEC, allowing for the maximum energy conversion (Têtu, 2016).

1.4.1 Passive Control

In passive control, the PTO system does not actively adjust its response based on real-time measurements or feedback from the WEC. Instead, it operates with a fixed or pre-defined relationship between the WEC's motion, and the load applied by the PTO. This simplicity in design can enhance the reliability and cost-effectiveness of the system, as there are fewer sensors and control components required. However, the lack of adaptability means that passive control systems cannot optimize energy capture over a wide range of wave frequencies, potentially leading to reduced efficiency, especially in irregular wave climates (Raffero et al., 2013).

Advantages:

Simplicity: Passive control systems are relatively simple to design and implement, requiring fewer sensors and control components.

Reliability: The absence of complex control algorithms and feedback loops can enhance reliability and reduce the risk of control system failures.

Cost-Effectiveness: Passive control systems are generally less expensive to manufacture and maintain compared to active control systems.

Disadvantages:

Limited Adaptability: Passive control systems cannot adapt to changing wave conditions or optimize energy capture over a wide range of wave frequencies.

Reduced Efficiency: The fixed relationship between WEC motion and PTO load can lead to suboptimal energy absorption, particularly in irregular wave climates.

1.4.2 Active Control

Active control strategies utilize real-time measurements and feedback from the WEC to dynamically adjust the PTO load, optimizing energy capture and enhancing system performance. These strategies allow the WEC to adapt to changing wave conditions, maximizing energy absorption over a broader range of wave frequencies. By continuously monitoring the WEC's motion and adjusting the PTO load accordingly, active control can improve system stability, dampen excessive motions, and increase the average power output of the device. However, the increased complexity of active control systems typically requires more sophisticated sensors, control algorithms, and actuators, which can lead to higher manufacturing and maintenance costs. Additionally, the energy consumed by the control system itself can slightly reduce the overall efficiency of the WEC (Coe et al., 2017).

Advantages:

Enhanced Energy Capture: Active control allows the PTO to adapt to changing wave conditions, maximizing energy absorption over a broader range of wave frequencies.

Improved System Stability: Active control can dampen excessive WEC motions, reducing structural loads and enhancing system stability in extreme wave events.

Increased Power Output: By optimizing the PTO load, active control can increase the average power output of the WEC.

Disadvantages:

Complexity: Active control systems require sophisticated sensors, control algorithms, and actuators, increasing complexity and potential points of failure.

Cost: The increased complexity of active control systems typically translates to higher manufacturing and maintenance costs.

Energy Consumption: Active control systems require a small amount of power to operate, which can slightly reduce the overall energy efficiency of the WEC.

1.4.3 Reactive Control

Reactive control is a key strategy for maximizing energy capture in Wave Energy Converters, particularly those using oscillating buoys.

Reactive control in wave energy converters can be viewed as a hybrid approach, combining elements of both passive and active control strategies. Unlike purely passive systems that rely solely on fixed mechanical properties, or fully active systems that demand continuous energy input for real-time adjustments, reactive control selectively engages under specific defined conditions.

It normally allows the wave energy converter to operate with the simplicity and cost-effectiveness of a passive system under normal wave conditions. However, when the system detects potentially beneficial energy capture opportunities (for example a large incoming wave), it can initiate changes in force/power transmission control. This activates a pre-determined set of actions, often involving adjustments to the system's mechanical reaction, to maximize energy absorption.

Advantages:

Increased Energy Capture: By dynamically responding to favorable wave conditions, reactive control can significantly enhance the energy harnessed compared to purely passive systems.

Reduced Energy Consumption: Unlike continuously operating active systems, reactive control only consumes power when actively adjusting the system, that can lead to higher overall efficiency.

Simplified Design and Control: Reactive control systems are generally less complex to design and implement than fully active control systems, striking a balance between effectiveness, cost and practicality.

Disadvantages:

Limited Adaptability: Reactive control relies on pre-defined responses and may not adapt optimally to rapidly changing or irregular wave conditions.

Prediction Challenges: Effective reactive control often depends on accurate short-term wave forecasting, which can be challenging in certain environments.

The main characteristic of reactive control is that not only does the system transmit energy from wave to electrical generation unit, but also when the buoy is under low energy profile part of the varying/sinusoidal cycle, it must release a part of energy previously captured from the peaks. This can be achieved by introducing energy storage into the system, through a series of accumulators (as in hydraulic system), mechanical springs or flywheels.

Both reactive and latching controls can be designed to match the phase optimality condition, whereby it is described that a phase lag of 90 deg between wave energy profile and buoy elevation profile helps in maximizing the converter efficiency (Andrade et al., 2016).

1.5 Power Take Off Machinery

Wave energy converters utilize a variety of PTO systems, each possessing unique advantages and disadvantages. The inherent dynamic behavior of the PTO machinery significantly influences the applicable control strategies for the WEC. These control strategies are critical as they directly govern the WEC's power absorption capabilities and overall energy extraction efficiency.

The specific type of machinery used in the PTO system significantly influences the WEC's performance, efficiency, and cost. The choice of PTO machinery depends on factors such as the type of WEC, the power output requirements, the operating environment, and cost considerations. (Têtu, 2016)

The main types of PTO machinery are shown in Figure 8. Their typical percentage of utilization and efficiencies are shown in Table 1 respectively.

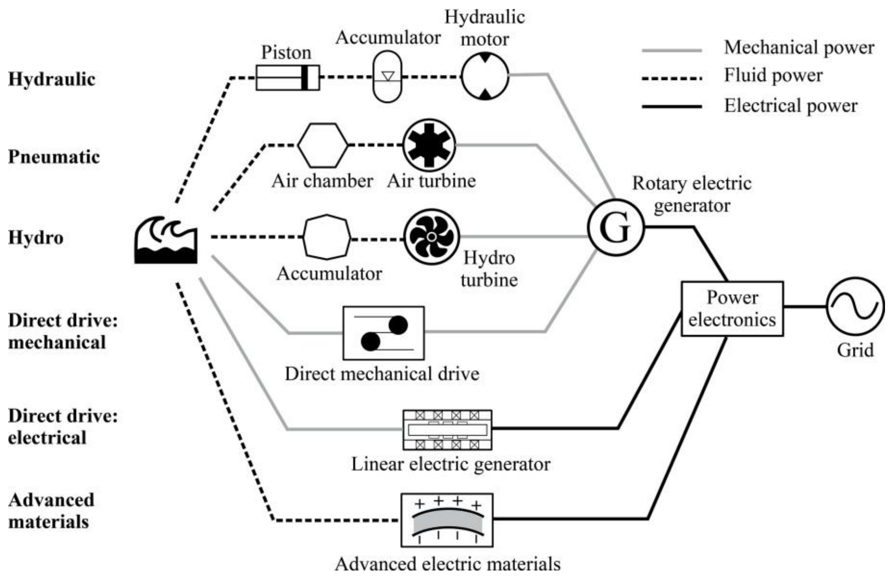

Figure 7. PTO models utilized for the wave energy conversion (Guo et al., 2022)

PTO system	Efficiency, %
Hydraulic	65
Pneumatic	55
Hydro	85
Direct mechanical drive	90
Direct electrical drive	95
Advanced electric materials	< 80

Table 1. Typical Efficiency of PTO systems (Guo et al., 2022).

1.5.1 Hydraulic Power Take Off Machinery

Hydraulic PTO systems are widely used in wave energy conversion, utilizing the buoy's motion to pressurize fluid and further drive a rotary generator. Their ability to handle high forces at low speeds makes them well-suited for harnessing wave power, contributing to their widespread use in the field. However, despite their suitability, hydraulic PTO systems often face limitations in power conversion efficiency. Whilst being the most easily adaptable and suitable for absorbing wave energy, hydraulic PTO machinery has relatively low power conversion efficiency.

1.5.2 Pneumatic Power Take Off Machinery

Pneumatic PTO systems, primarily used in Oscillating Water Columns and pressure differential devices, utilize air turbines driven by oscillating air pressure to generate electricity.

Advantages:

No Submerged Moving Parts: The absence of submerged moving parts reduces maintenance requirements and the risk of corrosion or biofouling.

Bidirectional Energy Capture: Advanced turbine designs with pitching blades can capture energy from bidirectional airflow, potentially enabling soft latching control.

Limitations:

Lower Energy Density: Air has a lower energy density compared to hydraulic fluid, meaning larger components are often required to achieve the same power output.

Noise: The operation of air turbines can generate noise, which might be a concern in certain locations.

1.5.3 Direct-Drive Power Take Off Machinery

Direct-drive PTO systems in wave energy conversion eliminate intermediate energy conversion steps by directly transforming mechanical energy from buoy oscillations into electricity. The buoy is directly connected to the moving component of a linear generator, simplifying the system and minimizing energy losses. These systems typically employ an additional mechanism to couple the buoy's motion to a conventional rotary generator (Vélez et al., 2014).

Whilst being the least mature technology among all the PTO types, direct-drive PTO machinery is currently in the spotlight of research and development, mainly due to its ability to generate any desired PTO control force and thus enable the potential to implement advanced power maximizing control strategies.

The SWEC PTO, patented by Oceanenergies AS is considered to be a type of Direct Drive PTO machinery, with a 3-crank system that converts liner motion of a large floater to rotary motion. This PTO system has tethers which directly transmits forces from the floating buoy to the 3-crank system, which is explained in later sections.

1.6 Power Conversion Efficiency.

The overall efficiency of a wave energy converter can be understood from the sequence of energy conversions, starting from wave energy to electrical power generation. Each stage involves some losses that are inherent to the conversion that reduce overall efficiency. Considering a heaving buoy type WEC the sequence of conversions are explained as follows.

Available Wave Energy: This represents the total energy present in the incoming waves, determined by wave parameters like significant wave height, time period and incident angle. It's the theoretical upper limit of what a WEC can capture.

Captured Wave Energy: A WEC can only capture a portion of the available wave energy. This captured energy depends on the buoy's size, shape, and method of interaction with the waves. Some wave energy is reflected or diffracted, while some energy is not captured. Optimizing the energy capturing device/buoys geometry and hydrodynamic design can minimize these losses.

Transmitted Energy: The captured wave energy is then transferred to a power take-off system, which converts it into mechanical or hydraulic power. Friction and mechanical losses within the PTO and transmission system lead to energy dissipation and losses.

Converted Electrical Energy: The electrical power generation system converts the transmitted mechanical or hydraulic energy into electricity. The efficiency depends on type of generator and losses associated within the generator.

Improving the efficiency of WECs can be effected by following methods:

Hydrodynamic Optimization: Designing WECs with shapes and sizes that maximize wave energy capture while minimizing reflection and diffraction.
Advanced Control Strategies: Implementing control systems that optimize the WEC's motion in response to incoming waves, maximizing energy extraction.
Efficient PTO Systems: Selecting and optimizing PTO systems with high energy conversion efficiencies, minimizing mechanical and hydraulic losses.
Materials and Components: Utilizing materials with low friction coefficients and incorporating high-efficiency generators, and power electronics.

By addressing these losses at each stage, overall efficiency of wave energy converters can be improved, making them a more viable and sustainable source of renewable energy.

Mechanical efficiency can be defined as the ratio of the mechanical power input to the PTO machinery to useful electrical power output.

(Efficiency η) = Electrical power output /Mechanical power input

Since the PTO receives the power from wave energy the overall power conversion efficiency can be defined as:

(Overall Efficiency η) = Electrical energy output /Wave energy input.

2. Theory and Bounds of Wave Power Absorption

This section delves into the hydrodynamic forces acting on a floating body in a wave field and introduces the concept of the Budal upper bound, a critical factor influencing the maximum power output achievable by any wave energy converter.

The motion of a floating body, such as the SWEC's buoy, is governed by the interaction between the body's inertia, the restoring forces (buoyancy and mooring), and the hydrodynamic forces exerted by the surrounding waves.(Falcão & Henriques, 2016)(Ligeikis & Scruggs, 2024). These hydrodynamic forces can be decomposed into two main components: the radiation force, which arises from the body's own motion-induced waves, and the excitation force, which is the result of the incident wave field acting on the body (Babarit et al., 2011).

2.1 Hydrodynamic Forces acting on Floating Object.

The motion of a floating body, such as the SWEC buoy/floater, when operating under influence of ocean waves can be described using Newton's Second Law (Fossen & Tristan, 2008). This fundamental law of motion, when applied to a floating body, results in the following equation (Fossen & Tristan, 2008):

$$\mathbf{M}\ddot{\boldsymbol{q}} = \mathbf{F}_{\boldsymbol{ext}} + \mathbf{F}_{\boldsymbol{r}} + \mathbf{F}_{\boldsymbol{b}} \qquad (1)$$

where M is the inertia matrix of the oscillating body and q is the displacement from the equilibrium position. $F_{\mathbf{ext}}$, Fr, and Fb are respectively excitation force, radiation force, and hydrostatic force. The radiation force can be represented as (Fossen & Tristan, 2008):

$$\mathbf{F}_{\boldsymbol{r}} = -\mathbf{A}(\omega)\ddot{\boldsymbol{q}} - \mathbf{B}(\omega)\dot{\boldsymbol{q}} \qquad (2)$$

where A(ω) and B(ω) are the frequency-dependent added mass matrix and damping matrix, respectively. Normally, it is assumed that the body is constrained to oscillate only in the heave direction. Hence, the hydrostatic force is calculated as (Fossen & Tristan, 2008):

$$\mathbf{F}_{\boldsymbol{b}} = -\mathbf{Gq} = -\boldsymbol{\rho g S_w}\mathbf{q} \qquad (3)$$

Where G is the buoyancy stiffness. ρ and g are the water density and gravity acceleration, respectively. Sw is the equilibrium water plane area of the body.

Then, Eq. (1) can be rewritten as (Fossen & Tristan, 2008):

$$[\mathbf{M} + \mathbf{A}(\omega)]\ddot{\boldsymbol{q}} + \mathbf{B}(\omega)\dot{\boldsymbol{q}} + \mathbf{Gq} = \mathbf{F}_{ext} \qquad (4)$$

And in the frequency domain (Fossen & Tristan, 2008):

$$\left[-\omega^2\left(\mathbf{M} + \mathbf{A}(\omega)\right) + i\omega\mathbf{B}(\omega) + \mathbf{G}\right]\mathbf{q} = \mathbf{F}_{ext} \quad (5)$$

2.1.1. Buoyancy Force

Hydrodynamic forces play a crucial role in dictating the motion of a floating body, like a buoy, within a wave field.

Buoyancy force is a crucial factor in the dynamics of a floating body, like a wave energy converter buoy, in water. According to the fundamental Archimedes' principle, the upward buoyant force exerted on a submerged or partially submerged object is equal to the weight of the fluid displaced by that object. In a static equilibrium situation, this buoyant force precisely counteracts the weight of the floating body, maintaining it at a specific equilibrium position.

However, when waves pass by the fluctuating water level around the buoy causes the volume of displaced water to change, leading to variations in the buoyant force. This, in turn, contributes to the vertical motion of the buoy as it responds to the dynamic changes in the buoyancy force. (Goodarzi, 2009).

The buoyancy force serves as a restoring force, consistently aiming to return the floating body to its upright equilibrium state. When waves tilt the body, the buoyant force shifts, generating a moment that counteracts the tilting motion and works to stabilize the body. Metacentric height is a crucial parameter for evaluating stability. It represents the distance between the body's center of gravity and a specific point known as the metacenter.

A larger metacentric height (GM) indicates greater stability, as the body will be more resistant to capsizing and can more quickly return to an upright position if disturbed. Conversely, a smaller metacentric height suggests lower stability, making the body more susceptible to capsizing. Furthermore, waves can dynamically alter the effective metacentric height. As waves pass the body, the changing water level around it modifies the distribution of the buoyant force, potentially impacting the overall stability of the floating structure.

2.1.2. Radiation Force

When a floating device, such as a wave energy converter, oscillates up and down in waves, it actively generates its own waves that propagate outward. These radiated waves transport energy away from the device, and this energy dissipation is experienced as a resistance to the device's motion.

Wave Generation: When a floating body oscillates in the water, it generates outwardly radiating waves. These waves carry energy away from the body.

Reaction Force: The act of generating waves creates a reaction force on the body itself, known as the radiation force. This force acts in opposition to the body's motion, effectively damping its movements.

Frequency Dependence: The magnitude and direction of the radiation force are highly dependent on the frequency of the body's oscillation relative to the frequency of the incoming waves.

Matching Frequencies: When these frequencies are close, the radiation force can significantly impact the body's motion, potentially leading to large oscillations.

Forces and Actions: The motion of a floating body in waves is governed by the interaction of these hydrodynamic forces, along with other forces like diffraction forces and incident wave forces.
Optimizing Energy Extraction: In the context of WECs, optimizing the buoy's shape and size, as well as its response to these forces, is key to maximizing energy capture from waves.

The radiation force acts like a damping mechanism, dissipating energy as the body oscillates due to waves. This force generates outgoing waves that carry energy away, reducing the body's movements. Additionally, the surrounding water adds inertia to the floating body, effectively increasing its mass. This "added mass" is influenced by the body's shape and the frequency of the waves. The radiation force can either amplify or reduce the body's motions, depending on the frequency of the waves and the body's natural frequency. When the wave frequency is close to the body's natural frequency, resonance can occur, leading to large and potentially hazardous motions. Buoyancy and radiation forces work together synergistically to determine the overall stability and response of the system. Buoyancy provides the restoring force, while radiation force influences the damping and added mass (Dong, 1978).

2.1.3. Diffraction Forces

Diffraction forces arise when waves encounter an obstacle, such as a floating buoy, and are scattered or bent around it. These forces are distinct from the incident wave forces and radiation forces previously discussed.

The significance of diffraction forces in the context of wave energy converters is twofold: Impact on Power Absorption: Diffraction forces can either enhance or diminish the wave forces acting on a buoy, thereby influencing the amount of energy that can be extracted. Understanding these forces is crucial for optimizing the shape and size of the buoy to maximize energy capture (Ruezga & C., 2020).

Accurate Modeling: Accurately predicting the performance of a wave energy converter requires accounting for diffraction forces in numerical simulations and theoretical models. Neglecting these forces can lead to significant errors in estimating the power output. The theoretical basis for calculating diffraction forces involves solving the wave diffraction problem, which is typically more complex than analyzing radiation forces. This complexity arises from the need to consider the scattered wave field generated by the buoy's interaction with the incident waves.

Understanding these hydrodynamic forces is crucial for various applications, including ensuring the stability of ships in rough seas, designing offshore structures that can operate safely in wave-exposed environments, and optimizing the shape and response of wave energy converter buoys to maximize energy capture while maintaining stability.

Accurate prediction of a floating body's motion is essential for designing safe and efficient offshore structures, including wave energy converters (Yetkin et al., 2021).

2.2 Budal Upper Bound

The Budal upper bound is a theoretical limit on the amount of power a wave energy converter can absorb from an incoming wave. It states that a WEC can capture, at most, an amount of power equal to the energy flux of the wave incident on a length equal to the WEC's width multiplied by a factor related to the number of oscillators used. This upper bound is independent of the WEC's design and serves as a benchmark for evaluating the performance of different WEC technologies (Aderinto & Li, 2019).

For heaving semi-submerged WECs, the WEC generated power is limited due to Budal upper bound (BUB), which is presented as follows (Falnes, 2007):

$$P \leq P_A \quad \text{and} \quad P < P_B$$

Where PA is known as left-hand upper bound, and PB is the right upper bound.

Figure 14 presents a schematic of Budal curves.

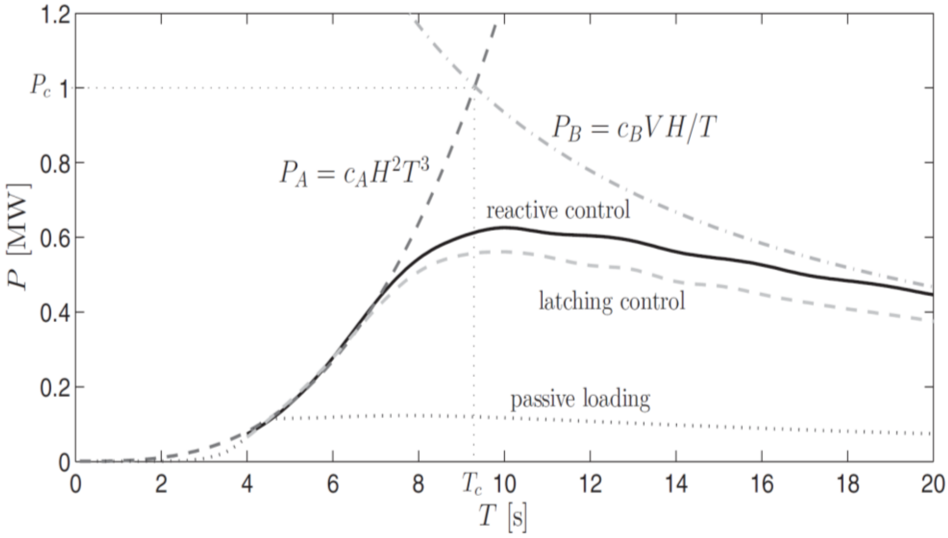

Figure 8. Budal upper bounds (Falnes, 2007)

The equations of PA and PB are given as follows (Falnes, 2007):

$$P_A = c_A H^2 T^3$$

$$P_B = c_b V \frac{H}{T}$$

where H and T are, respectively, the wave height and wave period. cA and cB are respectively equal to(Falnes, 2007):

$$c_A = \frac{\rho(\frac{g}{\pi})^3}{128}$$

$$c_B = \sigma \rho g$$

where ρ and g are seawater density and gravity constant. σ equals to π/4 , typical value.

As shown in Figure 8. Budal upper bounds, the PTO control system greatly influences the average power generation.

Typical values of the ratio of the maximum absorbed power Pmax to the intersection-point power Pc for each control strategy roughly follows (Falnes, 2007):

$$\frac{P_{max}}{P_c} \begin{cases} 0.6 & for\ reactive\ control \\ 0.5 & for\ latching\ control \\ 0.1 & for\ passive\ control \end{cases}$$

2.3 Forces and Torques in Crankshaft based PTO

2.3.1. Slider Crank Mechanism

Determining the torque generated at the crankshaft is essential, in wave energy convertors having direct crankshaft conversion mechanism. The PTO torque is a function of the crank geometry and the force transmitted through the links.

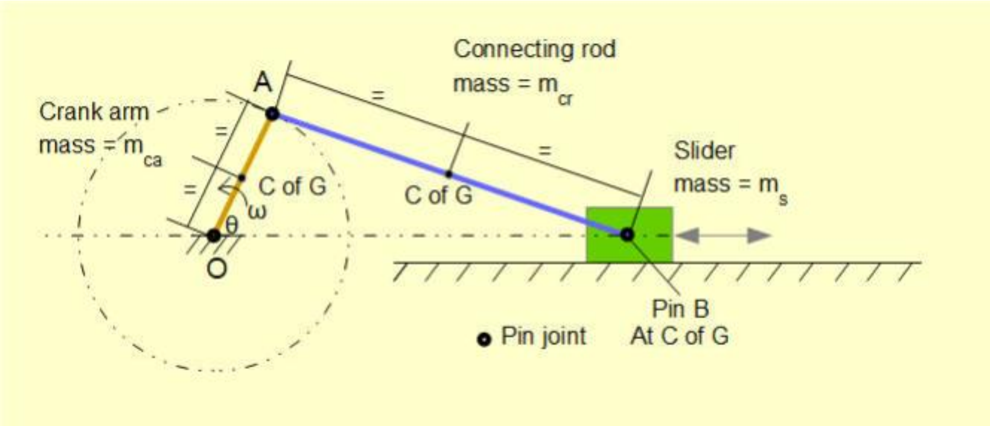

Figure 9 Slider Crank Mechanism schematic ("https://www.alistairstutorials.co.uk/tutorial16.html")

The forces and torques within a PTO composed of crankshaft mechanism and links that transmit forces from a floating buoy is analogous to a slider-crank mechanism.

Piston Force: The force transmitted by a heaving buoy to the PTO is analogous to the forces imparted by piston.

Connecting Rod Force: This force is transmitted through the connecting rod or links of PTO and has both horizontal and vertical components, with the horizontal component contributing to the torque on the crank.

Crank Torque: This is the rotational force experienced by the crankshaft due to the combined effects of the horizontal component of the connecting rod force and the crank radius.

Torque Variation with Crank Angle: The torque generated by a slider-crank mechanism is not constant throughout the crank's rotation. It varies with the crank angle due to the changing geometry of the system.

The basic equation for crank torque is: T = Fx*r, where T is the crank torque at a given crank angle, Fx is the horizontal component of the connecting rod force, and r is the crank radius.

Factors Affecting Torque Variation are as follows:

Crank Radius: A larger crank radius amplifies the torque for a given force.
Connecting Rod Length: The ratio of the connecting rod length to the crank radius influences the magnitude of the torque variation, with longer connecting rods generally leading to smoother torque curves.
Piston Force Profile: The way the piston force changes during the cycle significantly impacts the torque curve.
Crank Angle: The torque varies with crank angle as explained in following equation.

$$T(\theta) = F \times R[\sin\theta] + \frac{\sin 2\theta}{2\sqrt{(n^2 - sin^2\theta)}}$$

F: Force acting on the system.
R: Radius of the crankshaft.
L: Length of the connecting rod.
θ: Crank angle.
n: L/R

2.3.2. Forces and Torques in Crank type PTO

In a WEC, the piston force is generated by the wave-induced motion of the buoy or oscillating water column. This force will be oscillatory and dependent on the wave height, frequency, and the WEC's hydrodynamic characteristics. We can represent this as:

$$F(t) = F\_max \times sin(\omega t + \varphi)$$

F(t): Time-varying force.
F_max: Maximum force (related to wave characteristics).
ω: Wave frequency.
t: time.
φ is a phase angle (representing the timing of the wave relative to the PTO).

Crank Angle (θ): The crank angle will be a function of the WEC's motion and the design of the PTO system. The relationship between buoy displacement and crank angle will depend on the specific geometry of the slider-crank linkage.

Combining these factors, the crankshaft torque in a WEC with a slider-crank PTO can be expressed as:

$$T(\theta) = F\_max \times sin(\omega t + \varphi) \times R[\sin\theta(t)] + \frac{\sin 2\theta\,(t)}{2\sqrt{(n^2 - sin^2\theta(t))}}$$

The equation highlights that the crankshaft torque will be highly time-dependent due to the oscillatory nature of both the wave force and the crank angle. This has implications for the design of the generator and power electronics, as they need to handle fluctuating power input.

The PTO system's efficiency in capturing wave energy will depend on how well the crank angle (θ(t)) and the wave force (Fp(t)) are synchronized. Ideally, it is desired to maximize the torque when the wave force is high and minimize it when the force is low to reduce energy losses.

Advanced control systems can be implemented to adjust the PTO damping or other parameters to optimize energy capture. This might involve adjusting the load on the generator or even actively controlling the motion of the buoy to better match the incoming waves (Handoko & Mukhtasor, 2021) (Ariefianto et al., 2021).

2.3 Flywheel Stored Energy

Flywheels store energy in the form of rotational kinetic energy, which is the energy of motion for a rotating object. The amount of rotational kinetic energy a flywheel has is given by:

$$KE = \frac{1}{2} \times I \times \omega^2$$

KE is the rotational kinetic energy

I is the moment of inertia of the flywheel

ω is the angular velocity (rotational speed) of the flywheel

The process of storing energy in a flywheel involves applying torque to impart rotational motion. This is typically done by leveraging external rotational forces, such as those transmitted through a crankshaft or shaft, and engaging clutches to transfer the energy to the flywheel.

As the flywheel spins faster, its angular velocity increases, and this increase in rotational kinetic energy allows the flywheel to store a considerable amount of energy.

To release the stored energy, the flywheel is allowed to slow down by connecting it to a load.

This load can be a generator, a mechanical system, or even just the resistance from overcoming friction. As the flywheel's rotational speed decreases, its rotational kinetic energy is transferred to the load, providing a source of rotational power. The flywheel essentially acts as a temporary energy storage device, allowing the captured energy to be discharged when needed to drive the connected load.

A flywheel is designed to have a significant moment of inertia, allowing it to store rotational kinetic energy effectively.

The general equation for moment of inertia (I) of a flywheel is given as:

$$I = K\, m\, r^2$$

K: inertial constant - depends on the shape of the flywheel
m: mass of flywheel
r: radius (m, ft)

3. Swell Wave Energy Convertor

Existing wave energy conversion facilities are predominantly small-scale devices designed to harness energy from waves near the coastline, operating at typical to high frequencies. However, these facilities are less commercially viable due to low power generation, high installation costs, and substantial maintenance requirements. The primary reason for the low power output is the geographical positioning of the devices. Wave energy converters situated in coastal regions face numerous challenges, including reduced power generation, elevated installation expenses, and significant maintenance needs. These limitations arise from the inherent characteristics of coastal waves, which are typically unidirectional, diminished in amplitude, prone to breaking, and exert high, potentially damaging loads on the wave energy conversion equipment. Specifically, the unidirectional and reduced-amplitude nature of coastal wave patterns limits the available energy from other wave directions. (Aderinto & Li, 2018)

To overcome the limitations of the small and coastal WECs mentioned above, this present study attempts to create a framework model for harvesting wave energy through the Swell Wave Energy Converter (SWEC). Swells often have a relatively long wavelength, which carry significantly more energy and dissipate slower than coastal waves.

Swell Wave Energy Converters target swell waves, which offer several advantages (Wang et al., 2020) (Drew et al., 2009):

Higher Energy Content: Swell waves, with their longer wavelengths, carry more energy compared to coastal waves.

Slower Dissipation: Swell waves lose energy at a slower rate, allowing them to travel long distances with less energy loss.
More Predictable: Swell waves exhibit greater predictability in their behavior, making it easier to forecast their energy potential and optimize energy capture.

By harnessing the energy of swell waves, SWECs aim to achieve higher power generation, improved efficiency, and reduced maintenance compared to traditional coastal wave energy converters.

To overcome the inherent limitations of conventional Wave Energy Converters that are often restricted to shallow coastal waters and susceptible to fluctuating wave energy levels, this analysis proposes a novel framework for harnessing the vast energy potential of ocean swells through the Swell Energy Converter.

Unlike their coastal counterparts, ocean swells, characterized by their longer wavelengths, possess a higher energy density and propagate across vast distances with minimal energy loss (Czech & Bauer, 2012). This inherent characteristic of swells makes them a more reliable and potent source for energy extraction.

To overcome the inherent limitations of conventional Wave Energy Converters that are often restricted to shallow coastal waters and susceptible to fluctuating wave energy levels, this analysis proposes a novel framework for harnessing the vast energy potential of ocean swells through the Swell Energy Converter. Unlike their coastal counterparts, ocean swells, characterized by their longer wavelengths, possess a higher energy density and propagate across vast distances with minimal energy loss. This inherent characteristic of swells makes them a more reliable and potent source for energy extraction (Aderinto & Li, 2018).

3.1 SWEC System Description

The SWEC studied in this academic work analyses an innovative power take-off (PTO) system, as shown in Figure 10 and Figure 11, which Ocean Energies AS has invented.

The SWEC distinguishes itself from traditional WECs through its innovative and patented Power Take-Off system, a brainchild of Ocean Energies AS. This PTO system, employing a unique crankshaft mechanism, efficiently captures the vertical motion of the SWC's large buoy structure, driven by the rise and fall of ocean swells, and converts it into rotational energy. This rotational energy then drives a generator, producing clean and sustainable electricity (Ren et al., 2023).

The SWEC's ingenious design allows it to operate optimally in deeper, offshore environments where swells are more consistent and powerful. This strategic deployment not only minimizes visual and environmental impact on coastal regions but also circumvents the challenges posed by the intermittent nature of coastal waves (Ren et al., 2023). This patented crankshaft mechanism transmits the linear motion from floater into rotational motion for crankshaft, which further transmits rotational motion and torque to a generator.

Combined with a large floating structure, this PTO system allows the SWEC to focus on the swell waves further offshore and reduce/remove the drawbacks associated with coastal installations (Moen, 2021). This results in SWEC to be able to capture higher wave energy and provide higher power output than existing WECs, which will help in significantly lower the Levelized Cost of Energy.

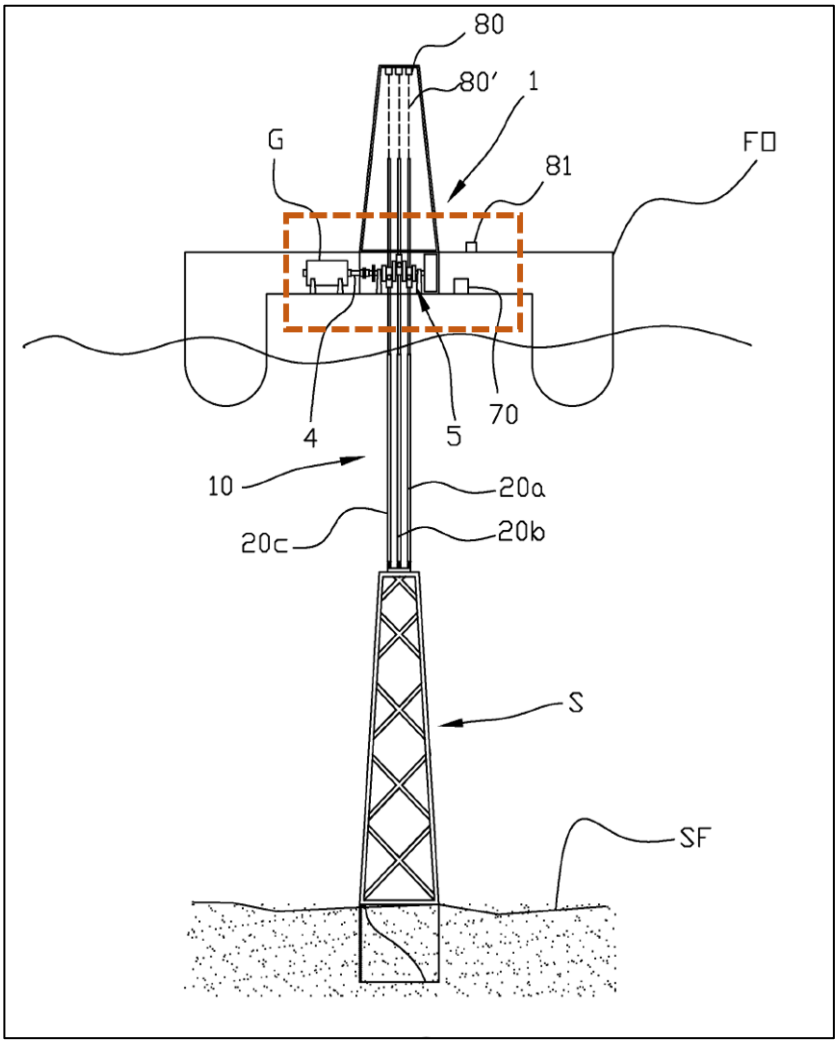

Figure 10. Swell Wave Energy Convertor (Moen, 2021)

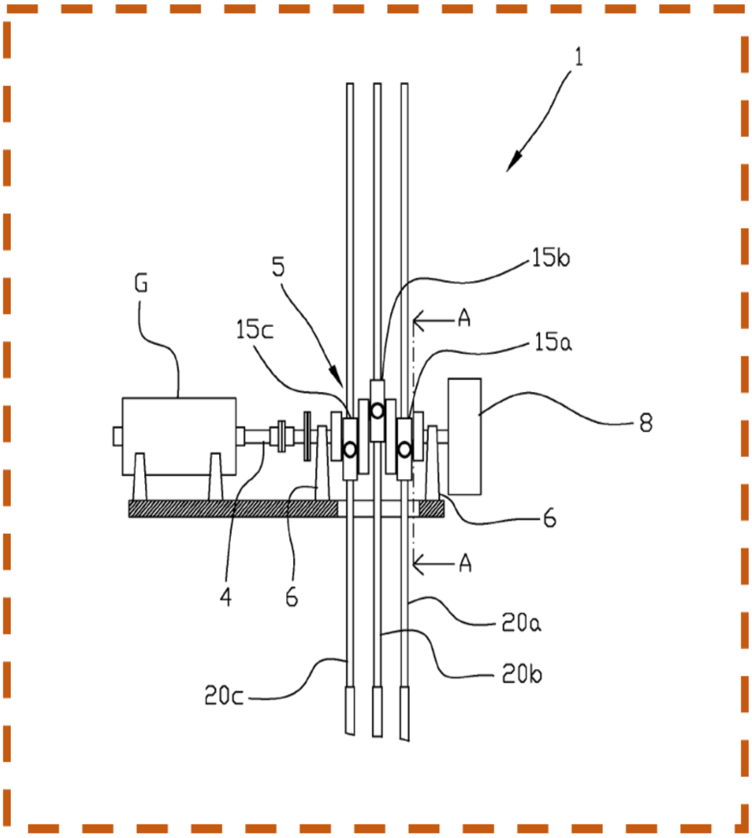

Figure 11. PTO system of SWEC (Moen, 2021)

3.2 SWEC PTO Working Mechanism

The main functioning of the SWEC's PTO system is defined by a sophisticated control mechanism that ensures unidirectional rotation of the crankshaft, maximizing energy conversion efficiency under various sea states. This mechanism employs a series of three tethers, each connected to the crankshaft via a clutch apparatus. These clutches, which can be actuated magnetically or hydraulically, engage and disengage in a carefully orchestrated sequence, dictated by the buoy's/floaters vertical motion relative to the seabed.

The PTO system, illustrated in Figure 12, centres around a rotatable main shaft that drives the power generation components, including a generator and flywheel. Three tethers (20a, 20b, 20c) connect to this shaft via crank pins and clutch apparatuses (15a, 15b, 15c), as detailed. These clutches, controllable via magnetism or hydraulics, enable engagement and disengagement between the tethers and crank pins. This selective coupling, managed by a dedicated control system, depends on the crank pin positions and the floating object's movement, allowing for optimized energy capture (Ren et al., 2023).

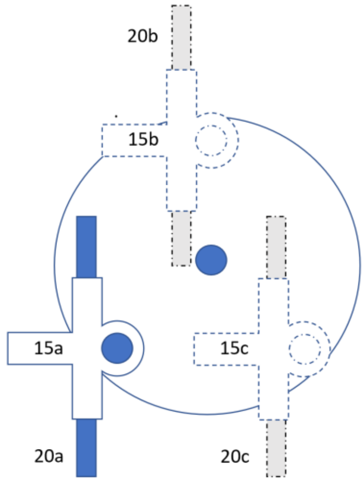

Figure 12. PTO – Tether and Gripper configuration (Ren et al., 2023)

3.3 Operation of PTO

Based on the movement of the FO compared to the sea floor, the operation of clutches in different positions can be classified into two cases.

3.3.1. Floater Object – Upward Motion

As shown in Figure 13, when the floating object rises relative to the seabed, the clutch mechanism within the green zone engages, entering "clutch lock" mode. Simultaneously, the remaining clutches disengage, entering "clutch unlock" mode. In CL mode, the tether and crankshaft are rigidly coupled, ensuring direct energy transfer. Conversely, CU mode allows independent movement between the tether and crankshaft. This selective engagement, dictated by the floating object's upward motion, ensures that vertical movement is effectively converted into rotational energy within the crankshaft (Ren et al., 2023).

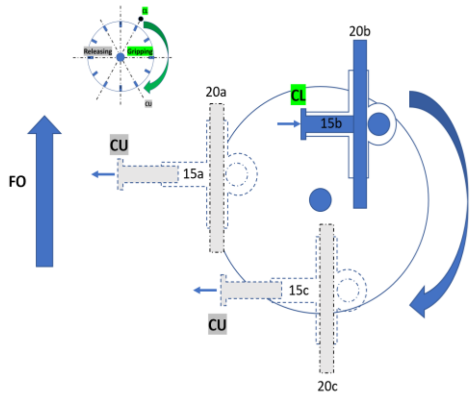

Figure 13. PTO action: Floating Object - Upward Motion (Ren et al., 2023)

3.3.2 Floater Object – Downward Motion

During the floating object's downward movement, the clutch mechanism in the green zone, as depicted in Figure 14, engages, while the other clutches disengage. This switching between CL and CU modes, synchronized with the object's vertical motion, ensures unidirectional rotation of the crankshaft, regardless of the direction of the floating object's movement (Ren et al., 2023).

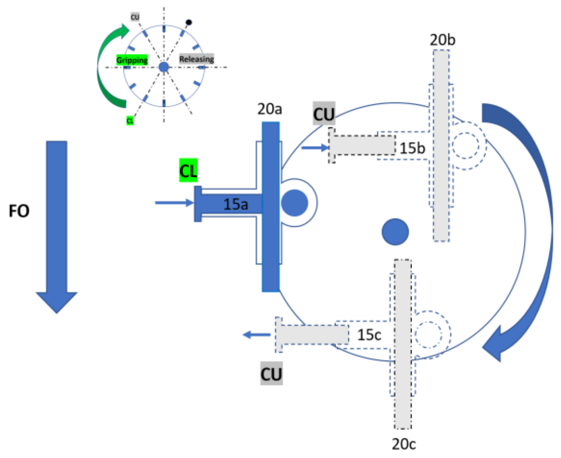

Figure 14. PTO action: Floating Object - Downward Motion (Ren et al., 2023)

The controlled engagement and disengagement of the clutch apparatuses enable the crankshaft to complete multiple rotations for both upward and downward movements of the floating object. This means that during a single wave cycle, with its corresponding rise and fall of the floating object, the crankshaft can undergo multiple rotations, enhancing energy capture. This design, independent of wave amplitude and wavelength, offers versatility for deployment in various marine environments, from shallow to deep waters (Ren et al., 2023).

4. Wave Statistics and Floater parameter selection

Selecting the right location for a wave energy converter is crucial for maximizing energy production and ensuring economic viability. To determine optimal deployment sites, wave data statistics area analysed, such as wave height, time period, and direction, to understand the energy potential of a location. Additionally, scatter diagrams help in predicting the long-term sea state, revealing patterns and frequencies of different wave conditions. This is essential for optimizing WEC design and predicting energy output.

In this study, wave parameters are selected based on site data from two different sites as shown in Figure 15. Wave statistics are represented in Figure 16 and Figure 17.

Figure 15. Sites compared for wave data statistics (Babarit et al., 2012)

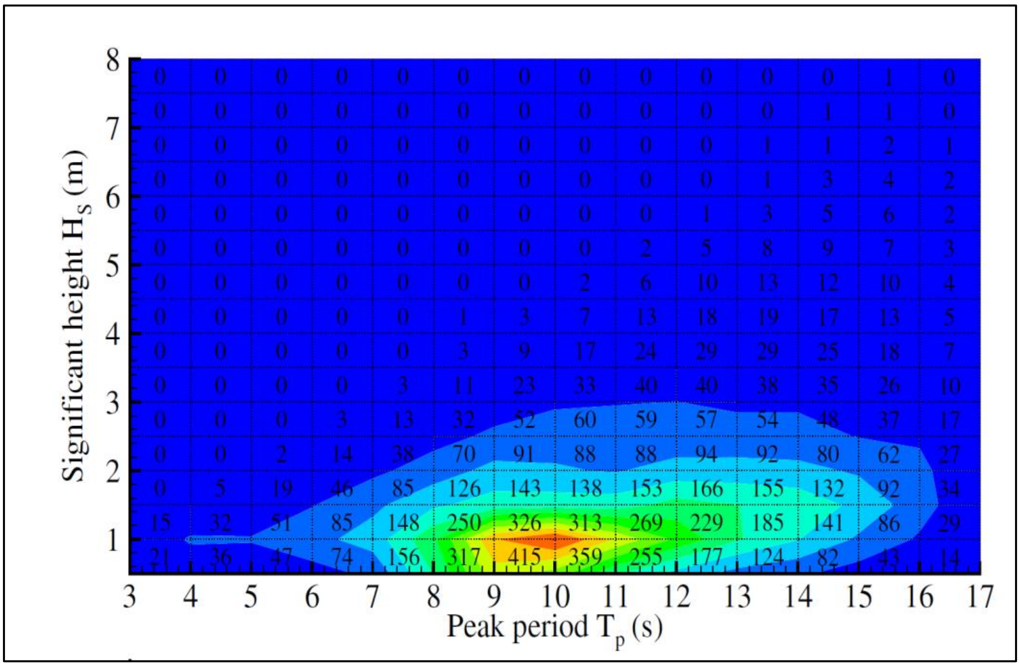

Figure 16. Scatter diagram representation SEM-REV
(Babarit et al., 2012)

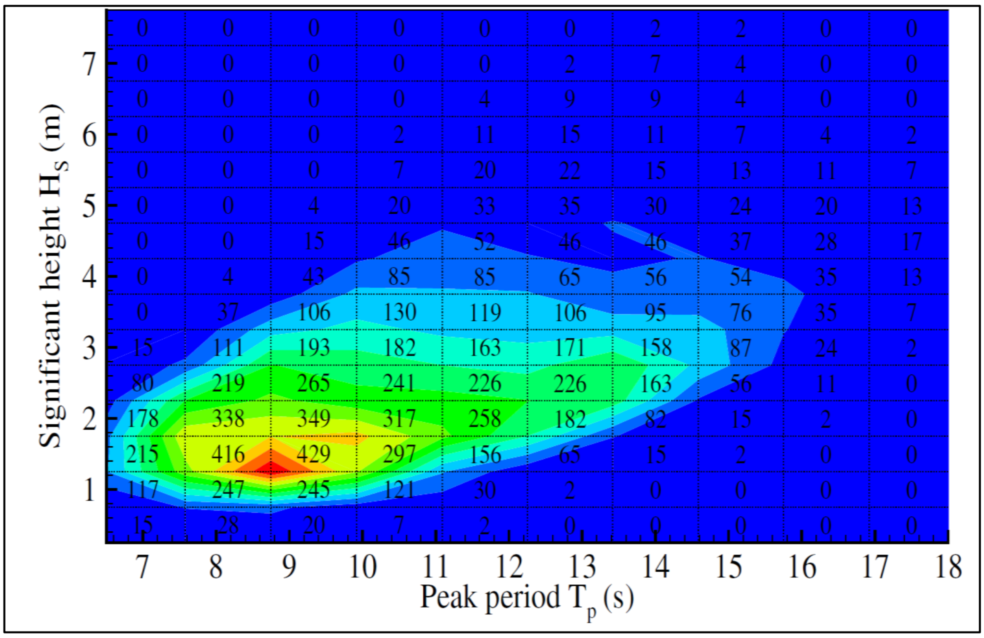

Figure 17. Scatter diagram representation Lisbon
(Babarit et al., 2012)

From the parametric study conducted in paper ‘Assessment of a novel PTO system for swell energy converters using digital twin modelling (Ren et al., 2023)’, the influence of floater size and ocean site on average power generation were roughly estimated.

The average power generation capacity estimation is shown in Table 2.

Site 1: SEM-REV	
Floater diameter (m)	Average power generation (kW)
20	70.74
60	102.13
100	102.13
Site 2: Lisbon	
Floater diameter	Average power generation (kW)
20	130.74
60	223.13
100	223.13

Table 2. Floater size and Power Generation capacity (Ren et al., 2023).

The estimated annual power generation capacity estimation is shown in Figure 18.

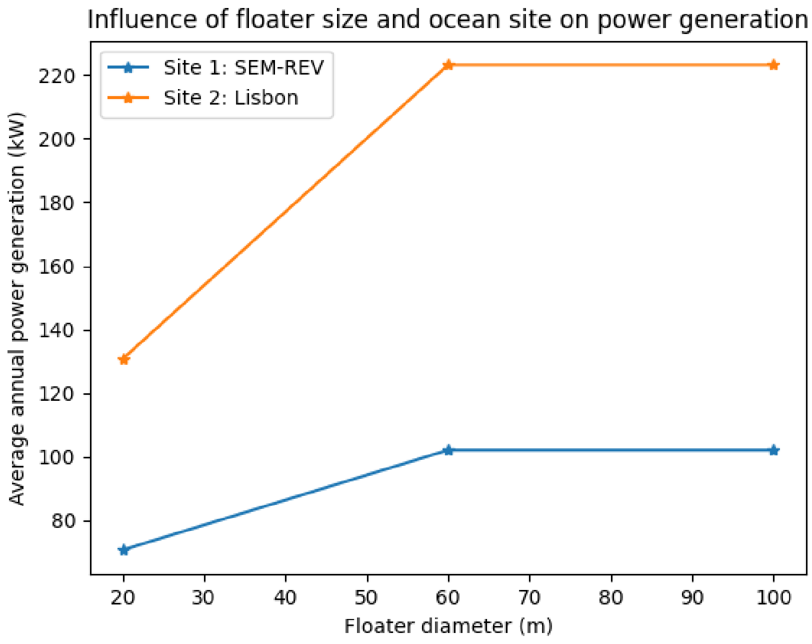

Figure 18. Floater Size and estimated power generation capacity (Ren et al., 2023).

Based on the estimations outlined in the parametric study and considering practicality in continuing the stated study objectives, floater diameter of 30m with a height of 5m is selected for further analysis. By focusing on this specific floater configuration, the study can delve deeper into more detailed analyses and optimizations, refining the design and operational parameters for a more realistic and achievable wave energy converter system.

Wave Height	1 to 5 m
Wave Time Period	6 to 12 s
Diameter of Floater	30 m
Height of Floater	5 m

Table 3. Wave and Floater size selected for the study

To further study the performance of the floater, 3D modelling will be done by using the chosen dimensions for the floater. By subjecting this initial model to virtual testing within a simulated ocean environment, we can assess its behavior and response when exposed to specific "sea state" conditions.

4.1 Floater Modelling

A 3D model of the floater was created using Autodesk Inventor software. This model, shown in

Figure 19, incorporates the key structural components of the floater. A notable design feature is the incorporation of provision for guides. These guides are positioned to constrain the floater's motion primarily to the heave direction, maximizing energy capture from the vertical component of wave motion while minimizing undesirable movements such as surge, sway, and yaw.

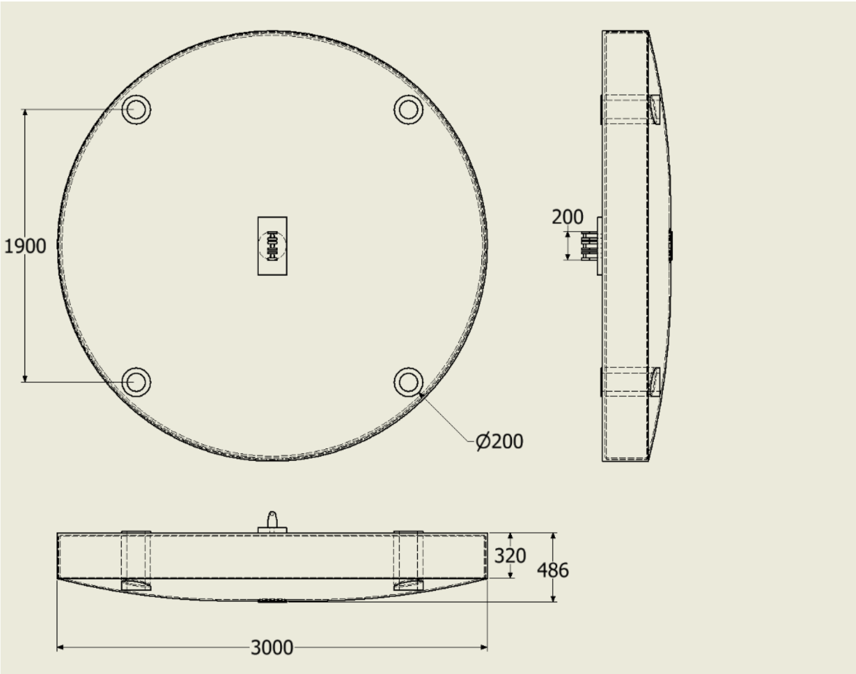

Figure 19. Floater Major Dimensions

This wave energy converter design offers flexibility with two possible configurations using the floater and guide arrangement.

Both configurations share a fundamental principle: they utilize guides to constrain the floater's motion primarily to the heave direction, ensuring efficient energy capture from the vertical rise and fall of the waves. The two configurations are represented in Figure 20 and Figure 21.

While the specific arrangement of floater and PTO may differ between the two configurations, the underlying mechanism for transmitting forces remains consistent. The floater's heave motion is translated into tension forces in the tethers connected to the power take-off system.

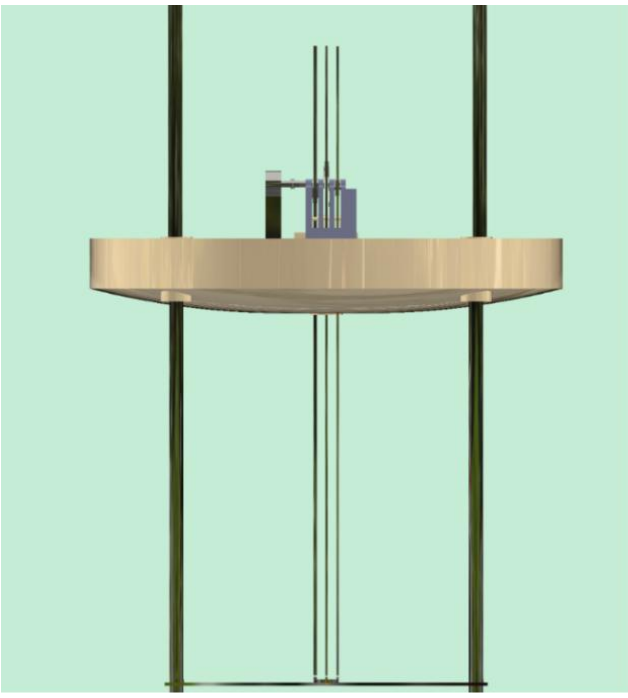

Figure 20. Floater, Guides and PTO configuration: A

Figure 21. Floater, PTO and Guides configuration: B

Therefore, regardless of the chosen configuration, the PTO's operation and the subsequent energy conversion process remain fundamentally dependent on the floater's motion in response to the incoming waves.

4.2 Pre-processing of Floater Model

The Floater Model must be processed to make it ready for being used in Diffraction analysis. Meshing and exporting of geometry is a key step in this process.

4.2.1 Meshing of Floater Model

To facilitate hydrodynamic analysis, the 3D model was exported to Gmsh, an open-source mesh generation software.

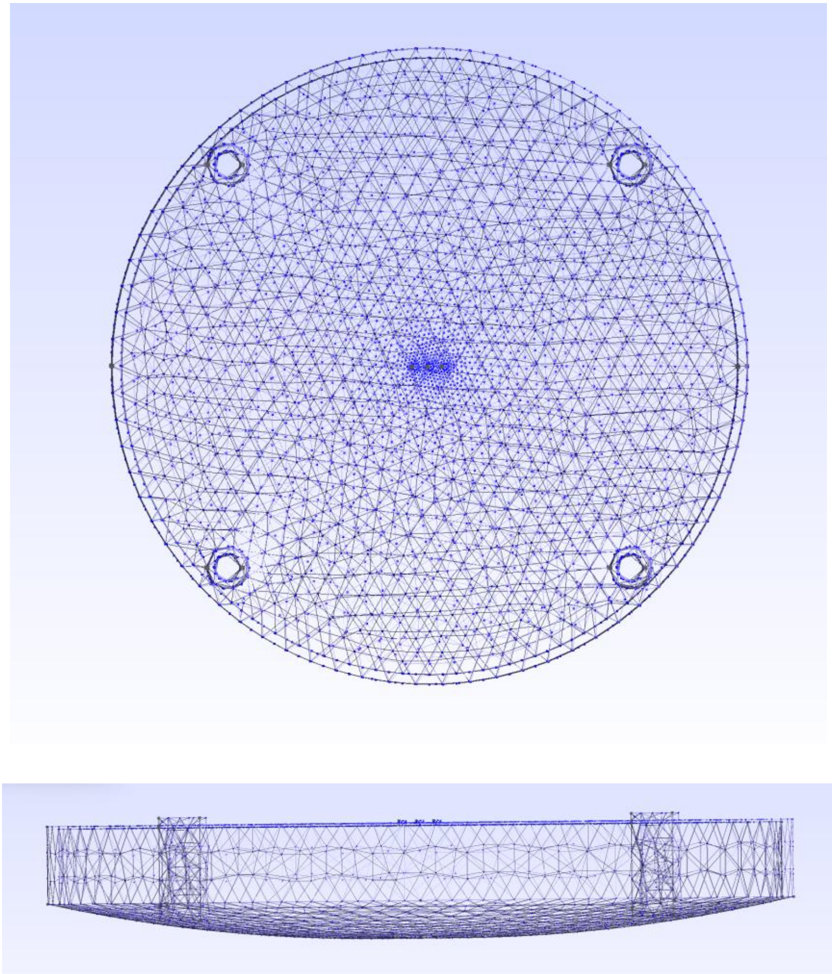

Figure 22. Mesh model of Floater, Plan and Elevation

A mesh consisting of nodes, elements and panels was generated, as shown in Figure 22. The mesh density was optimized to balance computational efficiency with the need to accurately capture the complex geometry of the floater, particularly around the curved surfaces of the floater.

This involved using finer mesh elements in areas of high curvature and coarser elements in regions where the geometry is relatively uniform.

This mesh forms the basis for the diffraction analysis and hydrodynamic analysis, allowing for the accurate calculation of RAOs, damping, added mass parameters etc. This is further utilized in subsequent simulation of its dynamic response in various sea states.

5. Diffraction Analysis of Floater with Orcawave

A comprehensive understanding of the floater's hydrodynamic behavior is crucial for predicting its performance and optimizing its design (Li et al., 2022). To achieve this, a diffraction analysis was conducted using OrcaWave, a leading industry software for analyzing wave-body interactions.

Diffraction analysis focuses on how the floater interacts with incoming waves, specifically how it scatters and diffracts them. This analysis is essential for several reasons:

Frequency-Dependent Behavior: The analysis reveals how the floater responds to waves of different frequencies (or periods). This frequency-dependent behavior is critical for understanding the floater's performance across a range of sea states.

Hydrostatics Calculation: OrcaWave calculates hydrostatic stiffness parameters of the floater, which are essential for stability and buoyancy considerations. This includes parameters like the center of buoyancy, metacentric height, and restoring forces, which are crucial for understanding how the floater reacts to changes in weight distribution and wave-induced tilts.

Optimization Insights: By varying the floater's geometry or other design parameters within OrcaWave, engineers can assess their impact on the hydrodynamic performance. This iterative process aids in optimizing the floater's shape for maximum energy capture and stability.

The results of the diffraction analysis in OrcaWave provide main information as follows:
Response Amplitude Operators: RAOs describe the floater's motion amplitude (heave, surge, pitch, etc.) in response to waves of unit amplitude across a range of frequencies.

Added Mass and Impulse Response: These parameters quantify the influence of the surrounding water on the floater's motion, affecting its natural frequency and damping characteristics.

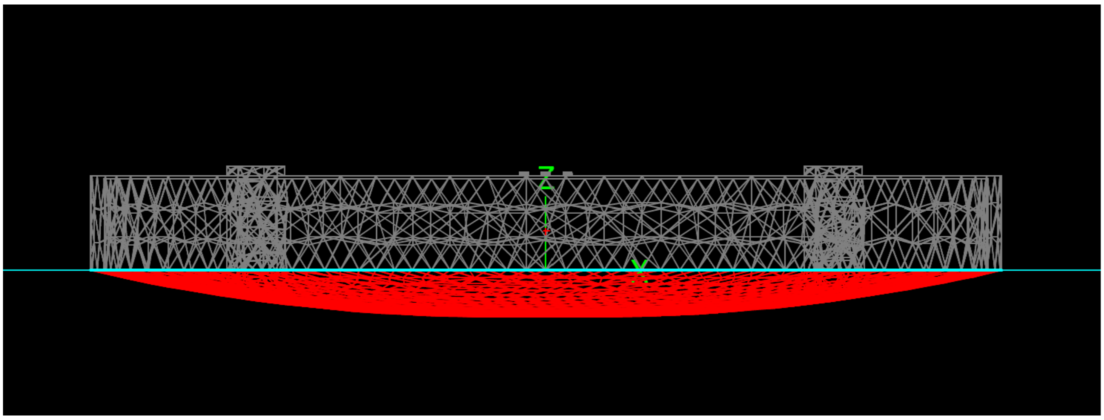

Figure 23. Orcawave Mesh view, coordinate axes and center of mass

5.1 Diffraction Analysis and Results

The following are the main parameters used for conducting diffraction analysis in Orcawave.

Wave Theory	Regular, Airy Waves
Wave Height	1 to 5 m, 0.5 m steps
Wave Time Period	6 to 15 s, 0.05 sec steps
Water depth	30 m
Incident Angles	0 to 360 deg, 10 deg steps
Diameter of Floater	30 m
Height of Floater	5 m

Table 4. Parameters for Orcawave analysis of the floater.

The hydrodynamic data obtained from OrcaWave, particularly the excitation forces, added mass, and damping coefficients, are seamlessly exported to OrcaFlex, a powerful time-domain simulation software. OrcaFlex utilizes the imported hydrodynamic data to model the floater's response to various wave conditions. This integration enables a more comprehensive analysis of the floater's dynamic behavior in a realistic ocean environment.

5.1.1 Hydrostatics Summary

The hydrodynamic properties of the floater, as determined by OrcaWave simulations, are summarized in the following table including inertia and stiffness matrices. These matrices encapsulate the system's hydrostatic characteristics, which are crucial for understanding its response to wave forces and for developing accurate control strategies.

Volume (m^3)	72.56052658					
Water plane area (m^2)	48.76239294					
Water plane moment Lxx (m^4)	5194.258821					
Water plane moment Lyy (m^4)	5191.637499					
Water plane moment Lxy (m^4)	3.497367913					
Mass (te)	280					
Centre of buoyancy (m) (x,y,z)	-0.004234516	0.0012854	-0.768627			
Centre of mass (m) (x,y,z)	0	0	1.3			
Inertia matrix	280	0	0	0	364	0
	0	280	0	-364	0	0
	0	0	280	0	0	0
	0	-364	0	24007.23	0	0
	364	0	0	0	24007.23	0
	0	0	0	0	0	45796.62
Hydrostatic stiffness matrix	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	490.15	5.30	5.53	0
	0	0	5.30	48015.73	-36.16	3.09
	0	0	5.53	-36.16	48040.21	-0.94
	0	0	0	0	0	0

Table 5 Hydrostatics summary from Orcawave simulation.

The diffraction analysis conducted in OrcaWave yielded crucial hydrodynamic characteristics of the floater, which are presented in the subsequent figures. Specifically, the load and displacement Response Amplitude Operators, added mass, and damping coefficients were derived from the analysis.

These parameters are particularly important for subsequent dynamic analysis as they directly influence the floater's response to wave excitation. high values in the Response Amplitude Operators indicate large amplitude motions of the floater for specific wave frequencies. This is generally undesirable as it can lead to increased mechanical loads, fatigue, and even compromise the stability of the structure. Therefore, understanding the RAO profiles is essential for assessing the floater's performance and survival in various sea states. The graphs obtained from the diffraction analysis are presented in the following sections.

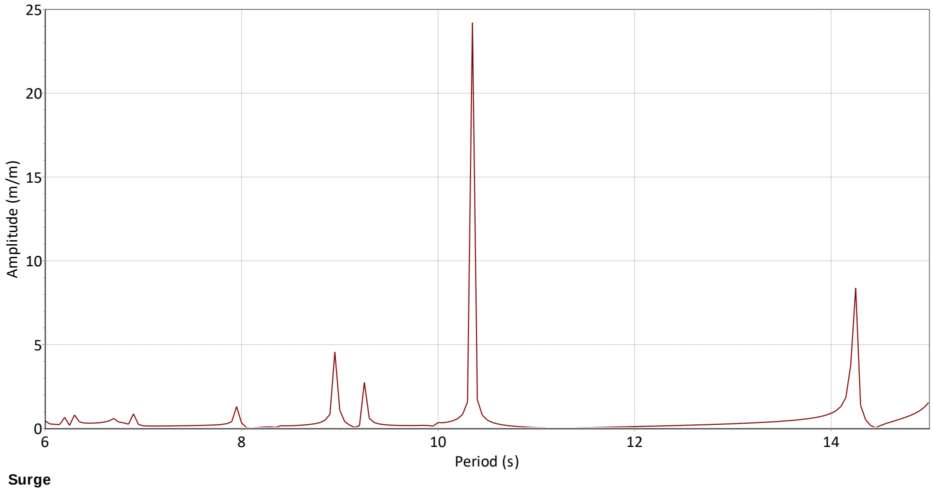

Figure 24. Displacement RAO, Surge

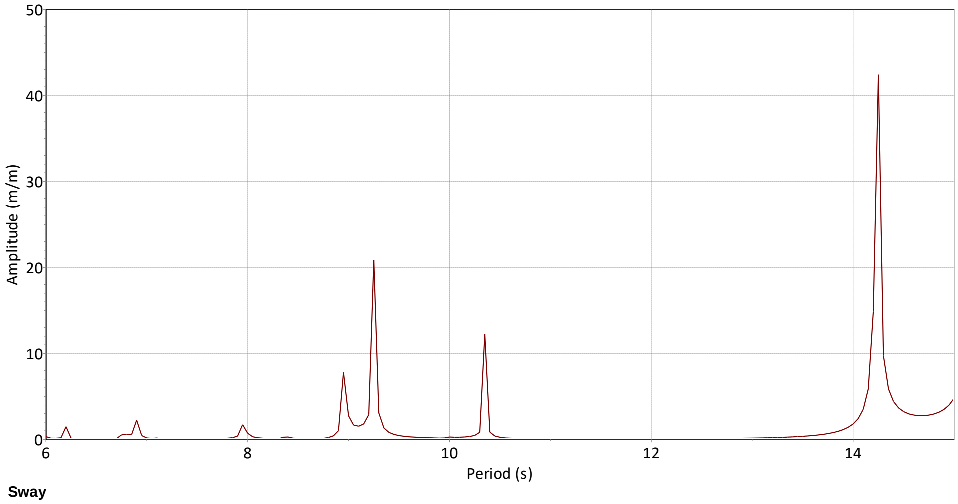

Figure 25. Displacement RAO, Sway

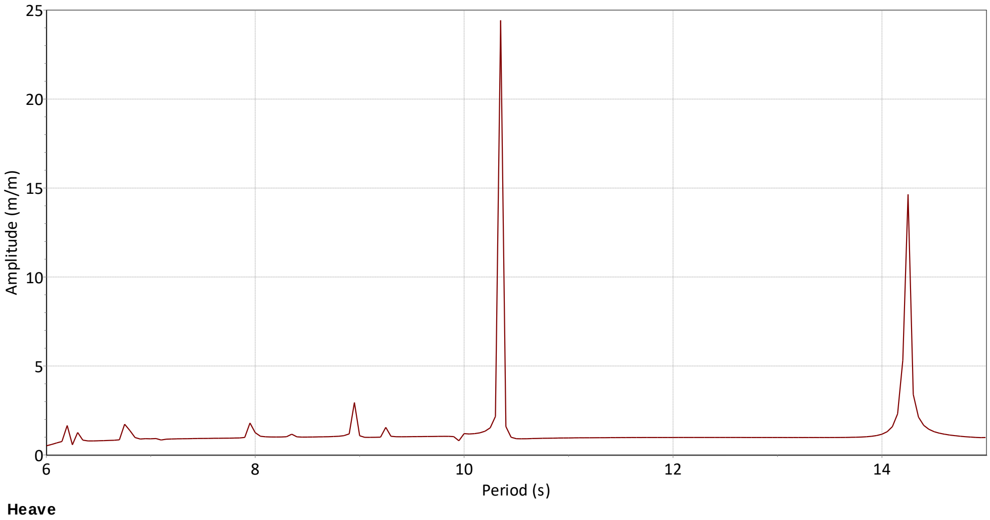

Figure 26. Displacement RAO, Heave

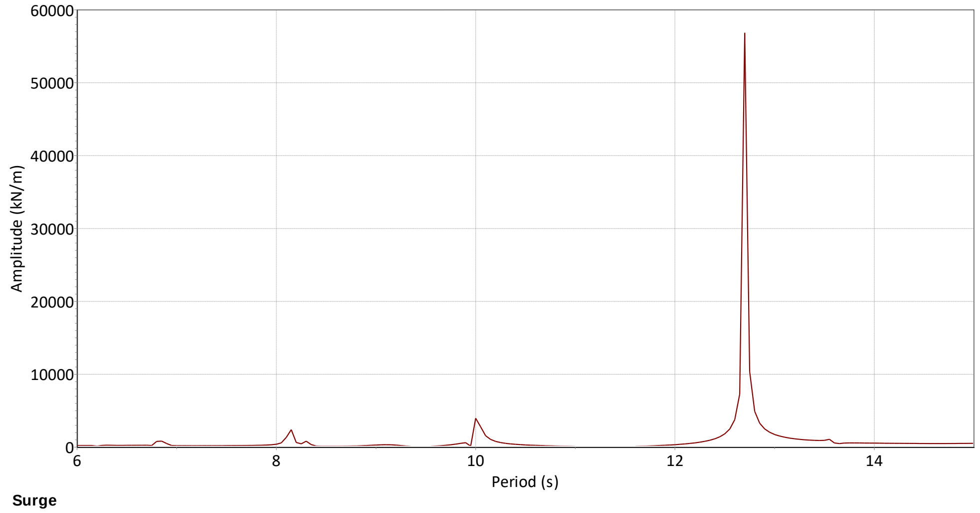

Figure 27. Load RAO, Surge

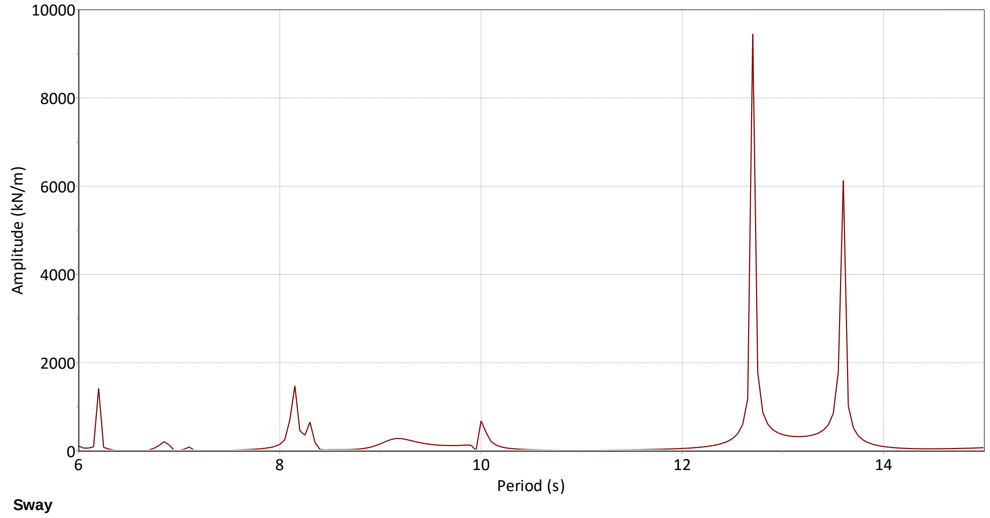

Figure 28. Load RAO, Sway

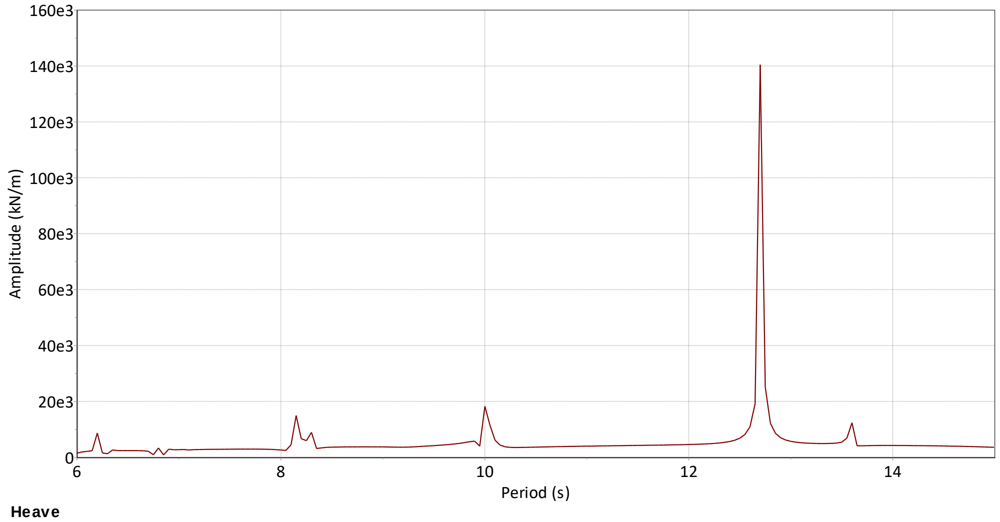

Figure 29. Load RAO, Heave

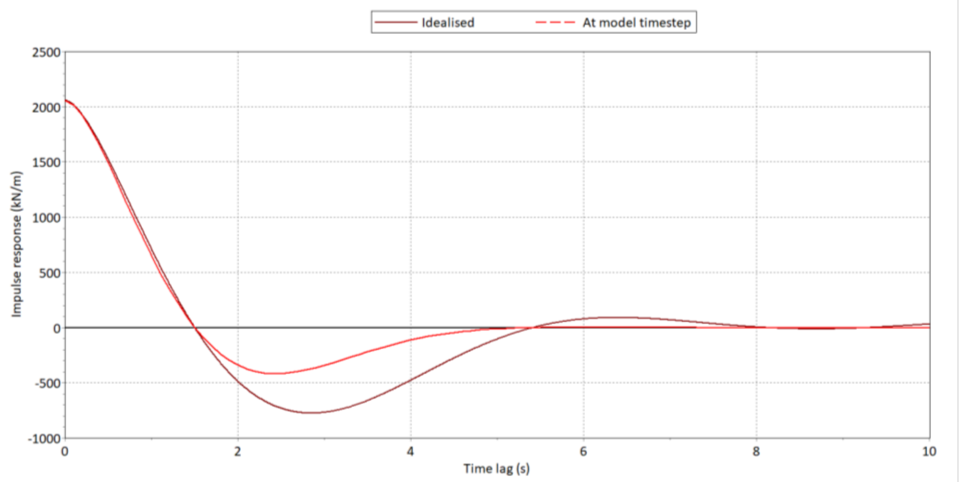

Figure 30. Impulse Response Heave-Heave

The impulse response provides insights into the stability of the floating body. A stable system will exhibit decaying oscillations or a return to equilibrium after a disturbance, while an unstable system will show oscillations that grow over time.

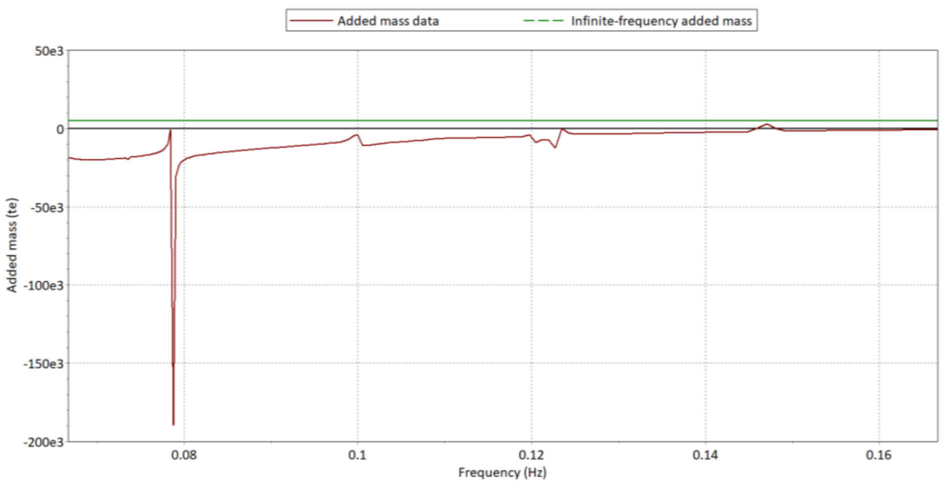

Figure 31. Added Mass Heave-Heave

The added mass and impulse response study are crucial for modeling the floater's dynamics. These parameters capture the influence of the wave parameters especially the time period (conversely frequency), which can affect the floater's natural frequencies and damping characteristics.

For further dynamic analysis, a specific wave time period of **9.5 sec** has been selected, corresponding to a range within the Response Amplitude Operators that is considered to be acceptable. This selection ensures that the floater's motions and loads remain within manageable limits during the analysis.

Furthermore, this chosen wave period aligns with a high-energy density region identified in the scatter diagram presented in the previous section. This combination of acceptable RAO values and significant wave energy density makes this particular time period particularly well-suited for investigating the forces acting on the floater. By focusing on this specific wave condition, the analysis can provide valuable insights into the floater's performance under realistic sea states

6. Dynamic Simulation of Guided Floater with Orcaflex

OrcaFlex is a powerful and versatile software tool specifically designed for simulating the dynamic behavior of offshore marine systems. Its capabilities extend to analyzing a wide range of structures and components, including floaters, mooring lines, risers, cables, and subsea equipment. This makes it an ideal platform for evaluating the performance of wave energy converters in realistic ocean environments.

OrcaFlex simulations generate a wealth of data that provide valuable insights into the floater's performance. This data includes:

Motion Analysis: Time-histories and spectral analysis of the floater's motion in all six degrees of freedom (heave, surge, sway, roll, pitch, yaw). This allows for a detailed understanding of the floater's response to waves and its stability characteristics.

Mooring Line Tensions: Dynamic tensions experienced by the mooring lines throughout the simulation. This data is crucial for assessing mooring line fatigue and ensuring the system's structural integrity.

Power Capture Performance: By incorporating a power take-off system model, OrcaFlex can estimate the power output of the WEC under various wave conditions.

Extreme Load Cases: The software allows for simulating extreme wave events to assess the survivability of the system under harsh conditions.

Figure 32 illustrates the OrcaFlex model developed for this study. The floater, complete with its guide structures, is represented within the software, including its geometry and hydrodynamic properties captured from output file of Orcawave analysis.

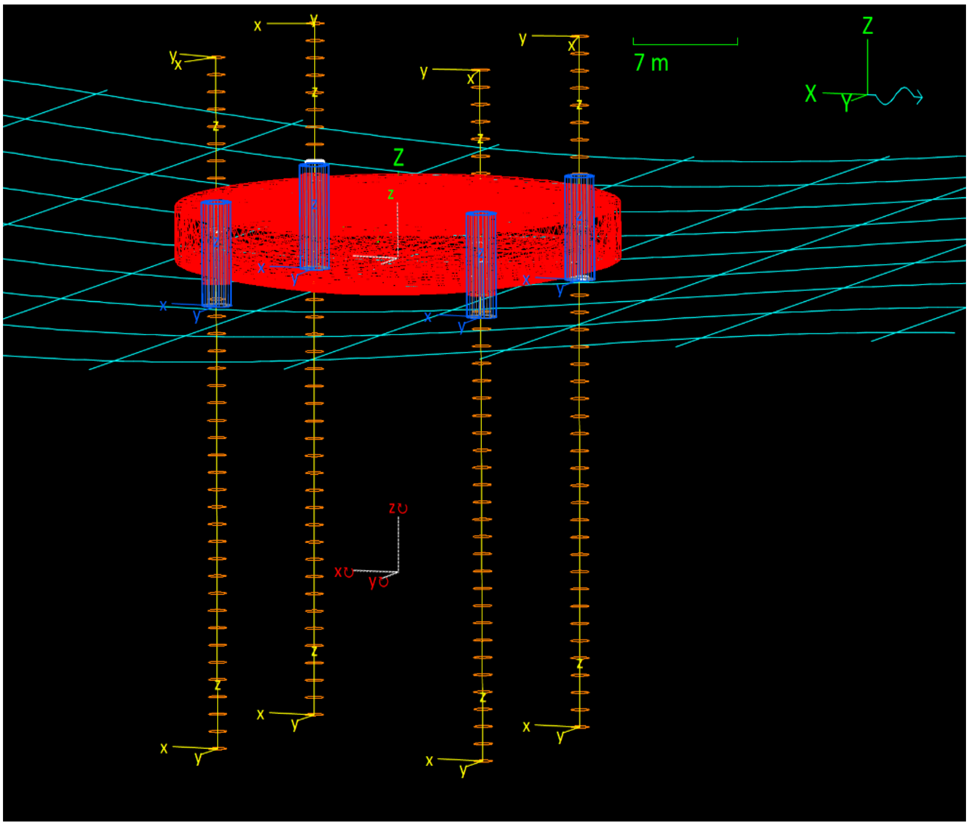

Figure 32. Orcaflex Simulation sample view

6.1 Dynamic Simulation results

A key objective of this study is to understand the energy extraction from the floater's heave motion and forces acting on the system. OrcaFlex simulation plays a crucial role in this by providing the time-history of the heave force acting on the floater.

PTO Design Optimization: The heave force data will be instrumental in informing the design and optimization of the Power Take-Off system. By understanding the magnitude and frequency characteristics of the force, we can tailor the PTO's parameters to efficiently capture and convert the floater's motion into usable energy.

Power Output Estimation: Having the time-history of the heave force allows to estimate the potential power output of the SWEC. By analyzing the force data, we can calculate the work done by the floater and subsequently determine the power generated.

System Efficiency Evaluation: By comparing the extracted power, derived from the heave force time series data, to the incident wave energy, the overall efficiency of the wave energy converter can be evaluated. This analysis will provide insights into the effectiveness of the SWEC in harnessing wave energy.

Parameters selected to run the simulation for the floater and guide system are as follows:

Wave Theory	Regular, Airy Waves
Wave Height	4.5 m
Wave Time Period	9.5 s
Water depth	60 m
Incident Angles	0 to 360 deg, 10 deg steps
Diameter of Floater	30 m
Height of Floater	5 m
Guides	4 no's
Simulation Time	150 s (Buildup phase: 50 secs)

Table 6. Parameters for Orcaflex analysis of the floater with 4 guides.

The OrcaFlex analysis yielded a set of results, providing insights into the dynamic behavior and performance of the wave energy converter. These results, which are visually presented in the following section in graphs, encompass:

Motion Analysis: Time-histories of the floater's movements across all six degrees of freedom, illustrating its response to wave excitation and overall stability.

Phase Relationship: Exploration of the phase shift between peak floater elevation and the peak force exerted on the floater, highlighting key hydrodynamic interactions.

PTO Parameters calculation: Time Series of force data in Heave which are considered to be further transmitted to the PTO system via the tethers. This data will be utilized to derive the torque generated in PTO crankshaft.

A key observation from the analysis is the phase shift between the floater's vertical displacement (heave) and the force acting on it. This phase difference arises due to the inertial effects of the floater during wave motion.

Inertia: The floating structure, due to its significant mass and buoyancy, exhibits substantial resistance to changes in its motion. As a wave crest passes, it initially applies an upward force on the floater, pushing it upwards.

However, owing to the significant inertia of the floater, it does not immediately respond by reaching its peak elevation. Instead, the floater's upward motion lags behind the wave crest, and it reaches its highest point only after the wave crest has already passed.

Hydrodynamic Reaction and Added Mass: As the floater moves within the water, it interacts with the surrounding fluid, leading to a phenomenon known as added mass. This means that the floater effectively experiences a higher inertia due to the water that it needs to accelerate along with its own motion. As the floater moves upwards, it must displace a significant volume of water, and this displaced water effectively increases the system's resistance to acceleration. Consequently, the peak hydrodynamic reaction force, influenced by this added mass, doesn't coincide with the floater's peak elevation. Instead, it lags slightly behind, reaching its maximum value a short while after the floater has reached its highest point. This offset, a direct consequence of the added mass effect, is a key factor in enabling the efficient extraction of energy from ocean waves. This phase shift between floater elevation and force is advantageous for energy extraction:

Enhanced Power Capture: The phase difference ensures that the force acting on the floater is maximized when the floater is moving at its fastest. This alignment of peak force and velocity leads to greater energy transfer from the waves to the floater, enhancing power capture (Li et al., 2022).

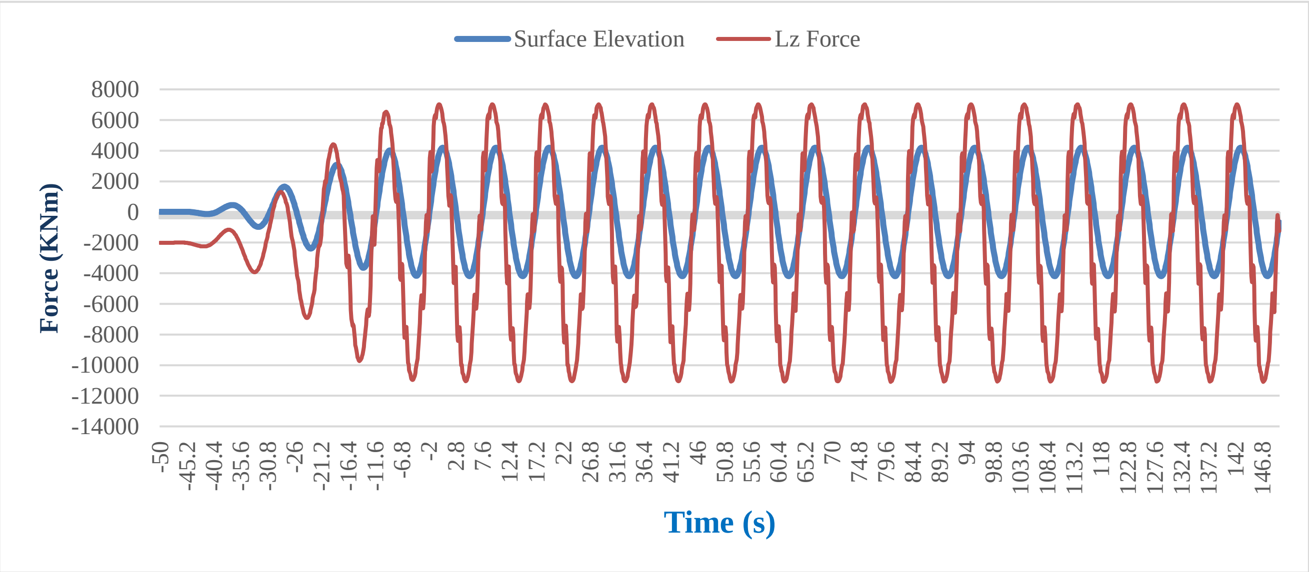

Figure 33 Floater Elevation and Force in Heave – Phase difference

The following Figure 34 illustrates the total force exerted by waves on the floater's body over a period. This graph also indicates the initial "build-up" phase of the simulation. During this phase, the wave forces gradually increase from zero to dynamically stable pre-defined values. This build-up is required because the simulation needs a short period to reach a state of equilibrium where the wave-structure interactions are fully developed.

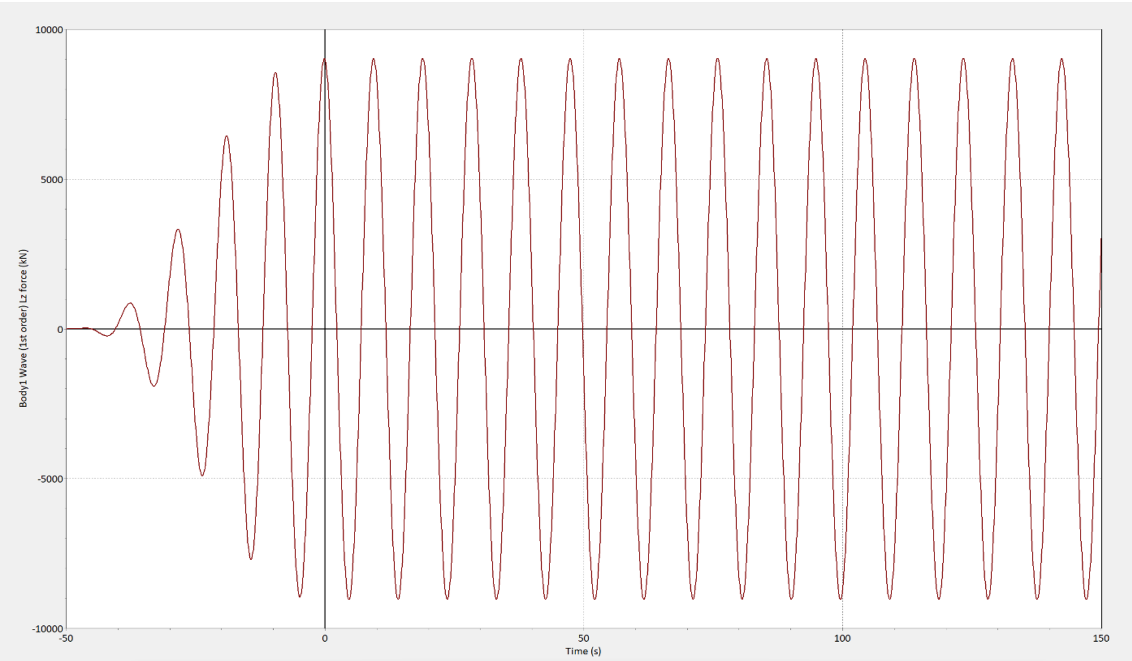

Figure 34. Total Wave Force on Floater, Z direction

The following Figure 36 illustrates the significant variation in the forces acting on the floater throughout its complete motion cycle, from wave crest to trough. A key observation is that the downward movement of the floater, driven by the combined influence of the wave and gravity, results in substantially higher forces compared to its upward motion. This difference is due to net force acting, due to wave force and the floater's mass, which under the constant pull of gravity, contributes to a greater downward force as the floater moves from a peak to a trough.

This amplified force during the downward stroke is a direct consequence of the floater's mass and represents a beneficial target for energy capture by the PTO system. The increased force during the downward motion creates a favorable condition for the PTO system to harness more energy, as the floater's downward velocity aligns with the direction of the force, leading to greater power transfer from the waves to the PTO.

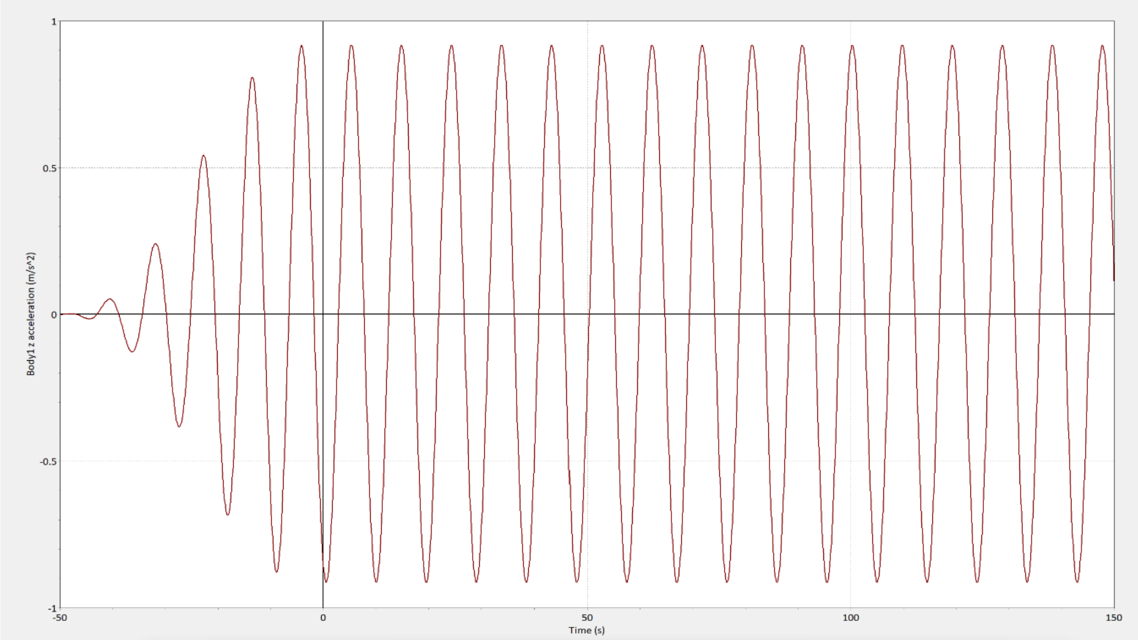

Figure 35. Acceleration of Floater, Z direction

It's important to acknowledge that the guide structures, while constraining the floater's motion, also experience reaction forces due to their interaction with the floater. These forces, arising from both the floater's motion and direct wave loading on the guides themselves, can influence the total vertical force (z-direction) transmitted from the floater. This effect is evident in the force-time history Figure 36, where fluctuations are observed in contrast to the smoother profile of the incoming wave.

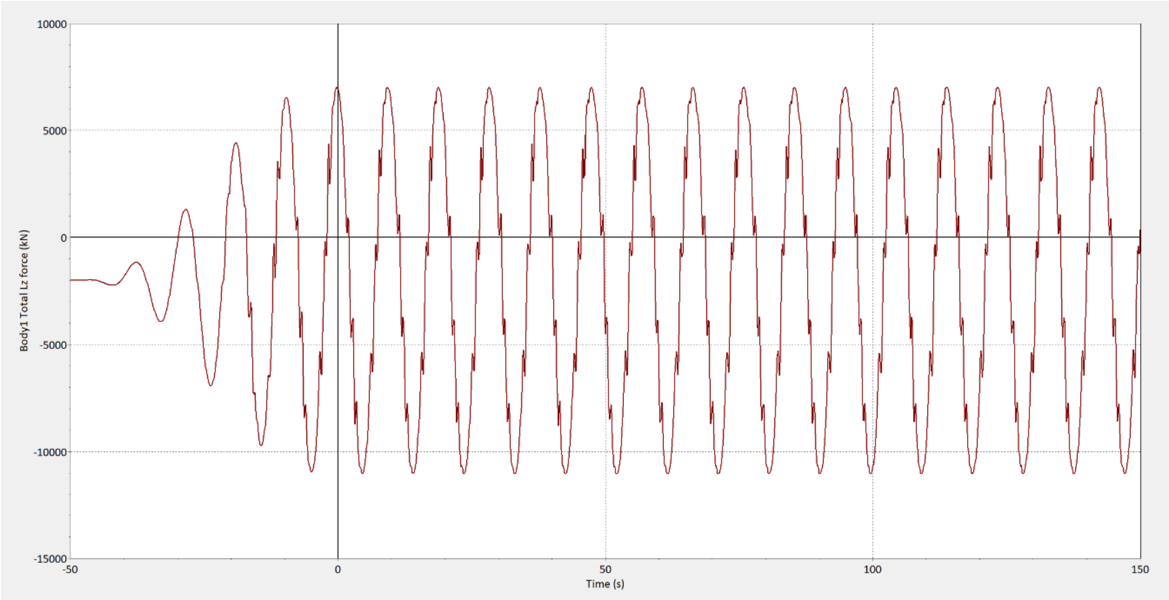

Figure 36. Total Force from Floater under motion, Z direction

The following Figure 37 to Figure 42 indicate the motion responses of the floater across its six degrees of freedom (surge, sway, heave, roll, pitch, and yaw). A key observation is the distinct influence of the guide structures on the floater's motion. Specifically, the heave response is supplemented by the guides, while other motions, such as surge, sway, roll, pitch, and yaw, are effectively constrained.

This selective motion control, facilitated by the guide structures, is highly advantageous for maximizing energy extraction. By assisting the heave motion, the system can more effectively harness the vertical forces generated by the waves, which are the primary drivers for the PTO system.

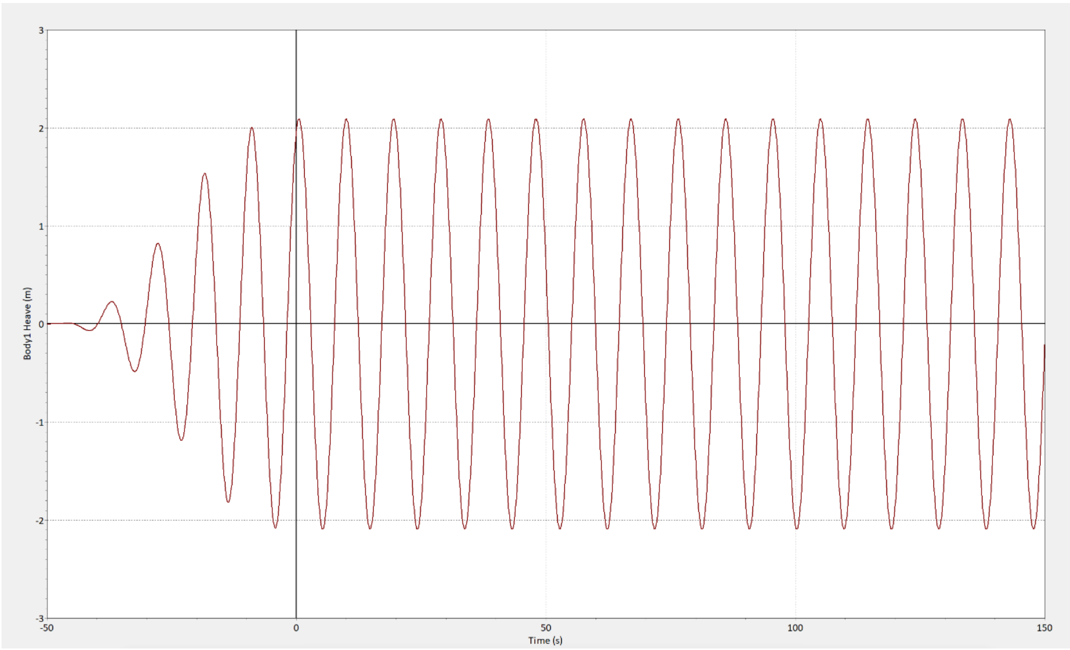

Figure 37. Floater Heave motion

Furthermore, the reduction in other degrees of freedom contributes to enhanced system stability and control. By minimizing undesirable motions, the guides help to maintain a more predictable and efficient operational profile for the wave energy converter.

This improved controllability not only enhances energy capture but also reduces mechanical stresses and fatigue on the system, contributing to its overall efficiency.

The forces on guides are indicated in Figure 43, Figure 44 and Figure 45. While this study recognizes the presence and potential significance of these guide-induced force variations, a detailed analysis of these forces is outside the scope of the current investigation. The graphs are presented to provide a comprehensive overview of the system's dynamic behavior, highlighting areas for further studies.

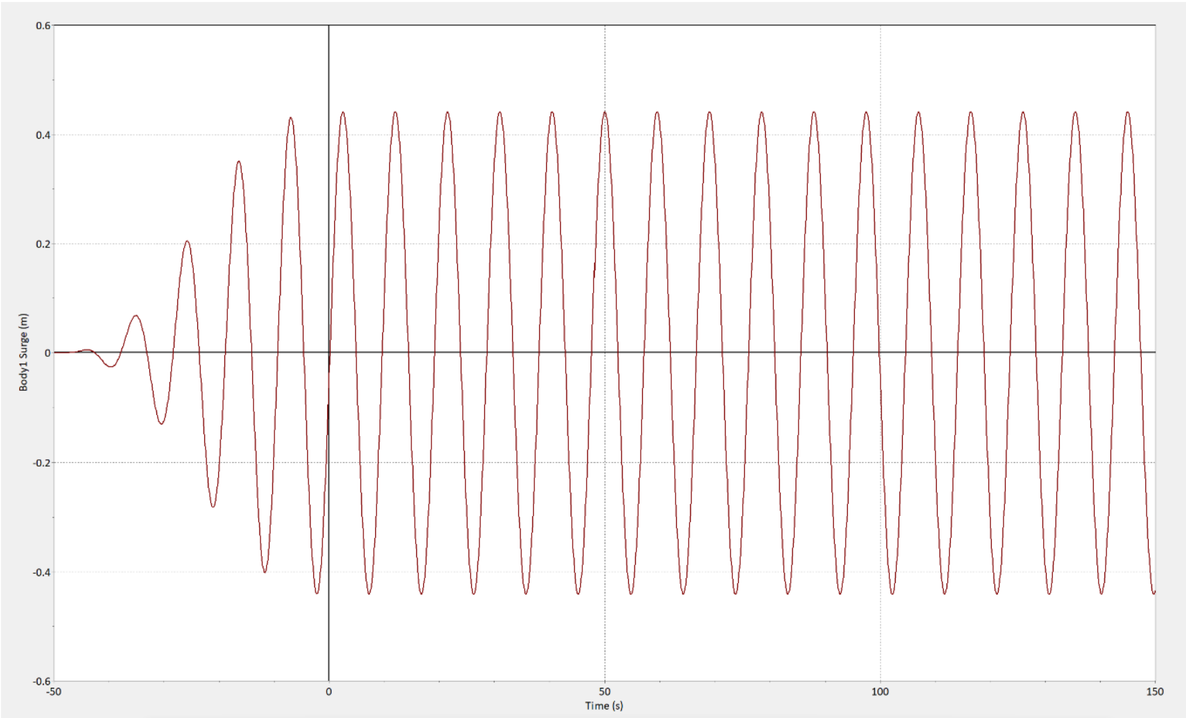

Figure 38. Floater Surge motion

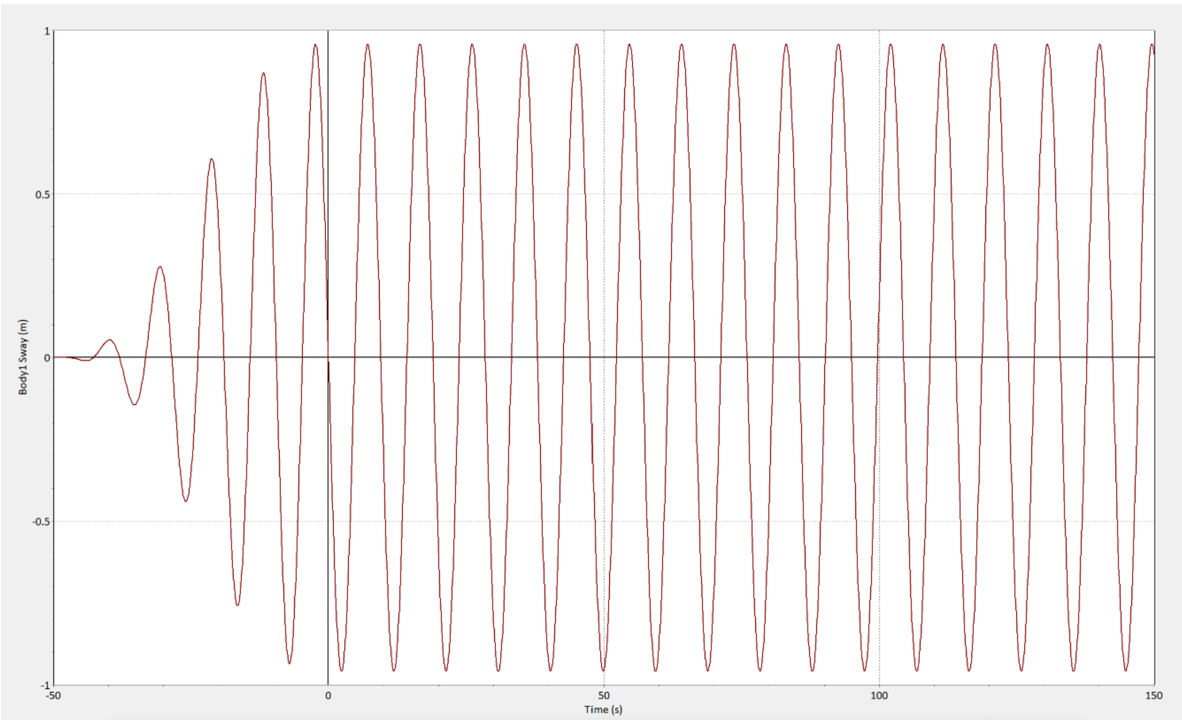

Figure 39. Floater Sway motion

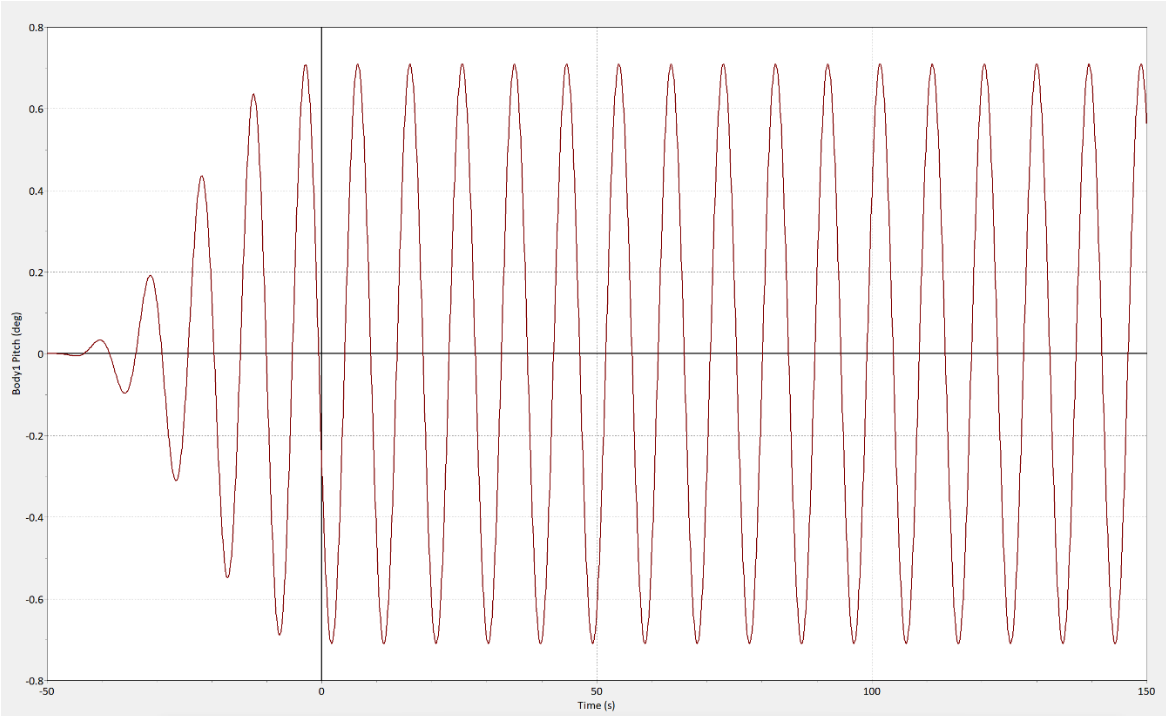

Figure 40. Floater Pitch motion

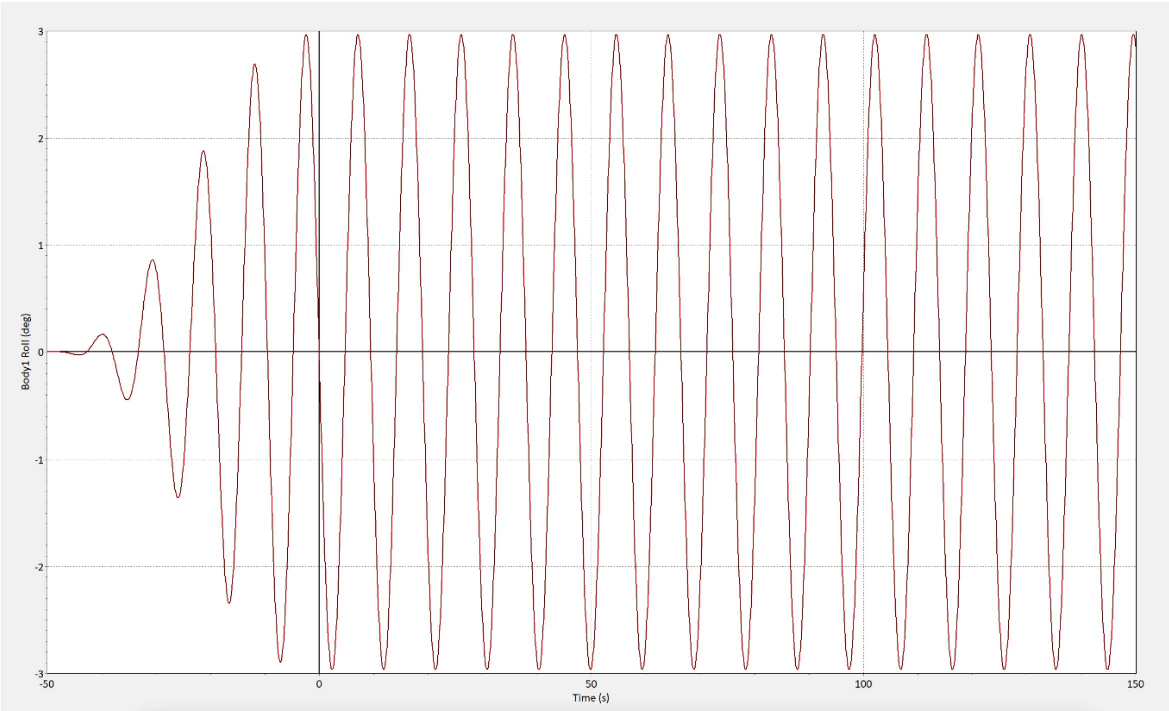

Figure 41. Floater Roll motion

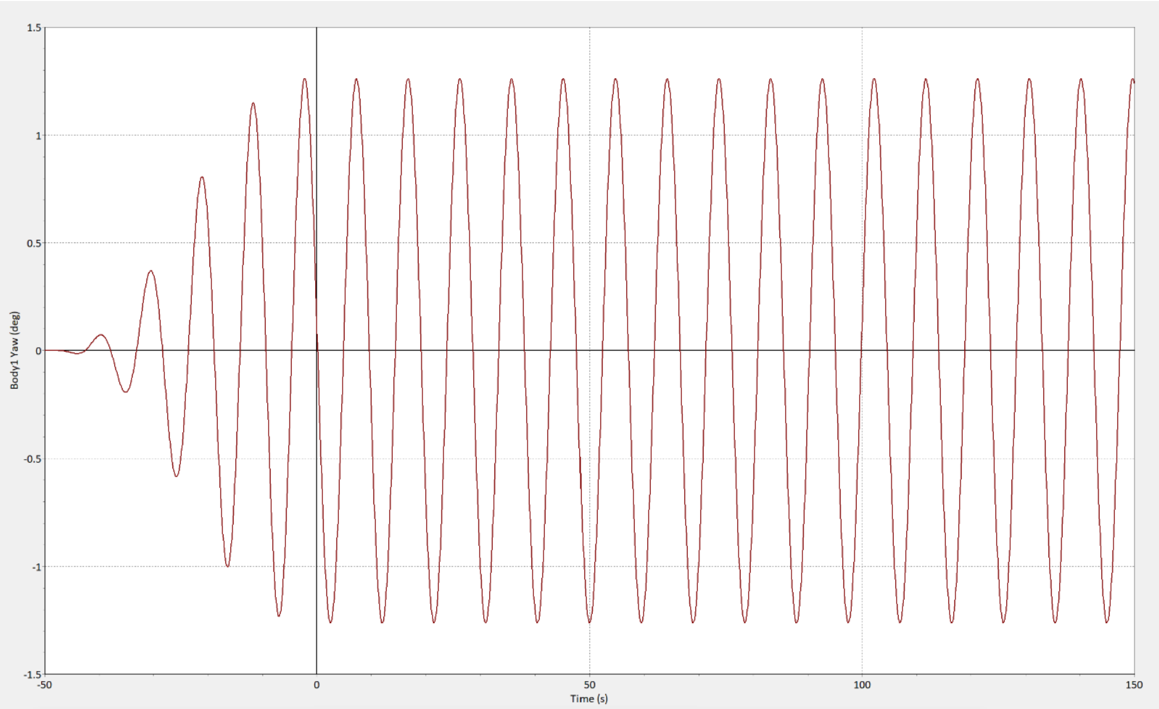

Figure 42. Floater Yaw motion

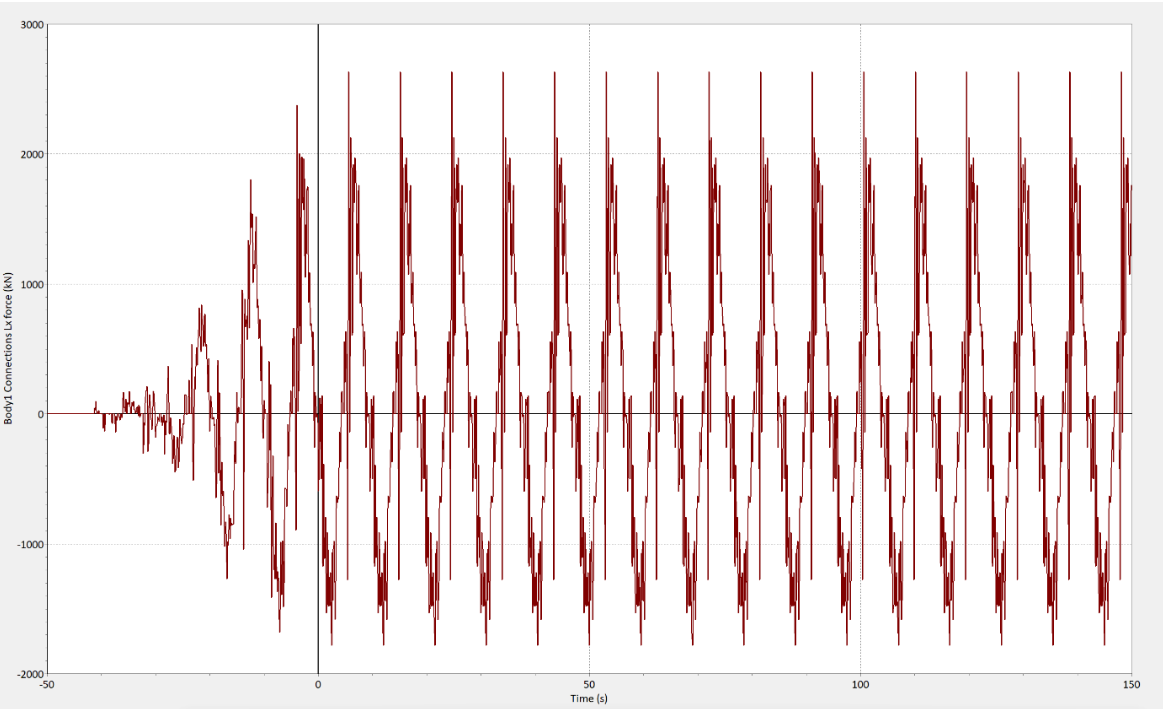

Figure 43. Forces on guides, X direction

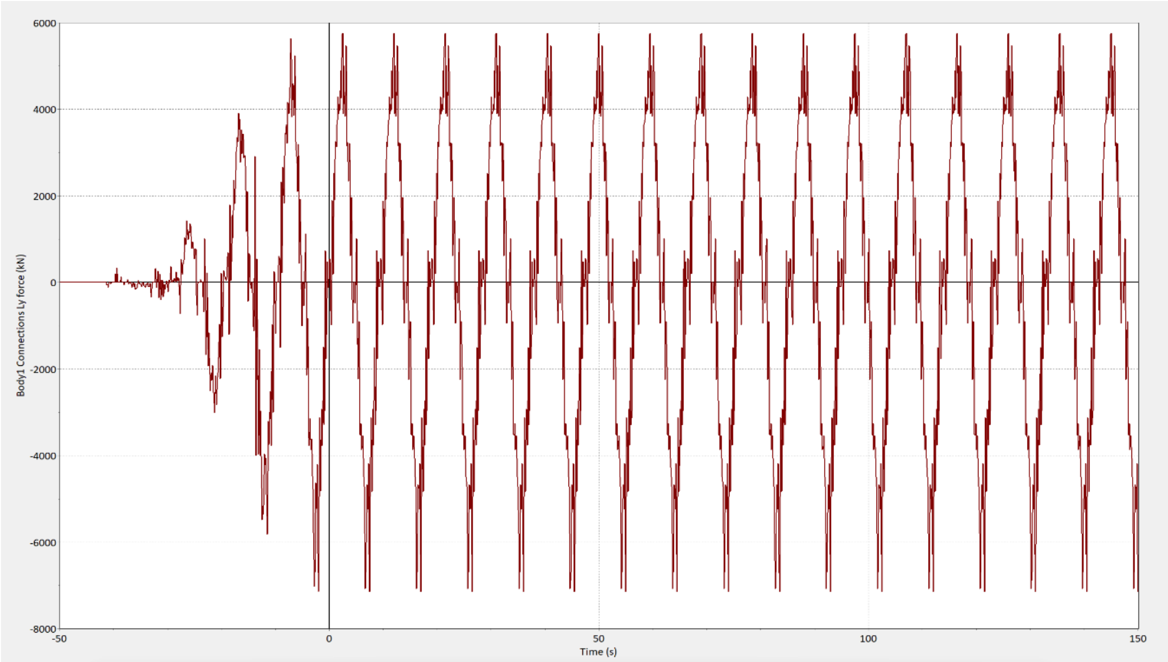

Figure 44. Forces on guides, Y direction

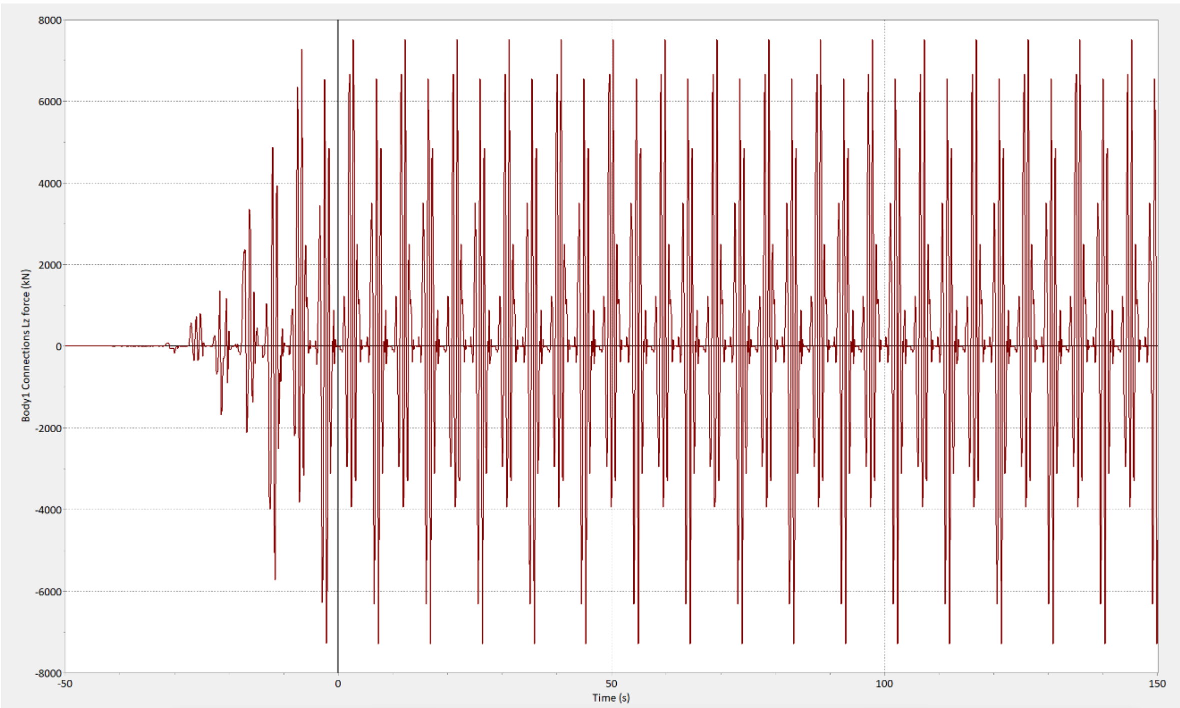

Figure 45. Forces on guides, Z direction

7. Analysis of forces and calculation of PTO Torque

The time series values were extracted from the dynamic simulation. A custom MATLAB code was developed to bridge the gap between OrcaFlex's simulation data and the calculation of usable torque for power generation. This code seamlessly imports the time-series heave force data from OrcaFlex, performs any necessary pre-processing, and then calculates the instantaneous torque based on the floater's PTO system geometry. The resulting torque data is then visualized to provide insights into its time-history, frequency content, and energy extraction potential, ultimately aiding in the optimization of the PTO system.

Torque Calculation: Utilizing the geometric and mass parameters of floater, tethers and the PTO system, the code calculates the instantaneous torque based on the imported heave force data. This calculation involve geometric transformations, considering lever arms, gear ratios, or other mechanical advantages within the PTO system.

The subsequent section will present graphical representations of the calculated torque data. These visualizations provide valuable insights into Torque Time-History to understand how the torque varies over time in response to the floater's heave motion and the wave conditions.

By utilizing this MATLAB code, a defined workflow for translating the raw OrcaFlex simulation data into meaningful insights regarding the PTOs torque generation potential is created. This analysis is fundamental for optimizing the design and control of the power take-off system to maximize energy extraction under the studied sea state. The main results are presented in following graphs.

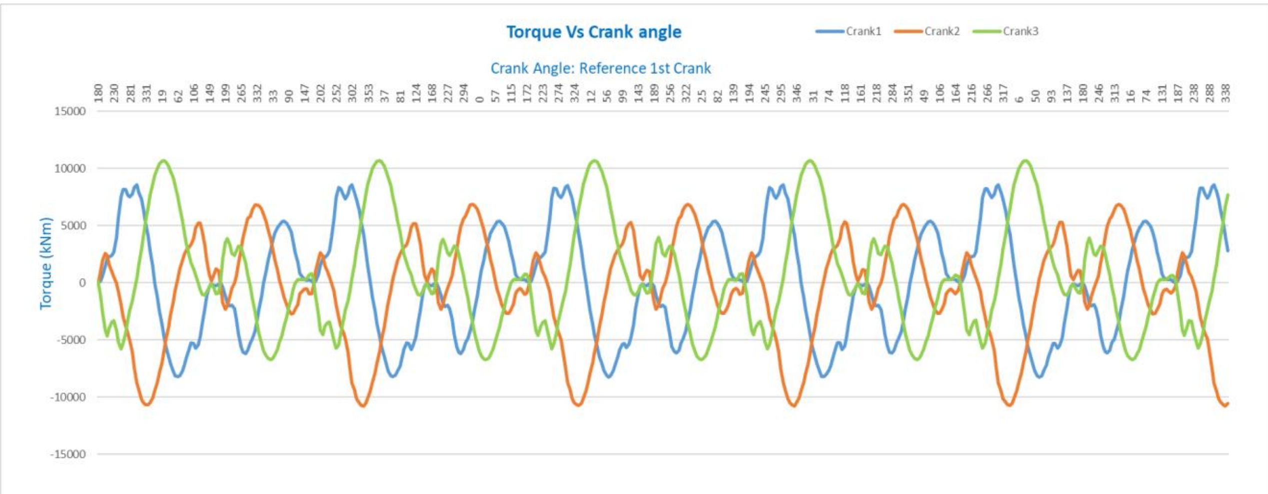

Figure 46. Total Torque Available from 30m tether length for 1m radius crankshaft, 12 rpm

With the selected wave height and wave period in this study, operation of two crankshaft rotations for every complete wave period is considered. This is considered to be effected through control system that integrates the crank-gripper mechanism explained earlier, with positional data from sensors.

Motion Detection: Sensors continuously monitor the floater's motion, accurately identifying whether it is moving upwards or downwards.

Angle Measurement: Angle sensors are strategically positioned to precisely measure the angular position of each of the three cranks within the system.

These simulated data from sensor is used to determine the optimal engagement and disengagement of the grippers.

Control Logic: A control algorithm, implemented in MATLAB, simulated a specific set of data representing the sea state parameters of present study, upward or downward motion and crank angles of three cranks (Crank1, 2 ,3). This algorithm determines the optimal timing for engaging or disengaging the grippers based on the floater's motion and the crankshaft positions.

2-on-1-off Methodology: The control logic employs a "2-on-1-off" strategy for engaging the cranks. This means that at any given time, two out of the three cranks are actively engaged with the floater, maximizing force transmission, while the third crank remains disengaged. This cyclical engagement pattern ensures a smooth and continuous transfer of power from the floater to the PTO system.

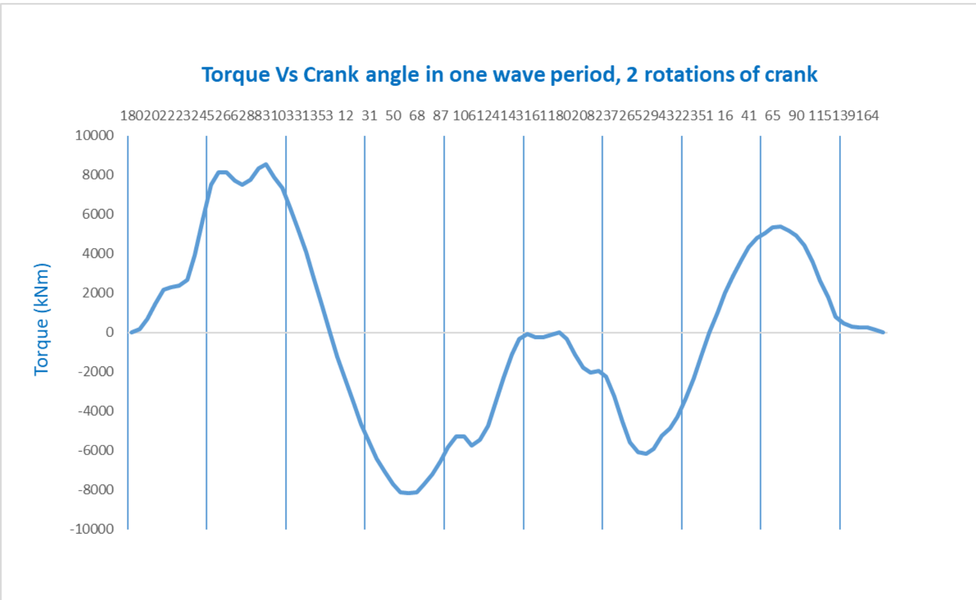

Figure 47. Torque in one wave period, 2 crank rotations

The resulting graph of transmitted torque, derived from the MATLAB code, reflects this relation between the floater's motion, the simulated data, and the control logics decision-making process.

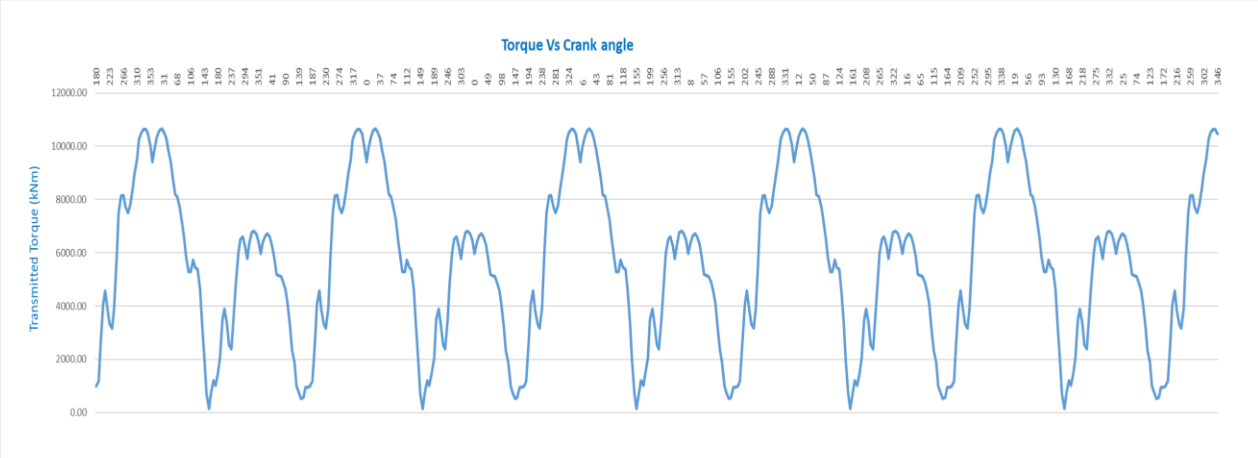

Figure 48. Total transmitted Torque with Sequential Gripping, 12 rpm.

The data from this transmitted torque series is further utilized in modelling a reactive control system for the PTO which is explained in subsequent sections.

8. Reactive Control using Flywheel system

The theoretical control method for optimal power extraction in wave energy converters is well-established, stemming from the pioneering work of researchers in the field. The implementation of reactive control strategies for wave energy converters has been extensively studied (Costa et al., 2010) (Valério et al., 2007) (Ligeikis & Scruggs, 2024)(Beirão et al., 2007).

Reactive control involves dynamically adjusting parameters such as inertia, stiffness, and damping in the wave energy converter system. These real-time adjustments are made to the system's characteristics to optimize power absorption from the incoming waves. By continuously tuning these parameters, the wave energy converter can respond more effectively to the constantly changing wave conditions, ensuring efficient and maximized energy conversion. Through this dynamic and adaptive control approach, wave energy converters can harness a greater proportion of the available wave energy, leading to improved overall system performance and increased energy generation potential. (Yetkin et al., 2021)

Incorporating a flywheel system into a Wave Energy Converter (WEC) with reactive control is a promising approach that offers several potential advantages. This approach leverages the ability of flywheels to store and release rotational kinetic energy in a controlled manner to enhance the energy capture and power output of the WEC system.

When the buoy is excited by waves, the reactive control system can direct a portion of the captured mechanical energy to spin up the flywheel. This helps regulate the buoy's motion, preventing it from moving too violently in response to large waves.

The flywheel acts as a buffer, storing energy during periods of high wave activity and releasing it during lulls, thereby smoothing the power output from the WEC. The flywheel provides the control system with an additional degree of freedom, allowing for finer control over the buoy's motion and optimization of energy capture across a wider range of wave conditions.

Advantages of Flywheel Integration:

Increased Energy Capture: By smoothing out power fluctuations, less energy is wasted, potentially leading to higher overall energy capture.

Improved Power Quality: The more consistent power output is beneficial for grid integration and reduces the need for extensive energy storage solutions.

Reduced Mechanical Stress: The flywheel can help absorb shock loads and reduce stress on the WEC structure, potentially increasing its lifespan.

Challenges of the system:

1. Complexity and Cost: Integrating a flywheel adds complexity and cost to the WEC system.
2. Size and Weight: Flywheels can be heavy and bulky, which can pose challenges for deployment and integration with the buoy.

Overall, using a flywheel system as part of a reactive control strategy for WECs is a promising approach to enhance energy capture, improve power quality, and potentially reduce mechanical stress. This study will delve into the specific benefits and practicalities of implementing a flywheel-based reactive control system within the SWEC. Through detailed analysis and simulations, this study will aim to validate the potential of this approach to enhance the SWEC's performance renewable energy solution.

8.1 Flywheel Integrated concept in SWEC PTO

A concept is developed where the crankshaft of the PTO is linked to generator input shaft through two clutches and a flywheel.

System Components:

- Crankshaft of PTO: Converts reciprocating motion from heaving floater into rotational motion via tethers/links.
- Flywheel: Stores rotational energy, smoothing out fluctuations in crankshaft speed.
- Clutch 1: Controls the connection between the crankshaft and the flywheel.
- Clutch 2: Controls the connection between the flywheel and the generator.
- Generator: Converts rotational energy from the flywheel into electrical energy.

Phase 1: Energy Capture and Flywheel Acceleration

WEC in Motion: The heaving floater of the WEC drives the crankshaft.

Clutch 1 Engaged: Clutch 1 is engaged, allowing the crankshaft to transfer torque to the flywheel.

Flywheel Acceleration: The flywheel spins up, storing energy as its rotational speed increases. During this phase, the flywheel absorbs excess energy from the crankshaft, smoothing out any sudden spikes in torque.

Clutch 2 Disengaged: Clutch 2 remains disengaged, preventing the generator from being driven by the fluctuating crankshaft speed directly.

Phase 2: Stable Power Generation

Flywheel Momentum: The flywheel, now rotating at a relatively steady speed, becomes the primary source of rotational energy.

Clutch 1 Disengaged: Clutch 1 can be disengaged to allow the crankshaft to move freely without affecting the flywheel's rotation. This is particularly useful if the WEC motion becomes erratic or opposes the flywheel's direction.

Clutch 2 Engaged: Clutch 2 is engaged, connecting the rotating flywheel to the generator.

Stable Power Output: The flywheel drives the generator at a relatively constant speed, producing a smooth and consistent flow of electrical power, even though the crankshaft torque may be fluctuating.

Clutch Control Strategies:

- Torque Monitoring: Sensors can monitor the torque output of the crankshaft. When the torque exceeds a certain threshold (indicating excess energy), Clutch 1 is engaged to transfer energy to the flywheel. When the torque drops below a threshold, clutch 1 can be disengaged.
- Speed Sensing: Sensors can monitor the rotational speed of both the crankshaft and the flywheel. Clutch engagement and disengagement can be controlled to maintain the flywheel within a desired speed range, ensuring optimal energy storage and smooth power output.
- Predictive Control: Incorporating wave forecasting and WEC motion prediction models can allow for more sophisticated clutch control, anticipating energy fluctuations and optimizing the system for maximum efficiency.

The heaving motion of the floater is inherently cyclical and often irregular due to varying wave conditions. This system with clutches and a flywheel is crucial for:

- Maximizing Energy Capture: By decoupling the generator from the fluctuating crankshaft, the system can capture energy more effectively even during irregular wave patterns.
- Protecting the Generator: The flywheel acts as a buffer, protecting the generator from potentially damaging torque spikes and ensuring a longer lifespan.
- Grid Integration: Smooth power output is essential for feeding electricity into the grid reliably.

8.2 Flywheel and Generator

Appropriate selection of a flywheel and generator pair is essential for this wave energy converter system. The flywheel's inertia and size impact energy storage and system size, while the generator's capacity and operating range must align with the system's power output and speed. These two elements are critical for smoothing the inherently variable power output from ocean waves, ensuring a consistent and usable energy supply.

The following sections will delve into the specific selection criteria and methodologies employed to identify the most suitable components for this wave energy converter, ensuring both performance and practicality.

8.2.1 Flywheel Parameter selection

Calculations were carried out from data available of mean torque available at crankshaft, to determine basic parameters required for the flywheel, that can provide sufficient restoring torque for stabilizing the system by not allowing available torque to go down too low in entire cycle of operations.

Following are the flywheel parameters utilized for further studies:

Radius	3 m
Weight	8000 Kg
Type	Rim Type
Moment of Inertia	18000 Kgm2

Table 7. Flywheel Parameters

8.2.1 Generator Type selection

This study focuses on a wave energy converter utilizing a direct-drive generator, a popular choice in such applications due to its inherent advantages in harnessing the unpredictable nature of ocean waves. Unlike conventional generators that require gearboxes to match speed and torque, a direct-drive system directly couples the generator's rotor to the prime mover, in this case, the wave energy converter's oscillating mechanism.

This direct coupling offers several key benefits:

Enhanced Efficiency: By eliminating the gearbox, energy losses associated with friction and inertia within those mechanical components are significantly reduced.

This direct energy transfer pathway translates to a higher overall conversion efficiency, crucial for maximizing energy capture from a variable source like ocean waves.

Robustness and Reliability: The absence of a gearbox simplifies the system's architecture, reducing the number of moving parts prone to wear and tear in the harsh marine environment. This inherent simplicity translates to a more robust and reliable system, requiring less maintenance and capable of withstanding the demanding operating conditions.

Simplified Control: The direct coupling between the wave energy converter and the generator allows for a more straightforward control scheme. Without the need to manage gearbox dynamics, the focus shifts to optimizing the generator's output based on the wave-induced motion, simplifying the control system's design and implementation.

Therefore, the choice of a direct-drive generator aligns perfectly with the wave energy converter's operational requirements, contributing to a more efficient, robust, and controllable system for harnessing the vast renewable energy potential of the ocean.

8.3 Torque Regulation with Flywheel and Clutch system

To maximize energy harnessing and regulate power output, a MATLAB code was developed to simulate and analyze the integration of a clutch system, flywheel, and generator within the power transmission pathway. This model specifically focuses on optimizing the transfer of torque from the crankshaft to the flywheel and subsequently to the generator, all meticulously managed by the engagement and disengagement of the clutch system.

The MATLAB code employs an iterative optimization approach to determine the most efficient control strategy for the clutch system. This involves defining specific tolerances and bounds for key parameters, for determining the optimal torque levels at which the clutch engages and disengages, dictating when energy is directed to the flywheel and when the flywheel provides restoring torque to the generator. The core objective of this optimization process is twofold:

Harnessing Peak Torque: Efficiently capturing and storing energy during periods of high crankshaft torque by engaging the clutch and accelerating the flywheel.

Bridging Low-Torque regions: Utilizing the stored energy in the flywheel to supplement the system during periods of low crankshaft torque, ensuring a more consistent energy supply to the generator.

By running numerous iterations with varying tolerances and bounds, the MATLAB code identifies the control strategy that yields the highest overall system efficiency. This involves striking a balance between maximizing energy capture during peak torque phases and effectively utilizing the flywheel to smooth out the inherent fluctuations in input torque. This optimized energy management system ensures a more consistent and reliable power output, maximizing the overall effectiveness of the wave energy converter.

The main results from this optimization step are presented as on following graphs:

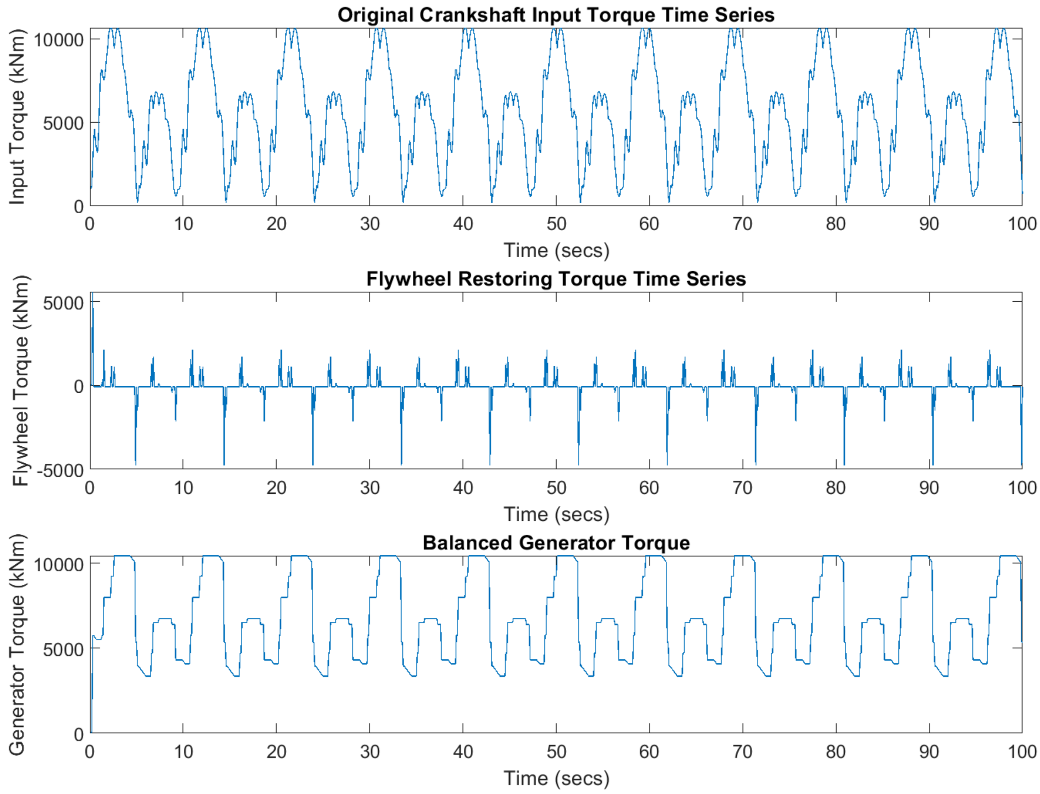

Figure 49. Crankshaft Torque Flywheel Restoring and Balanced generator Torque

The following figure represents clutch engage and disengage states for Clutch 1 and 2. The figure represents state 1 as engaged and o as disengaged.

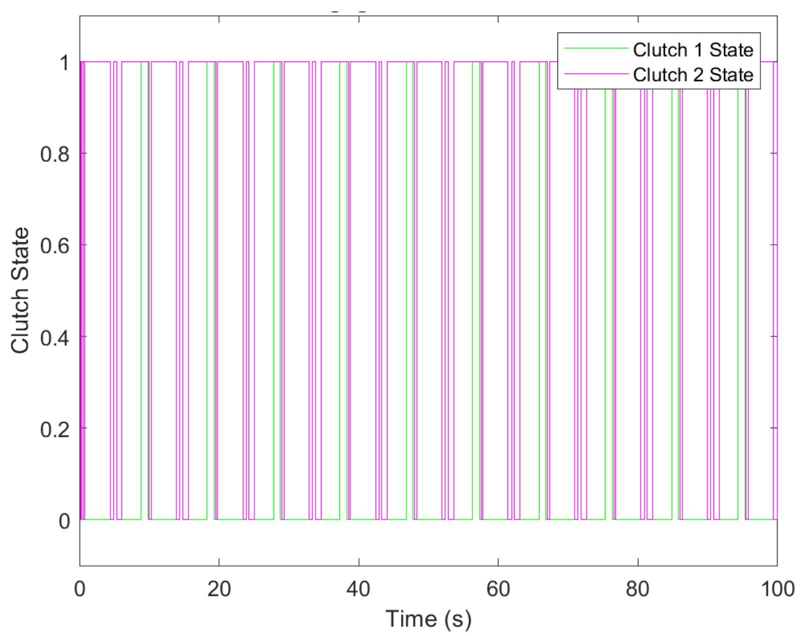

Figure 50. Clutch engagement states over time

8.4. Optimizing Reactive Control for Improved Performance

While the current MATLAB model effectively demonstrates the potential of clutch-controlled flywheel integration, a more refined and realistic system necessitates further development in two key areas:

8.4.1 Gradual Clutch Control

The existing model employs instantaneous clutch engagement and disengagement for simulation purposes. However, in a real-world application, such abrupt transitions would lead to undesirable shock loads and accelerated wear and tear on the mechanical components.

A more sophisticated approach involves implementing a gradual ramp-up and ramp-down strategy for the clutch. This means controlling the clutch pressure to ensure a smooth and controlled transfer of torque between the crankshaft, flywheel, and generator. This gradual engagement and disengagement minimize stress on the system, enhancing its overall durability and operational lifespan.

8.4.2 Advanced Generator Management

Direct-driven generators, commonly employed in wave energy converters due to their simplicity and robustness, present unique challenges in terms of power output stability. The inherently fluctuating nature of wave energy often results in variable generator speeds, leading to inconsistent voltage and frequency output.

To address this, a sophisticated generator control system is essential. This system would go beyond simply regulating voltage and frequency and would actively manage the generator's output to compensate for the fluctuating input torque. This could involve

Variable Speed Operation: Allowing the generator to operate within a defined speed range to accommodate the fluctuating input torque while still delivering usable power.

Energy Storage Integration: Incorporating additional energy storage elements, such as supercapacitors or batteries, to further buffer the power output and provide a more stable supply to the grid.

Power Electronics Control: Utilizing advanced power electronics, such as inverters and converters, to regulate the generator's output voltage and frequency, ensuring compatibility with the grid and maximizing power quality.

By incorporating these refinements – gradual clutch control and advanced generator management – the wave energy conversion system can achieve a higher level of performance, reliability, and grid compatibility. This paves the way for a more viable and sustainable approach to harnessing the vast energy potential of ocean waves.

While a highly refined system with gradual clutch control and advanced generator management holds significant potential for maximizing energy efficiency and power output stability, delving into such complexities falls outside the scope of this particular study.

The primary focus of this research is to establish a fundamental understanding of the system's behavior and demonstrate the potential benefits of incorporating a flywheel and clutch system for improved energy capture from wave energy. Developing and optimizing the intricate control strategies required for gradual clutch engagement and advanced generator management would necessitate a dedicated, in-depth investigation.

These more advanced control aspects present a compelling avenue for future research, building upon the foundational knowledge gained in this study. Subsequent investigations can explore various control algorithms, optimization techniques, and hardware implementations to fully realize the potential of this integrated wave energy conversion system.

9. Conclusion

This study investigated the potential of a novel 3-crank power take-off system integrated with a reactive control strategy for enhancing the energy extraction capabilities of a wave energy converter. A comprehensive dynamic simulation, incorporating hydrodynamic coefficients derived from diffraction analysis and dynamic simulation, was employed to model the floater's response to a range of defined sea states (characterized by significant wave height and peak period). The simulation captured the floater's heave motion, and the resulting forces were used to calculate the instantaneous torque available at the crankshaft of the 3-crank PTO.

A key contribution of this work is the development and implementation of a reactive control methodology utilizing two clutches and a flywheel system. This strategy, inspired by similar approaches in wind energy, enables the system to effectively bridge periods of low wave energy, a common challenge faced by WECs.

By engaging Clutch 1 during periods of high wave activity, excess energy is captured and stored in the flywheel. Conversely, during periods of low wave energy, Clutch 1 disengages, and the stored energy in the flywheel is released through Clutch 2 to drive the generator, ensuring continuous power generation.

The simulation results demonstrate the effectiveness of this approach, highlighting the system's ability to maintain a more consistent energy output compared to conventional WEC systems that lack energy storage mechanisms. This enhanced reliability is crucial for grid integration, as it reduces power fluctuations and improves the predictability of energy delivery.

This study demonstrates the significant potential of integrating reactive control with a multi-crank PTO and flywheel system to enhance the reliability and efficiency of wave energy conversion.

Further development and optimization of this approach holds promise for advancing the viability of wave energy as a renewable energy source. Future research will focus on refining the control strategies for both the PTO and generator sides of the system. This will involve:

- Developing advanced control algorithms: These algorithms will optimize clutch engagement and disengagement based on real-time wave conditions, predicted wave profiles, and energy demands, maximizing energy extraction while minimizing mechanical stress on the system.
- Generator-side control: Implementing control strategies on the generator side will further enhance the stability and quality of the power output, ensuring compatibility with grid requirements.

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