ISSN: 0974-5823 Vol. 7 No. 2 February, 2022

International Journal of Mechanical Engineering

Implementation of WEC-Sim for Modelling of the Novi Ocean Wave Energy Converter

Mr. Dhananjay Khankal,

Research Scholar, Department of Mechanical Engineering, Sinhgad College of Engineering, Vadgaon (Bk.), Pune, Maharashtra, India

Dr. R. L. Edlabadkar,

Professor, Department of Mechanical Engineering, PVGs College of Engineering Technology, Pune.

Abstract - Ocean waves hold potential to help in meeting the global demand for electricity. The conversion of energy from the waves to useful electrical power is done with the help of devices called wave energy converters. Modelling of the wave energy converter is important to be able to analyze different aspects of the device without developing the system in real time. The Novi Ocean wave energy converter has been modelled using MATLAB. The aim of this thesis is to model this device using WEC-Sim, an open-source code which is an extension to Simulink. The process of modelling the device using WEC-Sim was found to be easier than in MATLAB. The WEC-Sim model produced similar results to the MATLAB model. A simple controller was also implemented to control the output torque on the turbine. It was also understood that WEC-Sim allows seamless integration of controllers with the device model.

Index Terms – WEC, Energy, Sim, Ocean.

1. INTRODUCTION

In the past few decades, the electrical energy consumption has increased abundantly [1]. The energy production also needs to match the energy consumption to provide for the constantly growing demand. Energy can be harnessed from different possible energy sources, i.e., both renewable and non-renewable energy sources. Renewable energy sources are preferred because they provide clean energy and since they can replenish themselves, they arethe ideal choice to be able to continually meet the demand in the future. Also, the harmful effects on the environment caused by the electricity generation from non-renewable energy sources [2] and their increasing prices [3] are major disadvantages.

In 2021, the share of renewable energy sources in electricity generation is projected toincrease up to 30 % [4]. All the countries in the world have set targets for themselves with respect to renewable electricity production [5]. By 2040, Sweden has targeted to be fulfilling its energy demand with only renewable energy [6]. Hydropower, solar and wind are the major sources of renewable electricity at the present [7]. Wave energy is a primitive source in comparison to these mentioned sources.

Ocean waves have a huge untapped potential as a renewable energy source [8]. The theoretical global wave energy potential is estimated to be 20000 TWh to 80000 TWh per year[9]. This amounts to roughly 100 % to 400 % of the current global electricity demand. If tappedeffectively, wave energy could be the key towards a future in sustainable electricity production.The engineering and research required to generate electricity from these ocean waves is challenging as both the economic aspects and the environmental effects need to be considered.Though the first patent with respect to wave power development goes back to 1799 [10], waveenergy technologies have not been successfully commercialized yet.

The energy associated with a moving wave is converted into useful mechanical or electrical energy using a device called wave energy converter (WEC). Ocean swell powered renewable energy (OSPREY) is the very first wave power plant that began operating in northern Scotland around August 1995 [11]. Even though this 2 MW power plant wasdestroyed by a storm, the research relating to wave power has not ceased. There have been so many different designs and types of WEC which are more efficient and more advantageous [12] [13] [14].

CLASSIFICATION OF WAVE ENERGY CONVERTERS

The classification of WECs can be done on the basis of different design characteristics[15]. Based on the operating principles they can be classified into oscillating water columns (OWC), overtopping systems (OTS) and oscillating body systems. On the basis of how these devices face the incoming wave, they are classified into terminators, attenuators and point absorbers. The OWC and OTS types of WECs are terminators whereas attenuators and point absorbers are oscillating body systems.

Terminators are devices that are perpendicular to the incoming waves and act as an energy absorbing wall. Theoretically, they absorb all the energy from the waves and leave calmwater behind. OWC WECs are devices that have a semi submerged or a hollow chamber whichhas air trapped in it. Energy is harnessed due to the oscillation of water inside this chamber caused by the waves. Examples for OWC devices are the Mighty Whale in the Tokyo Bay [16];Pico plant in the Pico islands, Portugal [17] and LIMPET in Islay, Scotland [18]. OTS WEC are devices that are partially submerged and have a reservoir. The incoming waves travel up a ramp to the reservoir and this converts the kinetic energy of the waves to potential energy. Thewater from the reservoir then flows through turbines and thus generates electricity. Examples for OTS devices are the Danish wave dragon [19] and the TAPCHAN device in Norway [20].

Attenuators are multi-segmented device that are placed parallel to the waves. The attenuators are said to ride the waves. The motion of the joints between the segments induced by the waves is resisted a hydraulic system and this runs a generator to produce electricity. TheMcCabe wave pump [21] and the Pelamis [22] are notable examples for attenuators.

A point absorber is a floating device smaller than the wavelength. It mostly consists of a floating buoy and a fixed body. The energy transfer between the waves and the device happens due to the relative motion between the buoy and the fixed body as the buoy rises and falls along with the waves. A few notable point absorber type devices are the Archimedes waveswing [23] and the Danish wave power float pump [24].

THE NOVI OCEAN WAVE ENERGY CONVERTER

The Novi Ocean WEC [25] is a point absorber type WEC. The rectangular float and theinverted hydropower plant power take-off (PTO) system are the two main subsystems that make up this WEC. Larger effective area for power absorption is ensured with the surfboard design of the rectangular float which resembles the shape of the wave. This also leads to very low surge forces leading to the device being more reliable even in the case of waves with veryhigh significant height [25]. The inverted hydropower plant PTO consists of a hydraulic cylinder and a Pelton turbine. A generator placed on the top of the float is driven by this Peltonturbine.

The Novi Ocean WEC is a non-resonant point absorber as it does not resonate at any particular frequency, and this makes it a more efficient device. The construction of this device as seen in Figure 1.1 is simple, i.e., it has lesser number of parts and therefore easier and cheaper to manufacture and install. It is lighter in weight compared to other devices but at thesame time it is robust and has a longer lifetime [25]. It is also easy to maintain since the generator and the control system are placed on the rectangular float. It gives a stable output andhas high reliability.

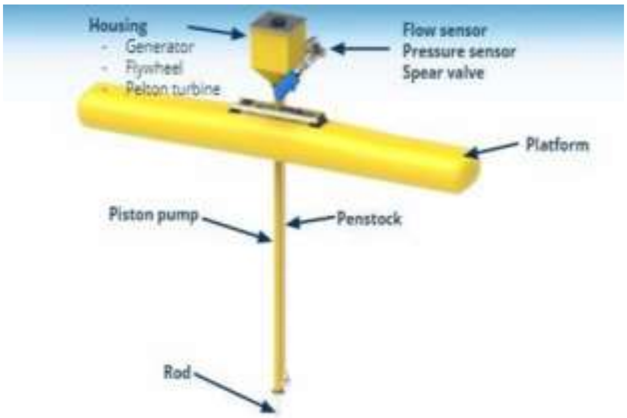

Figure 1.1 An overview of the Novi Ocean WEC.

BACKGROUND FOR THE PROJECT

Wave energy converter simulator (WEC-Sim) [26] is an open-source code that simulates the energy conversion process in a WEC. WEC-Sim is capable of modelling devices that are made of either rigid or flexible bodies, joints, PTO systems and mooring systems in MATLAB/Simulink using multi-body dynamics solver. Time domain simulations are done bysolving the equations of motions in the six degrees of freedom (DOF). The WEC-Sim code is adaptable to the different situations that may arise while working with a WEC.

The existing wave-to-wire time domain model for the Novi Ocean WEC has been donein MATLAB [27]. Since WEC-Sim is an addition to the Simulink library, all available blocks can be used in the WEC-Sim model. This helps in integrating controllers seamlessly with the WEC model whereas doing the same will not be easy in the time domain model in MATLAB.

OBJECTIVES

The main objectives of this project are as follows.

1. Model the Novi Ocean WEC using WEC-Sim and determine the possible outputs.
2. Compare the WEC-Sim model and the existing time domain model in MATLAB.
3. Implement a simple controller which can be replaced as required in the future.

2. THEORY

HYDRODYNAMIC INTERACTION

The motion of a floating body can be described along any of the six DOFs. Heave, surgeand sway are the three translational DOFs whereas the DOFs in rotation are yaw, roll and pitchas shown in Figure 2.1. Only the heave DOF is considered for the Novi Ocean WEC as it is themain DOF that contributes to energy transfer.

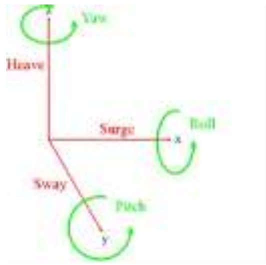

Figure 2.1 The six degrees of freedom [28].

FORCES ACTING ON THE NOVI OCEAN WEC

The interaction between the waves and the WEC results in different types of forces acting on the WEC. Excitation force, radiation force, hydrostatic stiffness force, mooring force and PTO force are the major forces acting on the Novi Ocean WEC and are depicted in Figure 2.2.

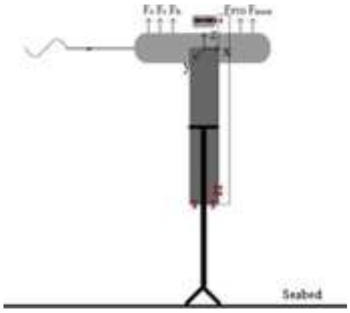

Figure 2.2 The different forces acting on the Novi Ocean WEC [29].

The force exerted by the undisturbed incoming wave on the WEC leading to the energy transfer from the wave and the WEC is called the excitation force Fe. It is given by the convolution shown in (2.1) where fe is the impulse response function of the excitation force and $z(r)$ is the elevation of the incoming wave.

$$F_e(t) = \int_{-\infty}^{\infty} f_e(t-\tau)z(\tau)d\tau \qquad (2.1)$$

The water displaced around the float exerts a force on the WEC called radiation damping force Fr. It is given as the convolution shown in (2.2) where fr is the impulse response function of the radiation damping force and $\dot{x}(t)$ is the vertical velocity of the buoy.

$$F_r(t) = \int_0^t f_r(t-\tau)\dot{x}(\tau)d\tau \qquad (2.2)$$

The hydrostatic stiffness force F_h is a spring like force corresponding to a part of the kinetic energy of the oscillating WEC stored as potential energy. It is proportional to the displacement of the buoy $x(t)$ as shown in (2.3) and G is the hydrostatic stiffness coefficient.

$$F_h = Gx(t) \qquad (2.3)$$

The force exerted by the PTO system on the WEC is the PTO force F_{PTO} and this can be a non-linear force because of the implementation of different control strategies. But when the WEC is being modelled, this force is linearized. (2.4) indicates that one component of thisforce is proportional to the displacement of the buoy $x(t)$ and the other component isproportional to the velocity of the buoy $\dot{x}(t)$. B_{PTO} and K_{PTO} are proportionality constants.

$$F_{PTO} = -B_{PTO}\dot{x}(t) - K_{PTO}x(t) \tag{2.4}$$

Similar to the PTO force, the mooring force F_{moor} is also non-linear but linearized while modelling the WEC. The mooring force as shown in (2.5) is proportional to the displacement of the buoy $x(t)$. K_m is the proportionality constant denoting the spring stiffness.

$$F_{moor} = -K_m x(t) \tag{2.5}$$

EQUATION OF MOTION

The motion of a floating body can be governed using Cummins' equation of floater motion [30] given in (2.6) when linear potential flow theory is applied.

$$[M + A_\infty]\ddot{x}(t) + \int_{-\infty}^{t} \dot{x}(t)[K(t-\tau)]d\tau - [C]x(t) = [F_e(t)] \tag{2.6}$$

where $[M]$ is the mass matrix, $[A_\infty]$ is the infinite frequency added mass matrix, $x(t)$ is the generalized motion vector, $[K]$ is the radiation damping impulse response function matrix, $[C]$ is the hydrostatic stiffness matrix and $[F_e(t)]$ is the excitation force vector.

OCEAN WAVE SPECTRUM

PIERSON-MOSKOWITZ SPECTRUM

The concept of a fully developed sea is the basis for Pierson-Moskowitz (PM) spectrum [31]. It states that there would be an equilibrium achieved between the waves and the wind when the wind blows steadily over a large area which is approximately five thousand wave lengths for a long time which is approximately ten thousand wave periods. It was determined to be of the form (2.7) after calculating the wave spectra for various wind speeds.

$$S_{PM}(\omega) = \frac{\alpha g^2}{\omega^5} e^{-\beta\left(\frac{\omega_0}{\omega}\right)^4} \tag{2.7}$$

JONSWAP SPECTRUM

The Joint North Sea Wave Observation Project (JONSWAP) [32] provided data that showed that the sea is not fully developed over any period of time, but it develops continuouslythrough non-linear, wave to wave interactions over long times and distances. The ocean spectrum was proposed to be as (2.8).

$$S_{JONSWAP}(\omega) = \frac{\alpha g^2}{\omega^5} e^{-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4} \gamma^r \tag{2.8}$$

where $r = e^{-\left(\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right)}$, $\alpha = 0.076\left(\frac{U_{10}^2}{Fg}\right)^{0.22}$, $\omega_p = 22\left(\frac{g^2}{U_{10}F}\right)^{\left(\frac{1}{3}\right)}$, $\sigma = \begin{cases} 0.07 \; for \; \omega \leq \omega_p \\ 0.09 \; for \; \omega > \omega_p \end{cases}$,

γ = 3.3, $\omega = 2\pi f$, ω is the wave angular frequency, f is the wave frequency, U_{10} is the wind speed at 10 m above the sea level and F is the distance over which the wind blows with constantvelocity called fetch.

LATCHING CONTROL

The power absorbed by a WEC is maximum when it is in resonance with the incomingwave. Latching [33] is a control strategy in which to achieve resonance the WEC is fixed at one position when the velocity of the float reaches zero and is released when the excitation force is maximum. The Novi Ocean WEC is hydraulically latched into position at the zero- crossing point of the velocity. The WEC does not generate power when it is latched. Latchingcontrol results in the torque on the turbine oscillate from zero when it is latched to a higher value when it is unlatched, and this might not be optimal. But the increase in efficiency becauseof latching is considered more advantageous that the losses caused by other effects of latchingare negligible.

3. METHOD

WORKFLOW OF WEC-SIM

A high-level view of the WEC-Sim's function can be seen in the Figure 3.1. A WEC- Sim model requires a set of input files. The outer surface of the float of the device must be defined in the WEC geometry file. The hydrodynamic coefficients need to be generated using a boundary element method (BEM) code. Using the WEC-Sim library blocks the WEC should be modelled as a Simulink/Simscape file. If the WEC uses a hydraulic PTO system, this can also be designed using the library blocks in the Simulink/Simscape model.

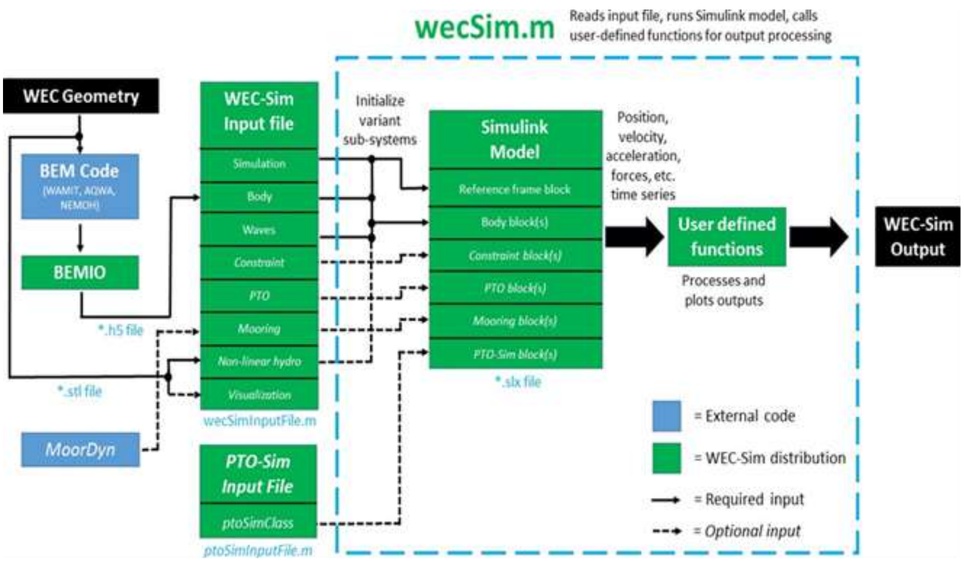

Figure 3.1 WEC-Sim workflow diagram

WEC-SIM INPUT FILES

GEOMETRY FILE

WEC-Sim requires the geometry of the float in the Stereolithography (.stl) file format.This can be done using any computer-aided design (CAD) program. The float can be modelledusing a CAD program and later exported to the required .stl file format. In this project, FreeCAD [35] was used to generate this input file. FreeCAD is an open-source program for 3- dimensional CAD modelling.

WEC-Sim requires the geometry file only for the Simscape Mechanics Explorervisualization when linear buoyancy is assumed. The rectangular float of the Novi Ocean WEC has a surfboard design. For the ease of designing, the float was designed to be rectangular without the curved edges resembling a cuboid as in Figure 3.2.

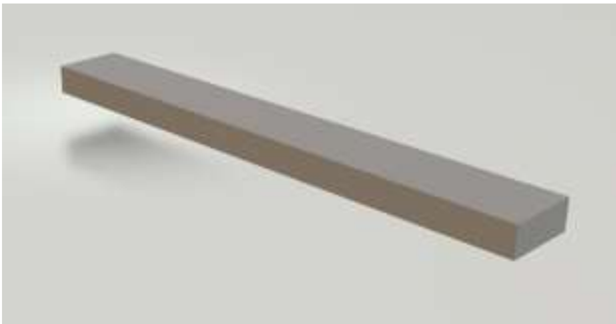
Figure 3.2 The rectangular float modelled using FreeCAD.

HYDRODYNAMIC DATA

The hydrodynamic coefficients required by WEC-Sim can be generated using any program that uses BEM code. WAMIT [36] was the program used in this project. The float was assumed to be rectangular similar to the geometry file. Among the possible output files from WAMIT, only the added mass and damping coefficients and the exciting forces from diffraction potentials are needed by WEC-Sim. Also, the hydrodynamic coefficients need to be generated with respect to wave periods and not wave frequencies. WEC-Sim only requires the

.OUT file that is acquired from WAMIT.

The .OUT file needs to be converted into the hierarchical data format 5 (HDF5) in orderto be accessible to WEC-Sim. To make this possible, WEC-Sim has developed a pre-processorcode called boundary element method input/output (BEMIO). The BEMIO code reads the hydrodynamic data from WAMIT and calculates the radiation and excitation impulse responsefunctions. It also calculates the state space realization for the radiation impulse response functions. This BEMIO code then saves the results in the HDF5 format (.h5 file).

SIMULINK MODEL

WEC-Sim requires a Simulink/Simscape model (.slx) file, which can be created using the additional WEC-Sim library blocks as seen in Figure 3.3. The geometry of the float can becoupled to the model using the rigid body block. In every model the global reference frame isimportant as it acts as the seabed. The PTO system can be designed using simple translationalPTO block if they are linear systems. If the WEC has a mechanical drivetrain or a hydraulic drivetrain as a part of the PTO system, PTO-Sim can be used.

PTO-Sim [37] is an additional WEC-Sim module that is used to model more complex PTO systems. The PTO-Sim library has many additional blocks that can be used, or new subsystem blocks as required can be created. In the case of the Novi Ocean WEC, the invertedhydropower plant PTO system needed to be modelled. This was done by using a combinationof the PTO-Sim library blocks and other subsystems that were designed specifically asdescribed in Figure 3.4.

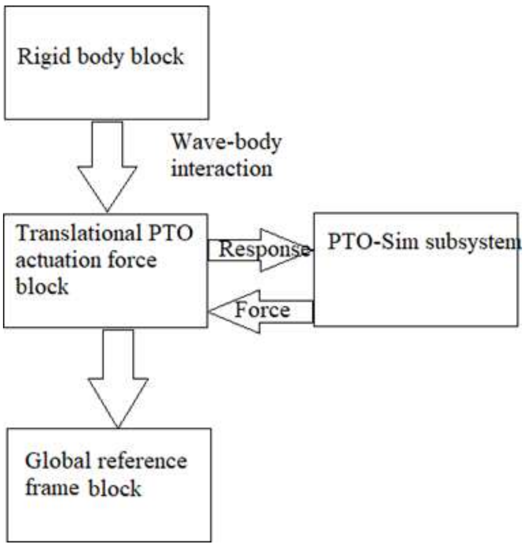

Figure 3.3 Schematic showing the implementation of the Simulink model for the Novi Ocean WEC.

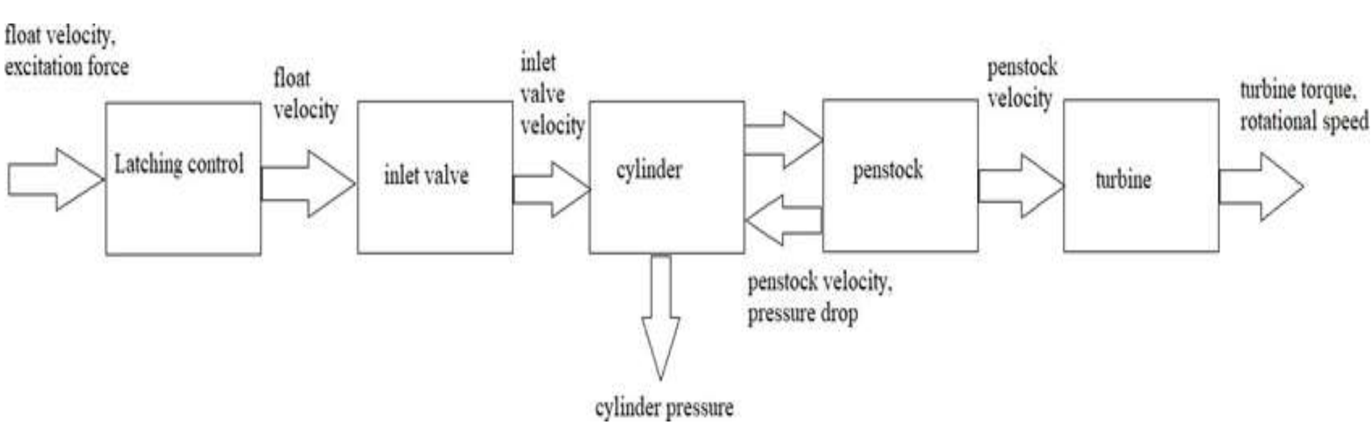

Figure 3.4 Schematic showing the implementation of the PTO system of the Novi Ocean WEC.

WEC-SIM INPUT FILE

For every run, WEC-Sim requires a WEC-Sim input file that specifies the simulation parameters, wave conditions and body properties. This file must be named 'wecSimInputFile.m'. This input file is divided into classes which initialize the objects required and also describe the components that are required to run WEC-Sim.

The simulation parameters and the solver settings that are required to run the WEC-Simmodel are initiated in the simulation class. The simulation model also needs to be specified inthe simulation class. The other parameters that can be initiated in the simulation class are presented in the Table 3.1.

Table 3.1 The simulation class properties that are a part of the WEC-Sim input file.

Simulation properties	Functions
simu = simulationClass ()	This initialises the simulation class.
simu.simMechanicsFile	This is necessary to specify the Simulink model file ('modelname.slx')
simu.mode	This is used to specify the simulation mode. The available modes are 'normal', 'accelerator' and 'rapid-accelerator'.
simu.solver	This specifies the ode solver settings. The variable step solver ode45 was used here.
. simu.startTime	This specifies the simulation start time.
simu.endTime	This specifies the simulation ending time.
simu.rampTime	This specifies the ramp time for the wave.
simu.dt	This specifies the maximum time step.
simu.g	This defines the value to be used for acceleration due to gravity.
simu.rho	This defines the density of the water.

The wave class defines the wave types and wave parameters. It helps in stating if the waves are regular or irregular and also the wave spectrum used. It is also possible to use any type of wave spectrum by feeding in a data file defining the wave spectrum. Table 3.2 presentsthe parameters than can be initiated and defined using the wave class.

Table 3.2 The wave class properties that are a part of the WEC-Sim input file.

Simulation properties	Functions
waves = waveClass('type')	This initialises the wave class and also the type of the wave. The wave types can be 'noWave', 'regular', 'irregular' and 'spectrumImport'.
waves.H	This defines the wave height in the case of regular waves and significant wave height in the case of irregular waves.
waves.T	This defines the wave period in the case of regular waves and the peak period in the case of irregular waves.
waves.spectrumType	This defines the wave spectrum used in the case of irregular waves. 'PM' corresponds to the Pierson Moskowitz spectrum and 'JS' corresponds to JONSWAP spectrum.
waves.spectrumDataFile	This directs to the spectrum data file and is necessary if the 'spectrumImport' wave class type is used.

The body class defines the mass and hydrodynamic properties of each body in the WEC. This also specifies the location of the hydrodynamic data file and the geometry file. The different parameters in the body class are presented in Table 3.3.

Table 3.3 The body class properties that are a part of the WEC-Sim input file.

Simulation properties	Functions
body(number) = bodyClass('hydroData/name.h5')	This initiates the body class and the number given to each body couples it to the corresponding body block in the Simulink model file. This also directs WEC-Sim to the location of the hydrodynamic data file for the body.
body(number).geometryFile('location')	This provides the location for the '.stl' for the corresponding body.
body('number').mass	This defines the mass of the body. If this is defined as 'equilibrium' the mass of the body is set to that of the displaced water.
body('number).MOI	This defines the moment of inertia of the body along the x,y,z axes.

The moment of inertia of the float was calculated using (3.1), (3.2), (3.3) which are theequations that calculate the moment of inertia for a solid cuboid along the 3 axes.

$$I_h = \frac{1}{12}m(w^2 + l^2) \tag{3.1}$$

$$I_l = \frac{1}{12}m(h^2 + w^2) \tag{3.2}$$

$$I_w = \frac{1}{12}m(l^2 + h^2) \tag{3.3}$$

where m is the mass of the solid cuboid, h, l, w are the height, length and width of the solidcuboid respectively and I_h, I_l, I_w are the moment of inertia of the solid cuboid along the 3 axes.Similar to the other classes, the PTO class defines the properties of the PTO system.

The different parameters are presented in the Table 3.4.

Table 3.4 The PTO class properties that are a part of the WEC-Sim input file

Simulation properties	Functions
pto(number) = ptoClass('name')	This imitialises the PTO class. Similar to the body class, the number couples the properties to the corresponding PTO block in the Simulink file.
pto(number).k	This defines the PTO stiffness value.
pto(number).c	This defines the PTO damping.
pto(number).loc	This defines the location of the PTO system. [0 0 0] correspond to the origin.

4. RESULTS

The Novi Ocean WEC WEC-Sim model was simulated in regular and irregular wave conditions with and without latching control and the results are presented. The simulation wasperformed for a time span of 300 s. The dimensions and the design parameters of the Novi Ocean WEC are not presented due to confidentiality reasons.

REGULAR WAVES

The Novi Ocean WEC WEC-Sim model was simulated in regular wave conditions witha wave height of 3 m and wave period of 13 s. The free surface elevation of the wave is plottedin Figure 4.1. The excitation force exerted on the float by the waves is plotted in Figure 4.2. The WEC was simulated with and without the latching control and the results are presented.

The position of the float without and with latching control is plotted in Figure 4.3. By comparing these two figures it can be observed that, the buoy does not travel as far as it does with latching and that it stays at the highest and the lowest position for a few seconds. This indicates that the WEC is latched.

The velocity of the float without and with latching is plotted in Figure 4.4. With latchingcontrol on, when the velocity of the float reaches zero, the float gets latched. It remains latcheduntil the excitation force starts increasing again.

The velocity of the water rushing out of the nozzle to the Pelton turbine is called jet velocity. It is plotted without and with latching in Figure 4.5. The torque on the turbine and the useful power generated without and with latching are plotted in Figure 4.6 and Figure 4.7 respectively.

With latching, the jet velocity has increased. This results in the increase in the torque on the turbine which leads to the generation of more useful power. This is the major advantage of latching control, and this can be observed from the figures.

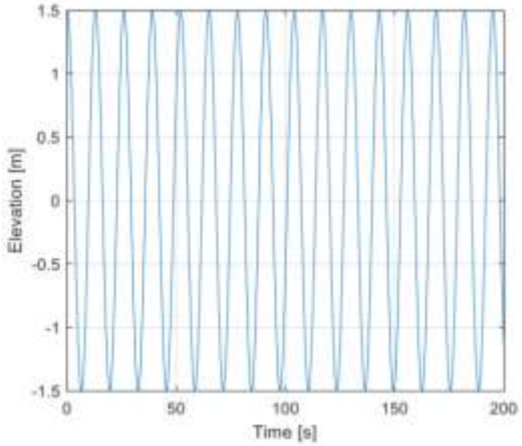

Figure 4.1 The free surface elevation (m) vs time (s) for regular waves with a wave height of 3 m and a wave period of 13 s.

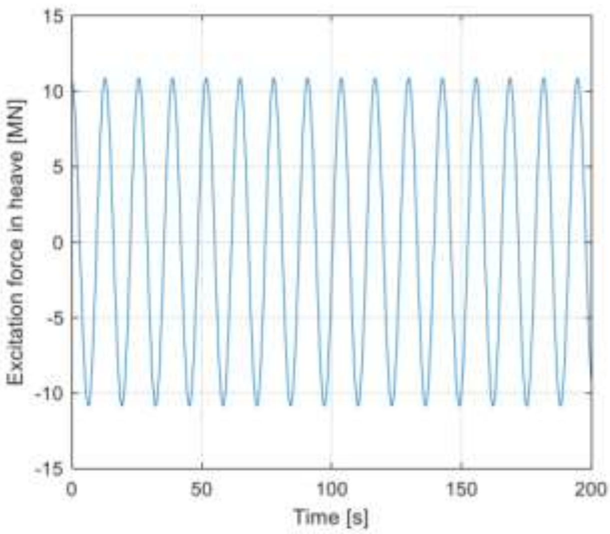

Figure 4.2 The excitation force (MN) exerted by regular waves with a wave height of 3 m and a wave period of 13 s.

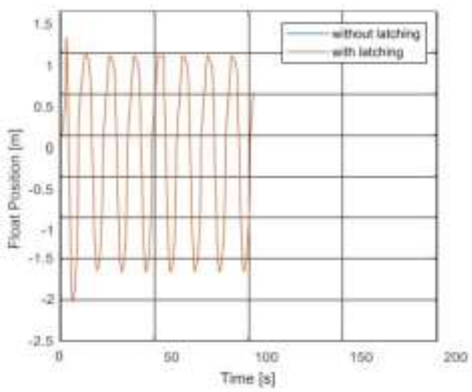

Figure 4.3 The position of the float (m) vs time (s) under regular wave conditions with and without latching control.

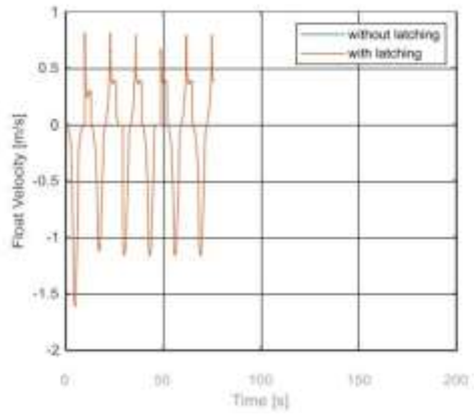

Figure 4.4 The velocity of the float (m/s) vs time (s) under regular wave conditions with and without latching control.

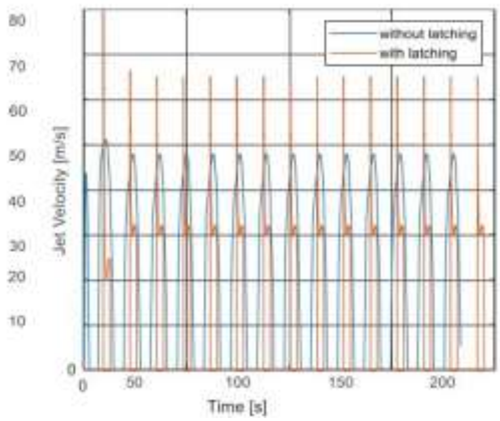

Figure 4.5 The jet velocity (m/s) vs time (s) under regular wave conditions with and without latching control.

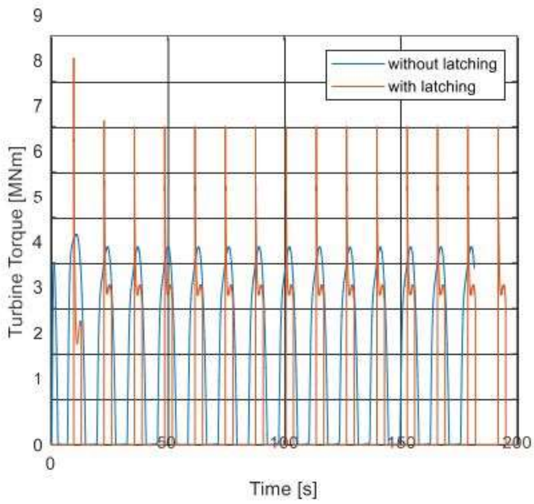

Figure 4.6 The turbine torque (MNm) vs time (s) under regular wave conditions with and without latching control.

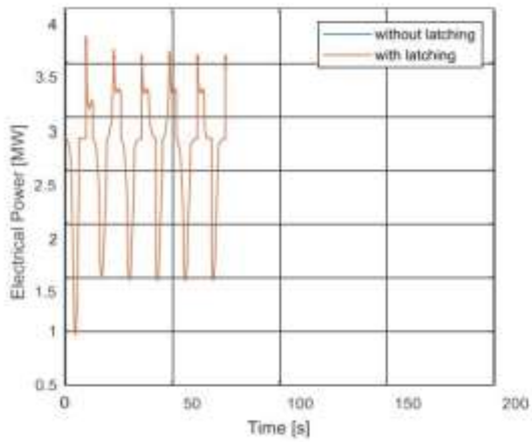

Figure 4.7 The electrical power (MW) vs time (s) under regular wave conditions with and without latching control.

IRREGULAR WAVES

The simulation was performed with irregular waves as per the PM spectrum with a significant wave height of 3 m and peak time period of 13 s. The wave elevation and the waveexcitation force when latching control was off are plotted in Figure 4.8 and Figure 4.9. The position of the float, velocity of the float, jet velocity, torque on the turbine and the useful power generated without latching control are plotted in the Figure 4.10 to Figure 4.14.

Similarly, the wave elevation and the wave excitation force when latching control wasoff are plotted in Figure 4.15 and Figure 4.16. The position of the float, velocity of the float, jet velocity, torque on the turbine and the useful power generated without latching control areplotted in the Figure 4.17 to Figure 4.21.

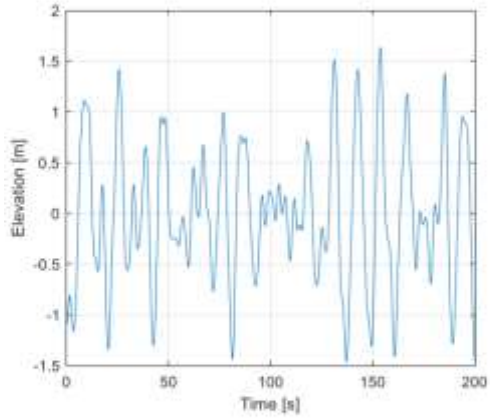

Figure 4.8 The free surface elevation (m) vs time (s) for irregular waves with a significant wave height of 3 m and a peak wave period of 13 s when latching control is off.

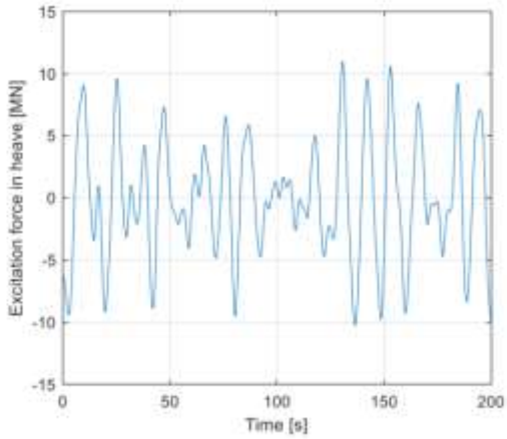

Figure 4.9 The excitation force (MN) exerted by irregular waves with a significant wave height of 3 m and a peak wave period of 13 s when latching control is off.

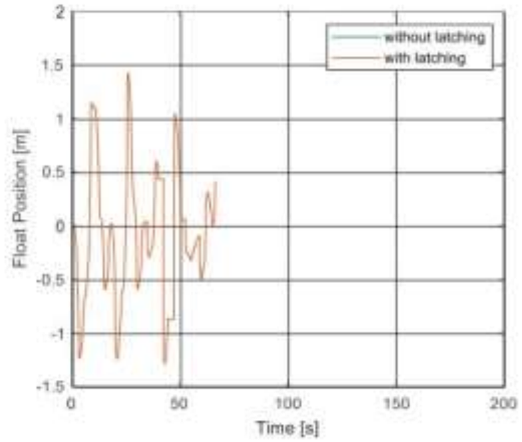

Figure 4.10 The position of the float (m) vs time (s) under irregular wave conditions with and without latching control.

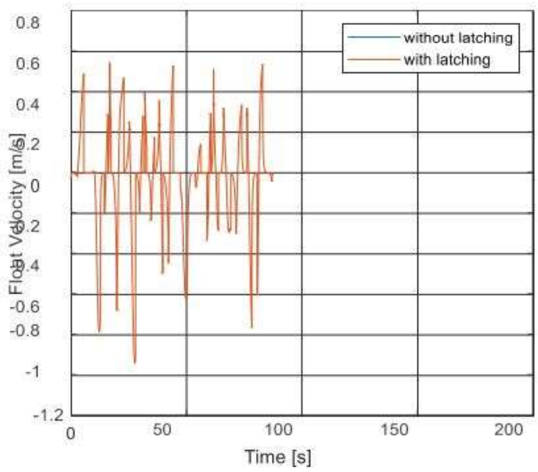

Figure 4.11 The velocity of the float (m/s) vs time (s) under irregular wave conditions with and without without latching control.

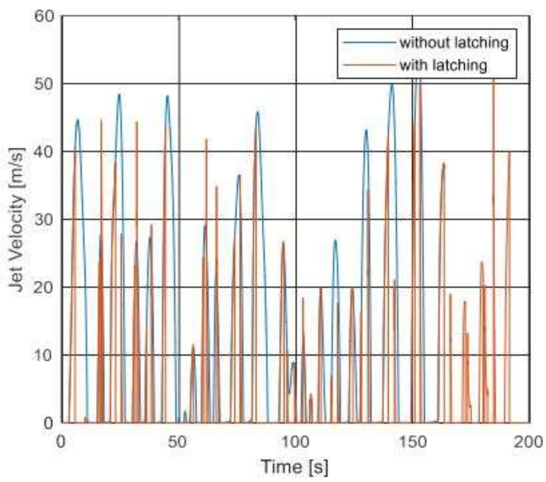

Figure 4.12 The jet velocity (m/s) vs time (s) under irregular wave conditions with and without latching control.

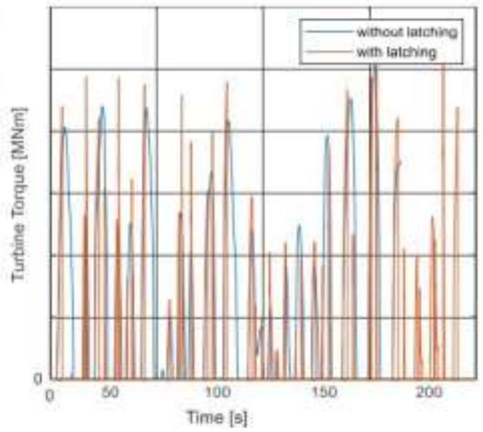

Figure 4.13 The turbine torque (MNm) vs time (s) under irregular wave conditions with and without latching control.

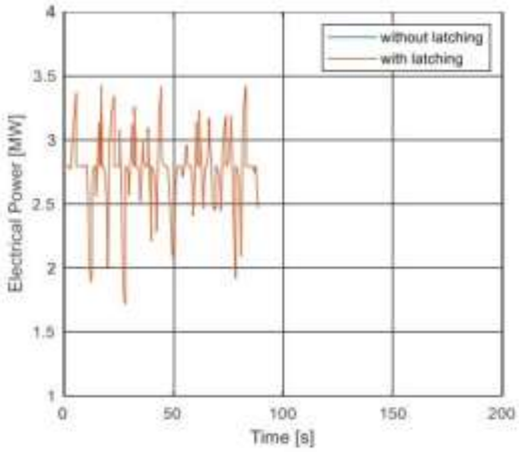

Figure 4.14 The electrical power (MW) vs time (s) under irregular wave conditions with and without latching control

CONTROLLER IMPLEMENTATION

A controller that controls the mean output torque on the turbine by changing the opening of the nozzle was implemented. The simulation was performed for a time of 300s under regular wave conditions with a wave height of 3 m and wave period of 13 s with latchingcontrol. The reference mean turbine torque was changed every 100 s, so there is a total of threedifferent reference torque. The variation in the opening of the nozzles is shown in Figure 4.23by plotting the cross-sectional area of the nozzle opening vs time. The output torque on the turbine is plotted in the Figure 4.22. These two plots prove that the output turbine torque was controlled and therefore deems the implementation of the controller successful.

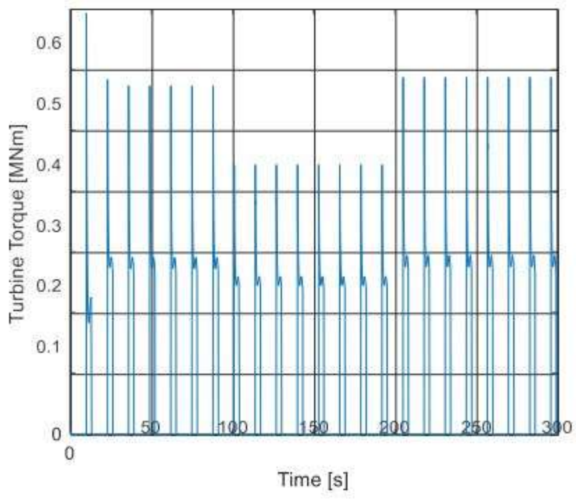

Figure 4.15 Turbine Torque (MNm) vs time (s) with the controller.

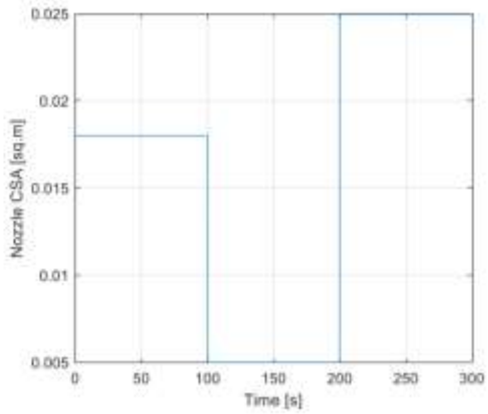

Figure 4.16 Nozzle CSA (sq. m) vs time (s) with controller.

5. DISCUSSION

The results obtained from the WEC-Sim model are similar to the results from the MATLAB model. There are a few advantages to the WEC-Sim model over the MATLAB model. The process of modelling is easier with WEC-Sim when compared to MATLAB. UsingMATLAB, the interaction between the wave and the body had to be modelled to calculate theposition of the float, velocity of the float, and the various forces. Whereas WEC-Sim simulatesthe wave-body interaction and calculates these parameters with the help of the hydrodynamic coefficients provided. The modelling of the PTO system is easier with the library blocks fromWEC-Sim and Simulink. WEC-Sim is capable of simulating the WEC with respect to all six degrees of freedom. Simulating along all DOFs would result is more realistic results when would help is understanding the WEC better.

WEC-Sim has PTO-Sim which has various blocks to model hydraulic PTO systems. But in the case of the Novi Ocean WEC's inverted power plant PTO system, the available blocks were not suitable and so subsystems as required had to be modelled. Therefore, the PTOmodelling is not easier, but it is not more complex than doing the same in the MATLAB model.

The WEC-Sim model has advantages with respect to future development. A simple controller was implemented to be an example. It would be easier to model a complex control system using the existing blocks from Simulink with the WEC-Sim model when necessary. Integrating a control system into the WEC-Sim model would be seamless when compared to the MATLAB model.

6. CONCLUSION

The aim of this project was to model the Novi Ocean WEC using WEC-Sim. One of the advantages of using WEC-Sim is that it simulates the wave-buoy interaction and calculatesthe forces and the output from the buoy. In the case of a MATLAB model, this needs to be separately modelled. The major modelling required with WEC-Sim is the PTO system and control strategies like latching. This can be done with the blocks available or by creating customsubsystems. WEC-Sim is compatible with the Simulink library which makes it easier to implement additional control systems. This was proved by the implementation of the controllerthat controls the torque on the turbine. Overall, modelling using WEC-Sim is simple, easy, and suitable for future additions to the system

REFERENCES

1. F. Flocard, Increasing power capture of a wave energy device by inertia adjustment, Appl. Ocean Res. 34 (2012) 126e134.
2. Q. Shou-qiang, Experimental Study on A Pendulum Wave Energy Converter, China Ocean Eng, 27, Chinese Ocean Engineering Society and Springer-Verlag Berlin Heidelberg, 2013, pp. 359e368. No. 3. [23] E. Harris, Mooring Systems for Wave Energy Converters: A Review of Design Issues and Choices.
3. Em 1110-2-1100, Water Wave Mechanics.
4. Wave information Network of Korea, URL < http://wink.kiost.ac.kr/main.do>.
5. Ansys, Inc. Aqwa theory manual version 18.2, URL <http://www.ansys.com .
6. F. Flocard, Laboratory experiments on the power capture of pitching vertical cylinders in waves, Ocean. Eng. 37 (2010) 989e997.
7. B. Bosma, Wave Energy Converter Modeling in the Frequency Domain: A Design Guide, IEEE, 2012, 978-1-4673-0803-8/12/$31.00 ©.
8. J. Falnes, Ocean Wave and Oscillating System e Linear Interactions Including Wave-Energy Extraction.
9. Kukner, A review of power take-off system employed in wave energy converters, J. Naval Sci. Eng. 10 (1) (2014) 32e44.
10. Bosma, On the Design, Modeling, and Testing of Ocean Wave Energy Converters.

11. Geography of South Korea, URL: https://en.wikipedia.org/wiki/Geography of South Korea.
12. B.W. Nam, Performance evaluation of the floating pendulum wave energy converter in regular and irregular waves, Int. J. Offshore Polar Eng. 24 (1) (March 2014) 45e51. ISSN 1053-5381.
13. J. Lavelle, Experimental Testing of the Langlee Wave Energy Converter, 2011, https://doi.org/10.13140/2.1.2439.5202.
14. C. Lim, The study on design of the floating pendulum wave energy converter (FPWEC) operation system, in: Proceedings of the Twenty-Fifth (2015) International Ocean and Polar Engineering Conference, 2015. Kona, Big Island, Hawaii, USA, June 21-26.
15. S.D.G.S.P. Gunawardane, Analysis of the hydrodynamics of four different oscillating wave surge converter concepts, Renew. Energy 130 (2019) 843e852.
16. S.D.G.S.P. Gunawardane, Modelling of 50 kW Top Hinged Flap Type Pilot Wave Energy Device for Southern Coastal Region in Sri Lanka.
17. G. Jackson, Persistence and survival in entrepreneurship: the case of the wave energy conversion corporation of America, New England Journal of Entrepreneurship 15 (2012). Number 1 Article 4.
18. W. Jamieson, Composite Design of a Curved Oscillating Surge Wave Energy Converter.
19. D. Sarkar, The modular concept of the oscillating wave surge converter,m Renew. Energy 85 (2016) 484e497.
20. N.M. Tom, Development of a nearshore oscillating surge wave energy converter with variable geometry, Renew. Energy 96 (2016) 410e424.
21. S. Zheng, Analytical study on hydrodynamic performance of a raft-type wave power device, J. Mar. Sci. Technol. DOI 10.1007/s00773-017-0436-z.
22. S. Zheng, Analysis for wave power capture capacity of two interconnected floats in regular waves, J. Fluid Struct. 75 (2017) 158e173.
23. S. Zheng, Numerical study on the dynamics of a two-raft wave energy conversion device, J. Fluid Struct. 58 (2015) 271e290
24. Y.-H. Yu, Design and analysis for a floating oscillating surge wave energy converter, in: Conference Paper NREL/CP-5000-61283, March 2014.
25. L. Wilkinson, The power-capture of a nearshore, modular, flap-type wave energy converter in regular waves, Ocean. Eng. 137 (2017) 394e403.