# MODELING AND SIMULATION OF WAVE ENERGY CONVERTER SYSTEMS

Submitted by
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In the fulfillment of the requirements of the degree:
Master of Renewable Energy and Energy Efficiency

University of Zaragoza
Zaragoza, Spain

September 2017

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# Abstract

Wind and solar energy have been taking the control of the renewable energy market, as costs have decreased rapidly and the threats from climate change have made clear the need to change from fossil fuels.

Wave energy have been underrated all the past years. Wave energy has more potential and more advantage the other forms of renewable energy. More predictable, consistent and controllable than either wind or solar power, with the right infrastructure in place, it could be a sustainable alternative for supplying base-load power. It also has a very low impact that neither disturbs aquatic life nor spoils the coastal view that prompts so much ire from the public.

The purpose of this thesis is to discuss different types of wave energy converters, we will have a full simulation of each type and discuss the functioning of each one of them.

The models are implemented and simulated by two programs: ANSYS; and Simulink. With their application: DesignModeler; ANSYS AQWA; and WEC-SIM.

On the basis of the simulated results, we can conclude that generating power from the wave is quite promising for our future and will be a great addition in the renewable energy market, and will contribute to face the global climate change problem.

# Acknowledgment

I would like to express my gratitude to my master thesis advisors José Antonio Domínguez Navarro and Jesús Sergio Artal Sevil for their guidance, help and advices through my thesis period.

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# Chapter 1: Introduction

Electricity generation is the leading cause of industrial air pollution in many countries in the world, most of the total electricity generated is produced by coal, nuclear, and other non-renewable power plants leading to the biggest and most important worldwide problem nowadays which is the global climate change.

With this problem keeps getting bigger and bigger and our concerns on the Earth keep increasing day by day, we find ourselves heading to the path of the renewable energy.

Renewable energy sources can be used to produce electricity with fewer environmental impacts. It is possible to generate electricity from renewable energy source without producing carbon dioxide (CO2), the main cause of climate change [(1)].

## Renewable Energy

Renewable energies are inexhaustible, clean and they can be used in a decentralized way (they can be used in the same place as they are produced). Also, they have the additional advantage of being complimentary, the integration between them being favorable. For example, solar photovoltaic energy supplies electricity on sunny days (in general with low wind) while on cold and windy days, which are frequently cloudy, the wind generators are in position to supply more electric energy [(2)].

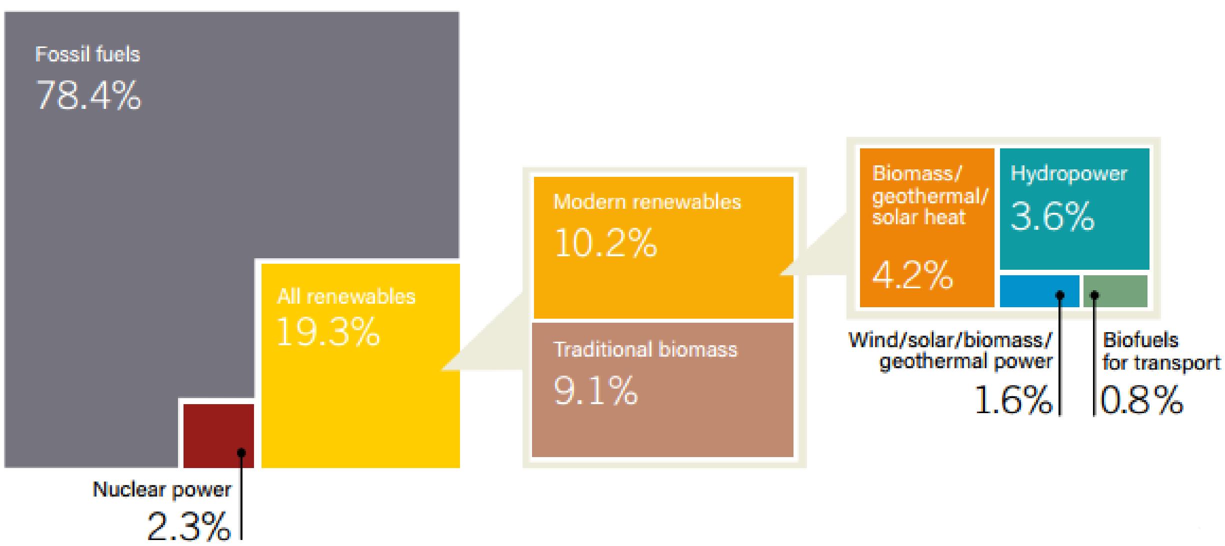


*Figure 1 Global final energy consumption for year 2014 [(3)]*

According to the annual global status report of the "Renewable Energy Policy Network for the 21st Century", as of 2015, renewable energy provided an estimated 19.3% of global final energy consumption [(3)].

The overall share of renewable energy in total final energy consumption has increased only modestly in recent history, despite tremendous growth in the renewable energy sector, particularly for solar PV and wind power.

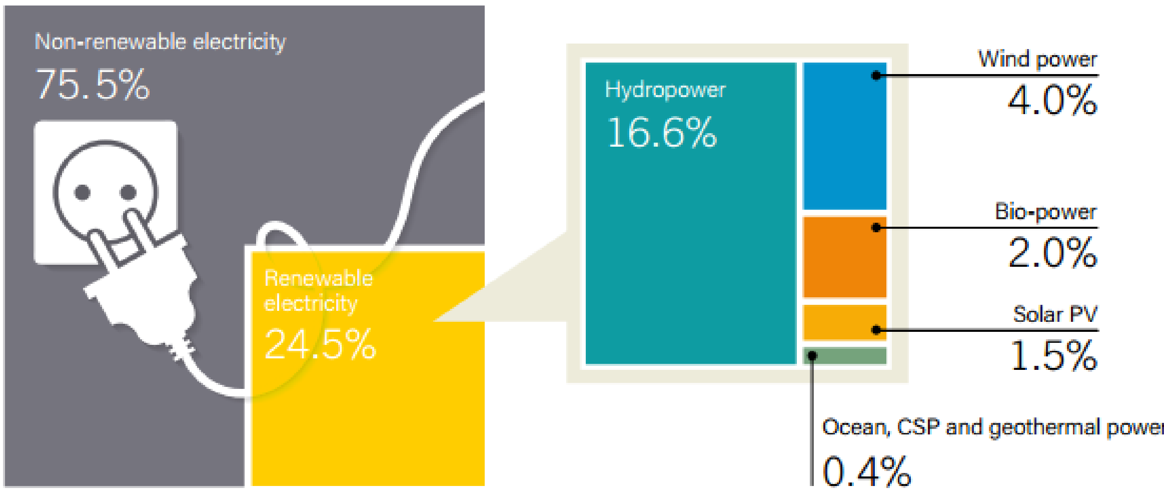


*Figure 2 Estimated renewable Energy share of global electricity production at the end of 2016* [(3)]

This is an estimated renewable Energy share of global electricity production at the end of 2016 according to the annual global status report of the "Renewable Energy Policy Network for the 21st Century "of year 2017.

By year's end, renewables comprised an estimated 30% of the world's power generating capacity enough to supply an estimated 24.5% of global electricity, with hydropower providing about 16.6% [(3)].

## Wave Energy

Wave Energy, it's the generation of electricity from the wave of the oceans and seas. A source of renewable energy that hasn't been fully utilized and developed.

Wave energy originates from the wind, which in turn originates from the sun. When the wind blows over the ocean, friction gives rise to water movement and waves are generated [(4)].

In general, ocean energy can be divided into six types of different origin and characteristics: ocean wave, tidal range, tidal current, ocean current, ocean thermal energy, and salinity gradient [(5)].

There are two basic ways we can trap wave energy using different wave power devices. The first way is trapping the wave energy at the surface of the wave from the surface motion of the waves and the second way is the pressure fluctuations caused below the surface of the waves.

There are various forms of wave technologies that have been developed recently and/or improved recently so as to capture the power of the waves in the most efficient way. First of all, we have to note that wave capturing devices can be installed at one of the following 3 locations: nearshore, offshore and far offshore. Choosing the right technology and the right type of location is done under a careful techno-economic evaluation.

The device that converts ocean wave energy to electricity is called a Wave Energy Converter (WEC). A WEC have various shapes and sizes [4].

There are four different types of wave energy capturing devices that even though all of them are installed at the surface or near the surface of the ocean they differ in the way they interact with the waves, capture the wave energy and the way they convert this energy into electricity.

These types are; Terminator devices, Point absorbers, Attenuators and Overtopping devices [6].

## Wave Energy Current Status

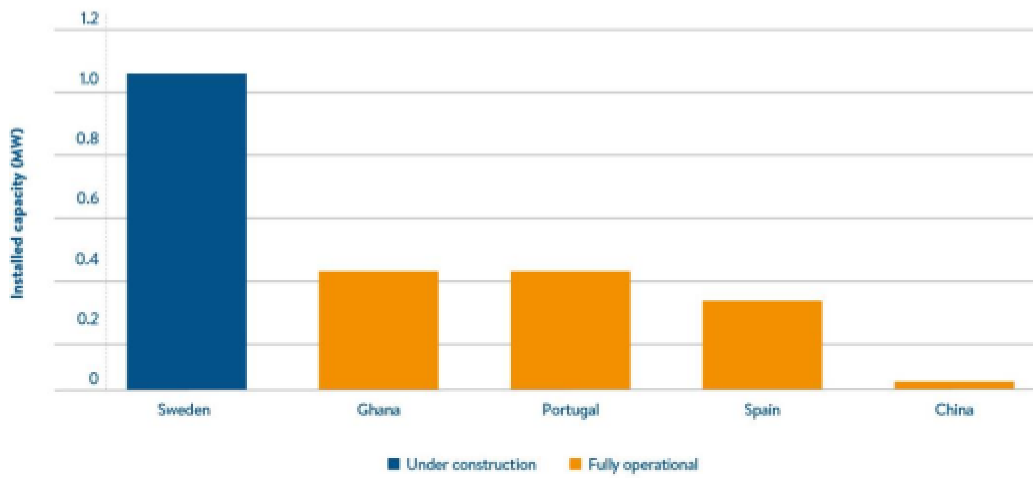


*Figure 3 Wave energy current status*

This is a graphical representation of wave energy installed capacity in operation or under construction according to the “World Energy Council” report of the year 2016 of the marine energy.

Sweden’s Seabased has begun construction the world’s largest commercial wave energy array at Sotenas. It will incorporate 42 devices and deliver 1.05 MW of capacity. They have also recently installed a second project in Ghana consisting of 6 devices, together providing 400 kW of capacity.

A host of pre-commercial demonstration projects are also underway and one of the highest profile has been in Australia where Carnegie has demonstrated 3 of its CETO 5 devices rated at 240 kW off Garden Island. Numerous other demonstration projects are taking place across the UK, Canada, Denmark, Korea, Spain and the United States among others.

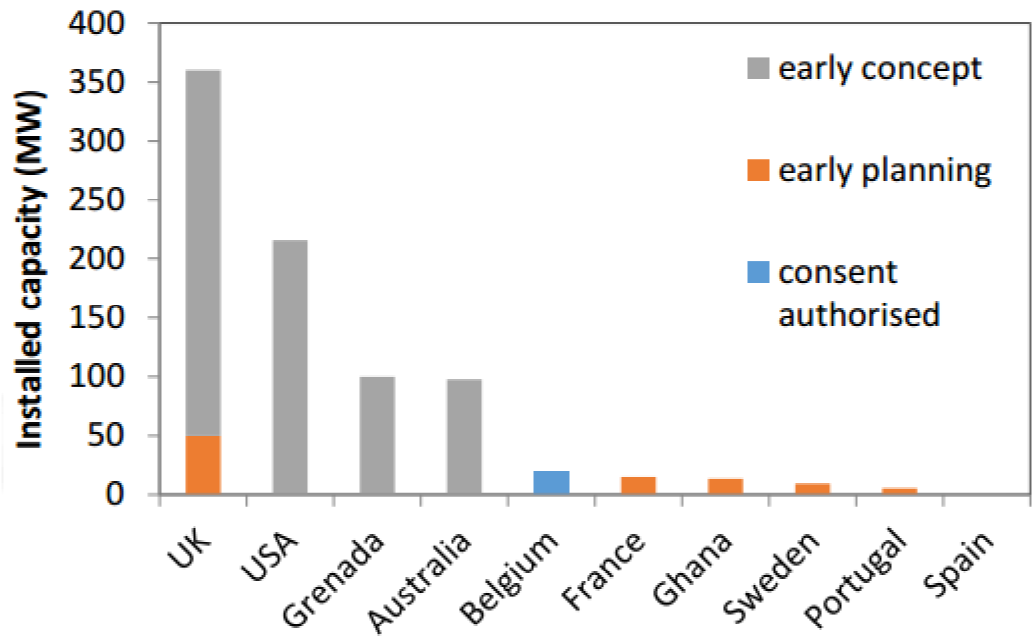


*Figure 4 Wave energy undergoing installed capacity* [7]

According to the "World Energy Council" report of the year 2016 of the marine energy, there is quite good future for the Wave Energy, this graph explains the wave energy installed capacity under development [7].

In total, 838 GW of wave energy projects are currently at different stages of development, however only 20 MW of this has received authorized consent relating to a project at Mermaid/Bligh Bank in Belgium [7]. In addition, there is 94 MW at the early planning and 725 MW at the early concept stage. See more wave energy projects **Appendix 1**.

## Introduction to the thesis

In this thesis we will discuss and explain the different types of wave energy technologies, we will see the different existing projects of wave energy and the technology used in each case.

Then, we will start in our investigation in three specific technologies which are; the Point Absorber which is the Buoy WEC (Wave Energy Converter), second the Attenuators which is The Pelamis WEC, finally we will discuss the Oyster WEC which is a hydro-electric wave energy device.

We will have a full mechanical, hydraulic and electrical simulation for each case with the results of each simulation and we will have a comparison between the different technologies discussed.

## Programs

This section is a small introduction on each and every tool used in this thesis. There are two main programs used: ANSYS; and MATLAB, the other tools are some application within these mentioned programs.

## ANSYS

### *DesignModeler*

ANSYS DesignModeler software provides the user with modeling functions for simulation that include parametric geometry creation, concept model creation, CAD geometry modification, automated cleanup and repair, and several custom tools designed for fluid flow, structural and other types of analyses.

### *AQWA*

ANSYS AQWA software is an engineering analysis suite of tools for the investigation of the effects of wave, wind and current on floating and fixed offshore and marine structures, including spars, floating production storage and offloading (FPSO) systems, semi-submersibles, tension leg platforms (TLPs), ships, renewable energy systems and breakwater design [(8)].

ANSYS AQWA software provides extensive tools for results interpretation and manipulation, allowing many common and more advanced processing requirements to be undertaken directly within the software and enabling a rapid assessment of extensive results data [(8)].

### *AQWA GS*

It's a sub-application form ANSYS AQWA. AQWA GS (AQWA-Graphical Supervisor) is used for mesh generation, model visualization, animation, post processing, graphing, analysis functions and cable dynamics [(9)].

## MATLAB

### *WEC-SIM*

WEC-Sim (Wave Energy Converter SIMulator) is an open-source wave energy converter simulation tool. The code is developed in MATLAB/SIMULINK using the multi-body dynamics solver Simscape Multibody.

WEC-Sim has the ability to model devices that are comprised of rigid bodies, power-take-off systems, and mooring systems.  Simulations are performed in the time-domain by solving the governing WEC equations of motion in 6 degrees-of-freedom [(10)].

# Chapter 2: Project Background

This chapter goes through a non-detailed background that is needed to understand the modeling of ocean waves and help understand the implementation of the needed wave types in each of our project types.

This chapter contains two parts: the basic concept or theory of waves and their effect on a surface body; and the wave implementation which is divided in the wave types and a detailed explanation of the used wave type later in the project.

## Basic Concept

In this project we only consider a two dimensioned waves, the x−z-plane. These waves are called plane waves, since their wave front moves in parallel planes. The coordinate system for the wave is defined such that the x-axis is in the direction of the wave propagation which later be defined according to the degree of wave direction for example a 0 or 90 degree wave, and the z-axis is vertical to the wave motion.

The value of the z-axis is zero at the starting point which means that it's on the same seawater level, which means zero wave amplitude.

To understand the wave theory and their implementation we have to define some important wave parameters.

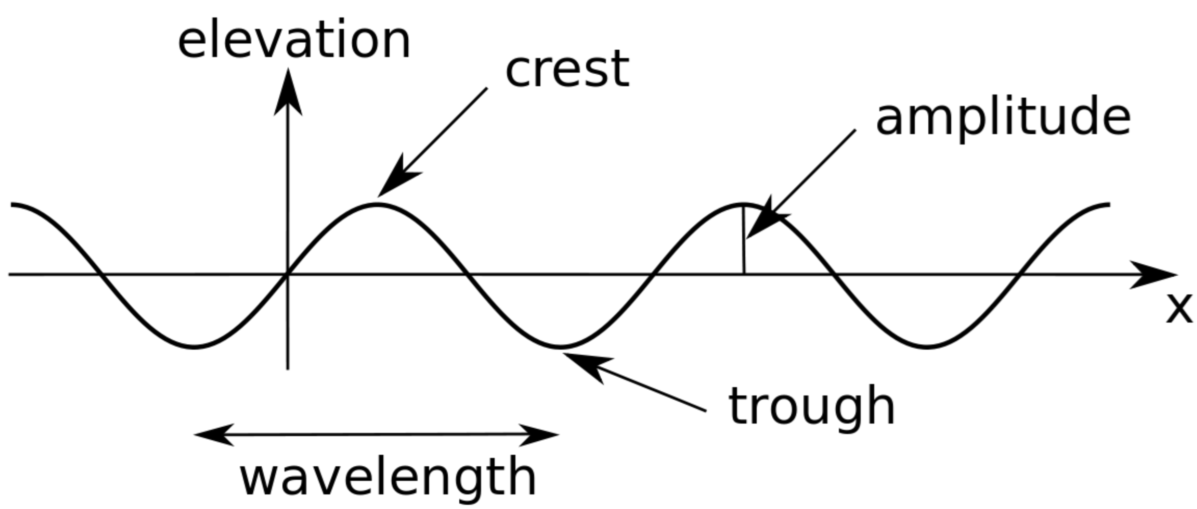


*Figure 5 Wave parameters*

First, the crest and trough, Waves have moving crests (or peaks) and troughs. A crest is the highest point the medium rises to and a trough is the lowest point the medium sinks to. With knowing that we can define a wavelength as the distance between two consecutive crests or two consecutive troughs [11].

Accordingly, a wave period is defined as the time required for two successive wave crests to pass a fixed point, or the time for a single wave crest to travel a distance equal to the length of the wave [12].

Second, a wave amplitude, one of the most important parameters that we will be using later in the project. A wave amplitude is the maximum displacement of points on a wave or it's the peak point of a wave.

Lastly, the wave height. The wave height of a wave is the distance between the elevations of a crest and a neighboring trough.

## Wave Implementation

### Body Motion

The general body motion is defined by six degrees of freedom; the movement in x,y,z directions and the rotations around the x,y,z axes. By common notation we call these six degrees of freedom: surge, sway, heave, roll, pitch and yaw.

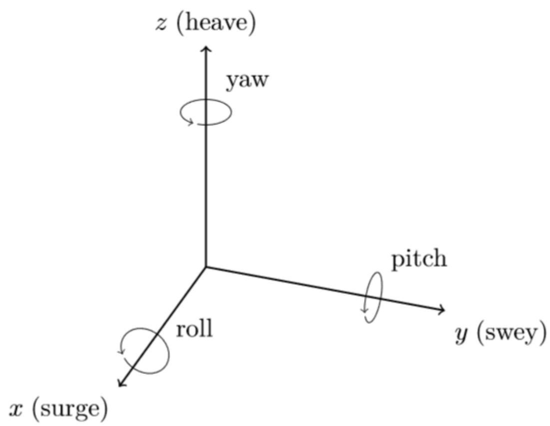


*Figure 6 Six degrees of freedom*

In some cases of this project, only three degrees of freedom are considered, since the waves are moving in two dimensions and the body is symmetric. These are surge, heave and pitch, where surge is the x-movement, heave is the z-movement and pitch is the rotation around the y-axis.

### Wave theory

We have to understand the ocean waves and their interaction with the each body to model the movement of the bodies. This section covers the theory of surface waves of the used wave types.

Ocean waves arise when the wind is blowing over the ocean, forcing the water surface to move. The gravity is then working as a restoring force. Ocean waves can also originate from other sources such as earthquakes and Coriolis force.

In this thesis, we consider both regular and irregular surface waves. A regular wave is sinusoidal and occurs if a steady wind blows during a long time period. Ocean waves mostly consist of super-positioned regular waves, since the wind speed varies. A wave that consist of a range of regular waves with varying shapes is called an irregular wave. However it depends on each case study because some wave energy converters doesn't fully operate on irregular waves for example.

### Regular Waves

Regular surface waves arise when the wind blows with constant speed for a long time over a large area. We let x be the direction of wave propagation and since we assume the waves to be two dimensional, x together with the time t are the only coordinates we need to describe the wave elevation. The surface elevation of a regular wave can be expressed with a sinusoidal function:

$$\eta(x,t) = \frac{H}{2}\cos(\omega t - kx)$$

Where H/2 is the wave amplitude, ω is the angular frequency, k =2π/λ is the wave number and λ in turn is the wave length.

### Irregular waves

The period T and the wave height H are important properties of a wave. For irregular waves we use corresponding properties called significant wave height Hs— calculated by taking the average value of the highest one-third heights of the incoming waves—and energy period, Te, which is the wave period of a regular wave, carrying the same amount of energy as the irregular wave.

In this thesis we consider using the Stokes 2nd Order Wave Theory as a regular wave type in our simulation and the Jonswap (Hs) as the irregular wave type. See the theory of the mentioned wave types in **Appendix 2**.

## Chapter 3: Methodology

In this section we will discuss our process and steps we have taken in this thesis to reach our desired goal. This section contains two parts: Mechanical Simulation; Electrical Simulation.

A Hydrodynamic Diffraction and a hydrodynamic response analysis are our major two parts in the mechanical simulation, these analysis are held by ANSYS AQWA program. While an electrical simulation and hydraulic implementations (if needed) are held by MATLAB, and in concrete WEC-SIM.

We have four different case studies in which we will investigate in, in these four case studies we have some common steps that we took in the investigation process.

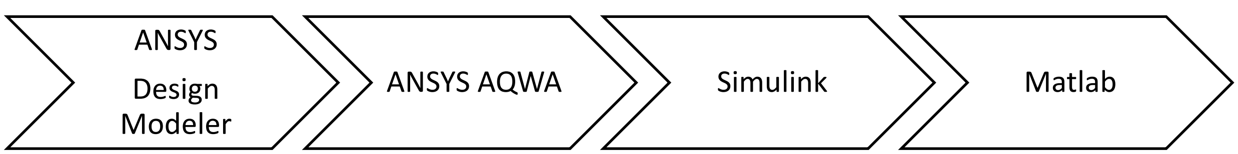


*Figure 7 Thesis procedure*

As we see the process diagram we can notice the following, first, we have the design phase in which we can draw our own 3D design by ANSYS MODELER. Second, comes the hydrodynamic diffraction analysis and the hydrodynamic response analysis done by ANSYS AQWA.

Third, after creating our environment and defining our simulations parameters we may start to design our electrical model in Simulink in which we will use in our next and final step, the electrical simulation in MATLAB, in which we will calculate the produced power by our WEC designed device.

The following diagram shows an overall view of the simulation procedures in each case study, also showing the output file format in each process and the perquisite of each one. This part will be discussed in details in the following sections.

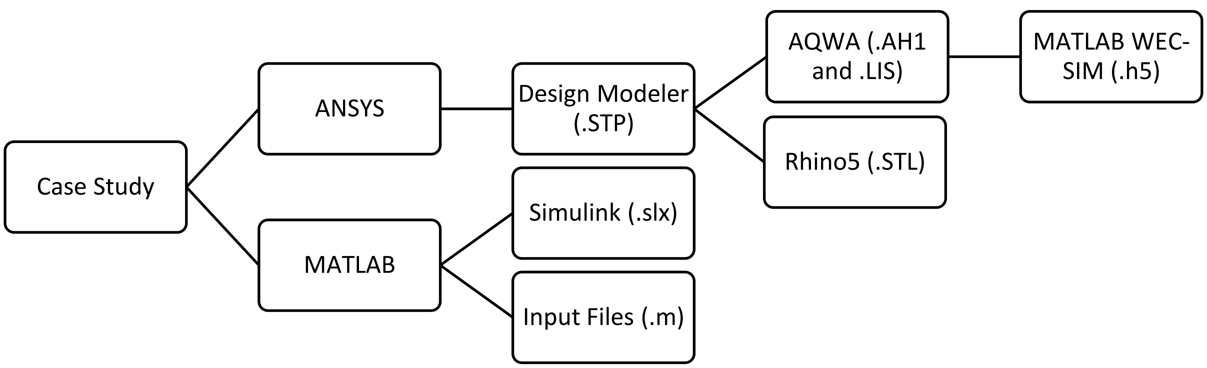


*Figure 8 Thesis detailed procedure*

The main goal of this thesis is to study the behavior of some wave energy converters and to measure the estimated produced power of each simulated to device. To reach this goal we will use WEC-SIM, a wave energy converter simulator which permits it's user to fully simulate and study their own design.

There are some main input files are needed to start a simulation in WEC-SIM which are:

1. Input File (.m)
2. Simulink Model (.slx)
3. Hydrodynamic Data (.h5)
4. Geometry Files (.stl)

After mentioning the main files needed in each case study we may now explain how to achieve each and every file.

First we may start by the geometry files, ANSYS permits the user to design and draw their own idea or design with the Design Modeler application. With having our dimensions and our design already planned, the drawing phase of the design starts generating an output file of (.STP) which we will need later on to convert to (.STL) file format. This change is very necessary as WEC-SIM only reads (.STL) geometry files.

After defining the structure dimensions, comes the next step of introducing the mass of the body and the moments of inertia on the body. The mass input is roughly estimated with having a mass reference of a previous project.

Defining the moments of inertia in ANSYS AQWA might be done by two ways, first by direct introducing the moments of inertia after introducing the mass or by introducing the coefficients of the inertia kx, ky, kz.

Defining the environment and its parameters is the first thing to do in ANSYS AQWA, environment parameters are like sea depth and water density.

Some parameters in the simulation depends on this step, for example the sea depth length act as boundary condition to the diffraction analysis. Also, the sea depth influence the minimum value of the wave frequency. In this thesis we will try to maintain the same simulation environment in all the case studies.

In some cases we will have to add specific joints to the structure for example in the case of the Attenuator or the Oscillating wave surge, ANSYS AQWA's hydrodynamic analysis allows structures to be connected by articulated joints. These joints do not permit relative translation of the two structures but allow relative rotational movement in a number of ways that can be defined by the user.

There are different types of joints in AQWA: Ball and socket joint; Universal joint; Hinged joint; and rigid joint.

After introducing all the factors and parameters acting on the body, and the parameters of the body itself. The meshing stage starts, the mesh is automatically generated on the bodies in the model; its density is based on the defeaturing tolerance and maximum element size parameters. These are the two main parameters in the meshing stage.

The Defeaturing Tolerance controls how small details are treated by the mesh. If the detail is smaller than this tolerance then a single element may span over it, otherwise the mesh size will be reduced in this area to ensure that the feature is meshed. The defeaturing tolerance cannot be greater than 0.6 times max element size.

Max Element Size controls the maximum size of the element that will be generated. In ANSYS AQWA this is explicitly related to the maximum wave frequency that can be utilized in the diffraction analysis.

Adjusting the settings of the hydrodynamic diffraction analysis is the third step in the simulation process.

First, the structure selection as we only have one structure which is the buoy so we don't have options to choose from, but we have to make sure that the buoy is selected. By selecting the buoy means that all the simulation parameters we are going to introduce will be applied on this selected structure. Second, the gravity input, as we know the gravity is a constant equals to 9.81 N/m.

Third the wave direction selection, ANSYS AQWA permits selecting a number of wave directions but at least 4 wave directions must be applied, also you can choose the range between each direction. The results are calculated in each and every introduced wave but you have to choose one specific wave direction to view the results and the graphs.

And to finish adjusting the hydrodynamic diffraction analysis settings, begins the part of choosing the adequate wave frequencies for this analysis, wave frequencies parameters depends on the environment, the structure settings and the mesh size.

While adjusting the analysis settings we have to make sure of three main settings:

- Output ASCII Hydrodynamic Database -> Yes
- Calculate Full QTF Matrix ->No
- Ignore Modeling Rule Violations ->Yes

Output ASCII Hydrodynamic Database set to yes means that we will be able to generate an (.AH1) file which will be need in the (.h5) file generation.

We can now start our hydrodynamic diffraction analysis simulation generating a lot of output files, the most important out files are (.LIS) and (.AH1). With these two file we can now head to MATLAB and generate our (.h5) file with the bemio (Boundary Element Method Input/Output) function of the WEC-SIM.

Generating the ".h5" file and saving the ".stl", designing the Simulink model is the next step, the model is designed depending on the structure and the number of bodies in the simulation, also choosing the right constraints which mean the right joints connecting the bodies if needed. After this we have to choose the type of the PTO system and if it's a direct drive generator or depending on a hydraulic system with compressible fluid.

Next comes the introduction of the WEC-SIM input file, which contains all the parameters of the simulation and the parameters of the Simulink model. After that we may run our simulation, as long as all the introduced parameters are correct and reasonable and all the required files are completed.

The following table is a summary of the past detailed information of the methodology used in this thesis:

*Table 1 Summary of the methodology*

| Function | Program | Application | Input | | Output | |
|---|---|---|---|---|---|---|
| | | | File Name | File Format | File Name | File Format |
| **3D Design** | ANSYS | DesignModeler | | - | "CaseStudy" | .stp |
| **Change design formats** | Rhino5 | - | "CaseStudy" | .stp | "CaseStudy" | .stl |
| **Hydrodynamic Diffraction Analysis** | ANSYS | AQWA | "CaseStudy" | .stp | ANALYSIS<br>ANALYSIS | .AH1<br>.LIS |
| **bemio** | MATLAB | - | bemio<br>ANALYSIS<br>ANALYSIS | .m<br>.AH1<br>.LIS | ANALYSIS | .h5 |
| **Model Design** | MATLAB | Simulink | - | - | "CaseStudy" | .slx |

## Point Absorber (Buoy)

The functioning concept of the Buoy is very simple. When submitted to the sea the floating buoy moves upwards under the influence of a wave crest and moves downwards under the effect of a wave trough. The resultant mechanical stroking drives an electrical generator.

The generated wave power can be transmitted onshore via an underwater power cable and then can be connected to the network.

The steps of the simulation are explained before in the previous section, in this part we will define mainly the parameters of this specific case study, and explaining the model of the buoy.

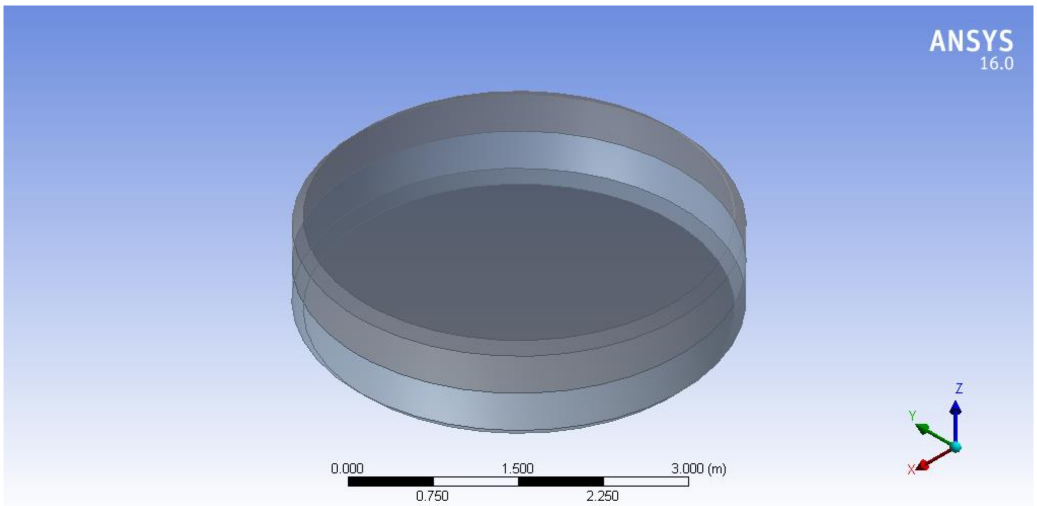


*Figure 9 Point absorber (buoy) design*

In the above figure is shown our design of the buoy, a diameter of 4 meters and 6700 kg of total structural mass. In this case we don't have any used joints as the buoy is a single body and isn't connected to another body, this may lead that in the Simulink model we won't include any constraints.

After designing the model we may know introduce the hydrodynamic diffraction parameters needed to start this analysis. The hydrodynamic diffraction analysis parameters are mentioned in the following table:

*Table 2 Buoy hydrodynamic diffraction analysis parameters*

| Buoy | |
|---|---|
| **Lowest Frequency (Hz)** | 0.01592 |
| **Longest Period (s)** | 62.83185 |
| **Highest Frequency (Hz)** | 1.7 |
| **Shortest Period (s)** | 0.58824 |
| **Number of Intermediate Values** | 20 |
| **Interval Frequency (Hz)** | 0.08019 |

Next we may now start our analysis and generate the ".AH1" and ".LIS" files that are needed to generate the hydrodynamic data file used in the WEC-SIM.

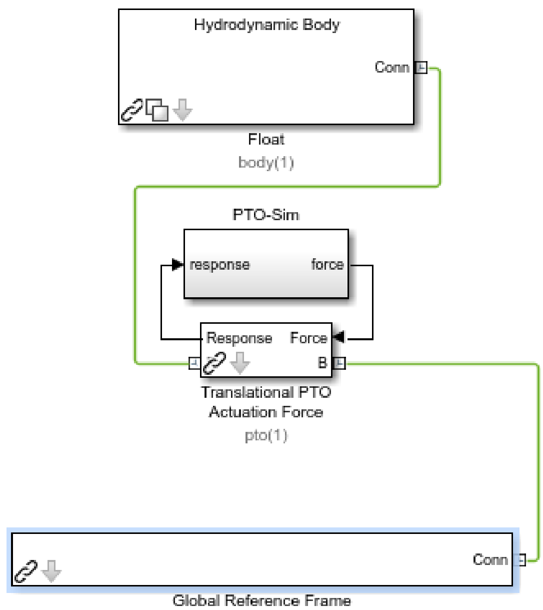


*Figure 10 Buoy simulink model*

Staring the Simulink model, as shown in the above figure a hydrodynamic body which is the buoy we designed before, connected to a PTO (Power Take Off) system and then connected to a Global Reference Frame which acts as a sea bed.

The PTO system consists of a Direct Drive generator and a transitional PTO, the transitional PTO is defined as the converter of the movement of the buoy in the z-axis which is defined in the block as the response. The response of the buoy due to the incident waves are the input of the PTO and the direct drive generator which then will converted to electrical energy. For the full WEC-SIM Input file see **Appendix 4.1**.

## Oscillating Wave Surge (Oyster)

The Oyster is a hydro-electric wave energy device that uses the motion of ocean waves to generate electricity. The Oyster concept is an oscillating wave surge converter: a buoyant, hinged flap attached to the seabed at around ten meters depth, around half a kilometer from shore. This flap, which is almost entirely underwater, moves backwards and forwards (in the y-axis direction) in the near-shore waves (13).

The movement of the flap drives two hydraulic pistons which push high pressure fluid onshore to drive a conventional hydroelectric turbine.

Our oyster design was taken from the design of the Oyster project of Aquamarine Power, Aquamarine Power installed Oyster at the EMEC in August 2009. In November 2009, Oyster was officially launched and connected to UK's national grid (14).

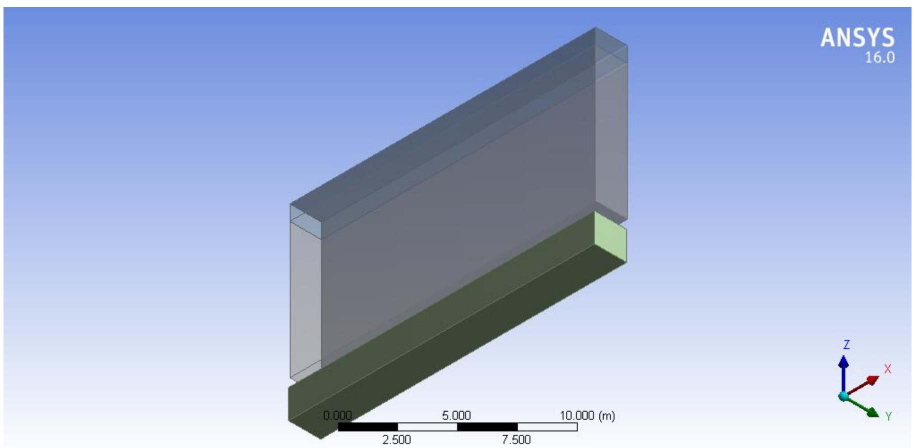


*Figure 11 Oyster design*

Flap design may be similar to the Aquamarine Power's Oyster dimensions, as it has the same width of 18 meters but differs in the length and depth, as our design has a length of 8.9 and depth of 1.8 meters. This body structure is defined in the Design Modeler as thin surface body not as a solid structure, so it can be set as "free moving body".

Base dimensions such as the length and width are the same as the flap, with only the change in length, as its length is equal to 1.7 meters. The body is set to be a fixed nonmoving body as its only main function is to be connected to the flap with the joint hinge support to give the flap the free mobility along the y-axis direction (forwards and backwards).

Wave direction in this case study must be very specific and precise as it depends on the flap direction and the hinge reactions direction. Wave must be perpendicular on the flap and in the right direction facing the front part of the hinge.

Oyster project is normally set and located near the shore as it's not exposed to high depths which in this case proposes a low wave height. We have to make sure to choose the right wave frequencies and the adequate wave amplitudes which is preferable no to be high amplitudes.

*Table 3 Oyster hydrodynamic diffraction analysis parameters*

| Oyster | |
|---|---|
| **Lowest Frequency (Hz)** | 0.02 |
| **Longest Period (s)** | 50 |
| **Highest Frequency (Hz)** | 0.61739 |
| **Shortest Period (s)** | 1.61972 |
| **Number of Intermediate Values** | 30 |
| **Interval Frequency (Hz)** | 0.01927 |

As the previous case study, we should now create the Simulink model. In the following figure we may see two bodies (Flap and Base) connected to the PTO system. The PTO system in this case consists of a hydraulic piston which drives a compressible fluid.

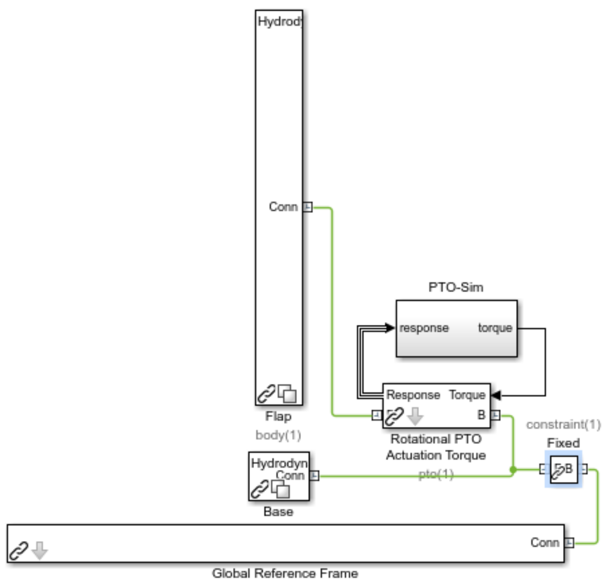


*Figure 12 Oyster simulink model*

But in this case we have to connect a constraint, this constraint acts as a hinge joint which may permit the movement of the flap in the y-direction but also maintain the bas in a fixed position. For the full WEC-SIM Input file see **Appendix 4.2**.

## Attenuator (Pelamis)

The machine operates semi-submerged, extracting power from the wave-induced motion of the hinged joints. This power is resisted by hydraulic rams, which pump high-pressure oil through smoothing accumulators to hydraulic motors. Each module contains a complete electro-hydraulic power generation system, with a single seabed cable linking several devices to the shore. The machine is held in position by a mooring system combining floats and weights that prevent the mooring cables from becoming taut [15].

The Design of the project comes from the original design of the P1, of the company Pelamis Wave Power (PWP).

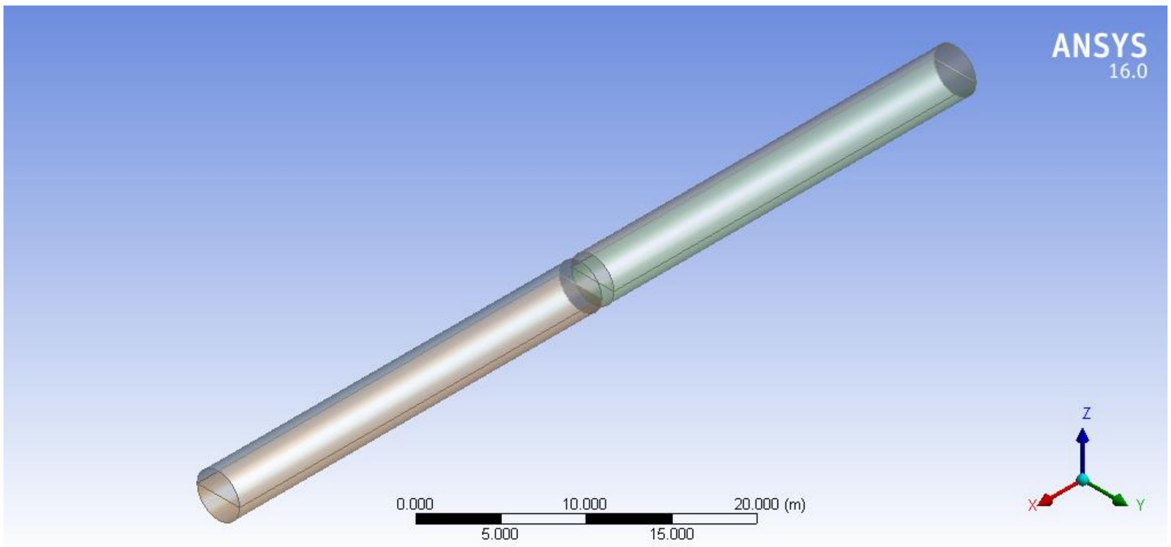


*Figure 13 Pelamis design*

There are two equal structures of 30 meters long each and a diameter of 3.5 meters. Each structure is set to a thin surface structure in ANSYS to undergo the simulation. There is a 1 meter between each structure to add the joint later in ANSYS AQWA, so the distance between the center of each body and the other is 31 meters. So the total length of the project is equal to 61 meters long.

Pelamis functions when the waves come along with it, it will not function correctly if the waves fall perpendicular all this may lead to damages and the failure of the whole project.

*Table 4 Pelamis hydrodynamic diffraction analysis parameters*

| Pelamis | |
|---|---|
| **Lowest Frequency (Hz)** | 0.01592 |
| **Longest Period (s)** | 62.81407 |
| **Highest Frequency (Hz)** | 0.86124 |
| **Shortest Period (s)** | 1.16111 |
| **Number of Intermediate Values** | 30 |

| | |
|---|---|
| **Interval Frequency (Hz)** | 0.02727 |

Now we can start our simulink model, which in this case will contain a new constraint which is "Floating (3DOF)" this consraint acts as the joint between the two structures permiting the movement of both structures in three degrees of freedom. It permits mainly the movement in x-axis and z-axis. For the full WEC-SIM Input file see **Appendix 4.3**.

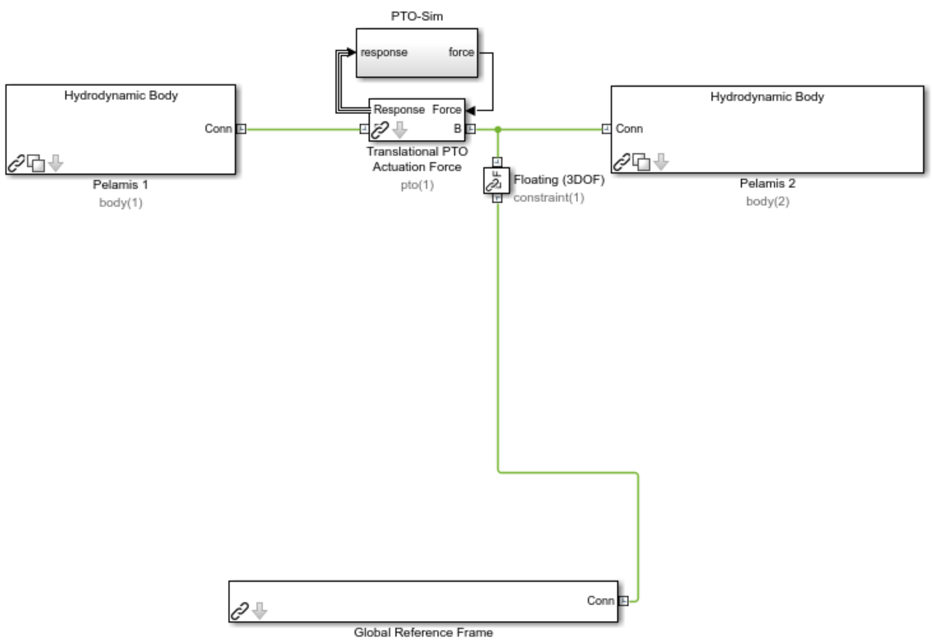


*Figure 14 Pelamis simulink model*

# Chapter 4: Results

A lot of results may be viewed and a lot of graphs may be generated but there are some very important graphs that we should study. In our point of view, the body movement and its position according to the incident wave and the Power graph, are the most important graphs that we will take in our consideration in the this section.

## Point Absorber (Buoy)

Starting with the regular wave result, we can see in the following graph that the structure position goes with a regular form as the input waves are regular with a regular time period, no changes in the wave frequency led to a uniform sinusoidal wave, along through the 60 seconds time duration. Also, it’s noticed that the structure moves up and down the water surface level uniformly in the z-axis.

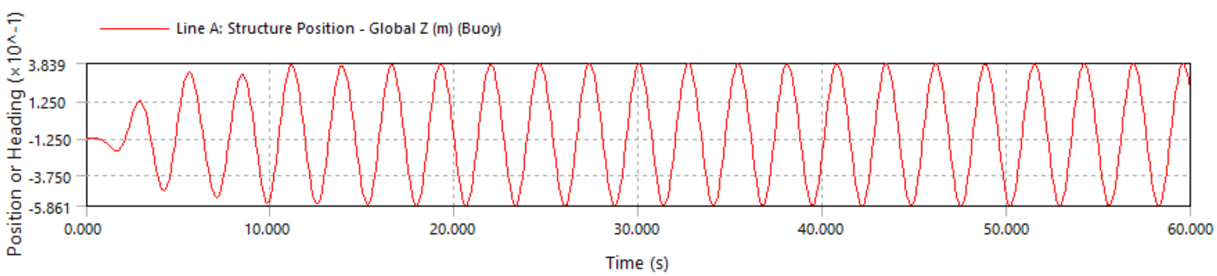


*Figure 15 Buoy position result with regular wave*

Having the negative value in the y-axis of the graph means that the center point of the buoy has been under water level surface, because the center of gravity of the buoy is at the pint (0,0,-0.1) and the position of the structure result is calculated according to the structure’s center of gravity point.

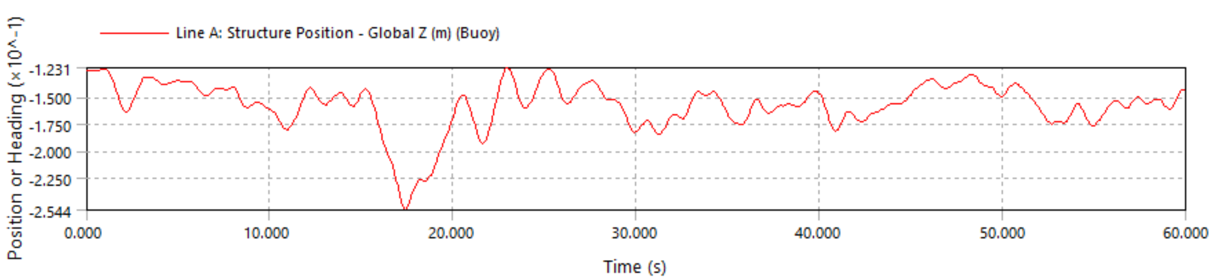


*Figure 16 Buoy position result with irregular wave*

In the above graph it’s noticeable that it’s not a uniform sinusoidal wave, the variation of wave frequencies have led to a variation of structure position along the z-axis in non-uniformly way.

It may notice in the graph that the wave affected a lot on the structure position as it tended to sink more than the other case.

Results from the WEC-SIM comes next and the measurement of the power produced. From the following curve we may see that it took 90 seconds to reach its stable power generation, the buoy in this curve shows that it's one of the most useful WEC taking in account its small size compared to other WEC devices. We can see that the buoy reach a maximum of 0.58 kW of generated electric power.

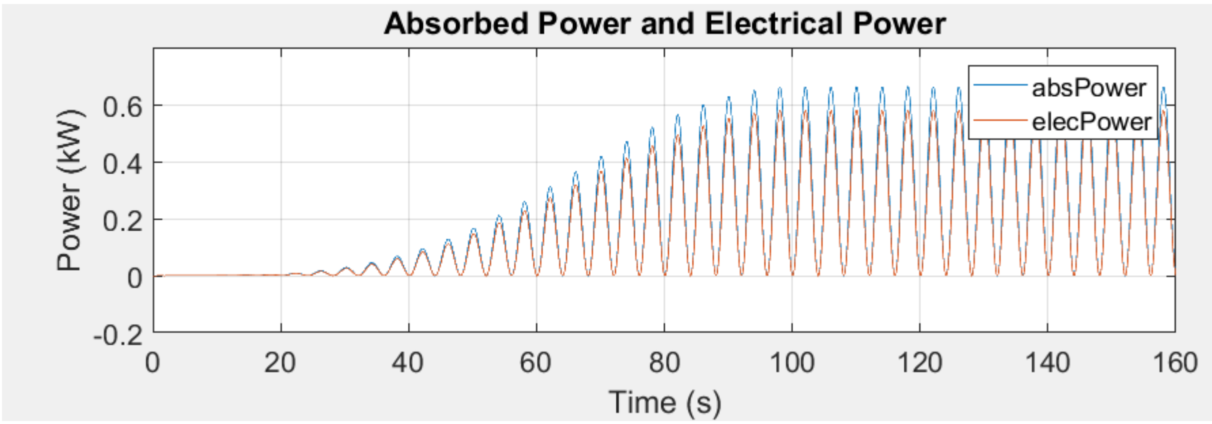


*Figure 17 Buoy absorbed power and electrical power*

## Oscillating Wave Surge (Surge)

In the previous cases we have viewed the result in terms of the z-axis direction as the previous case studies the buoy moves up and down along the z-axis, in this case is different as the flap goes backwards and forwards along with the wave in the y-axis direction.

With that being said our result graphs will be the flap position with the respect to the y-direction. Starting with the regular wave result as seen in the following graph:

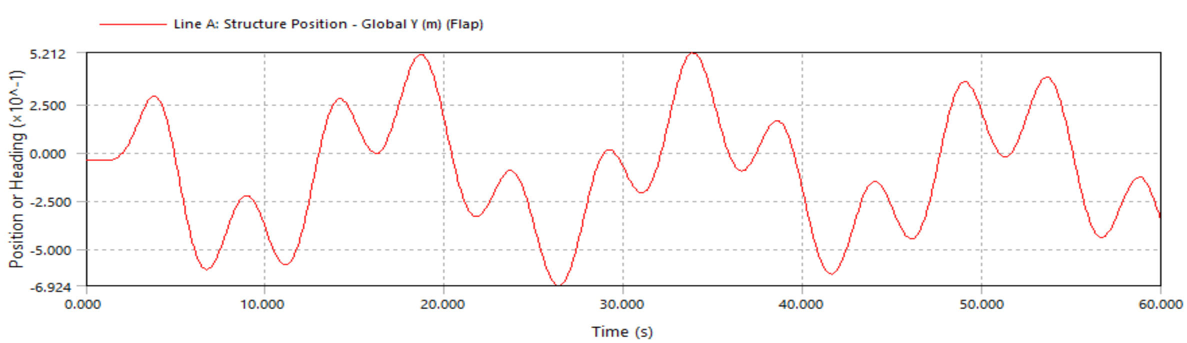


*Figure 18 Oyster position result with regular wave*

From the above figure it can be noticed that the flap has been forward and backward from the y-axis position, the graph is not all uniform as the graphs seen before in the other case studies, but it can be noticed the regularity of the waves.

The following graph shows the result of the irregular waves, from which it can be noticed the irregularity of the waves and the non-symmetric and non-uniform motion of the flap along the y-direction.

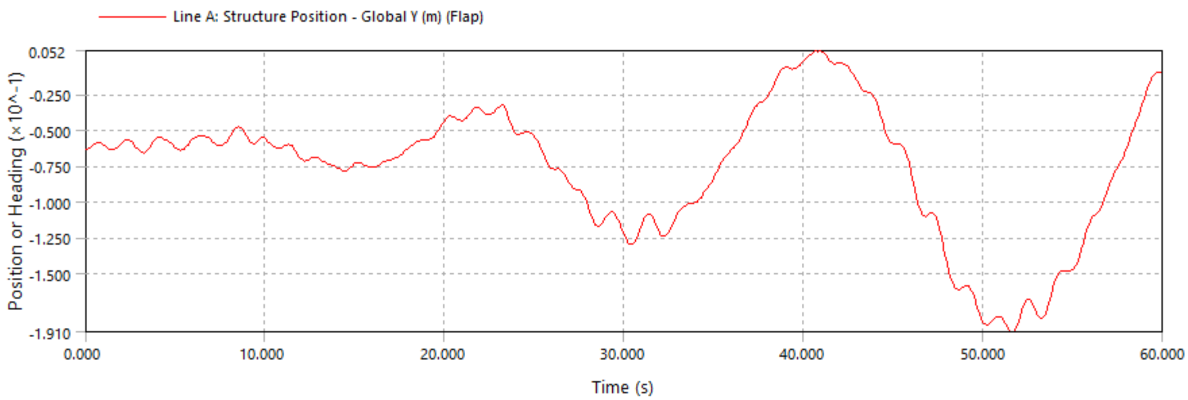


*Figure 19 Oyster position result with regular wave*

There isn't any results shown for the base structure as it's a fixed structure that doesn't have any movement and doesn't affect our output power.

After simulation in WEC-SIM, we may see the results of the Oyster, the results may not be the same as the previous case as the oyster took more simulation time due to the size of the device. However, it reach a high electrical power generation clearly greater than the buoy but yet it didn't reach a stable phase. Recording a maximum of 90 kW of electrical power and a maximum of 210 kW of absorbed power.

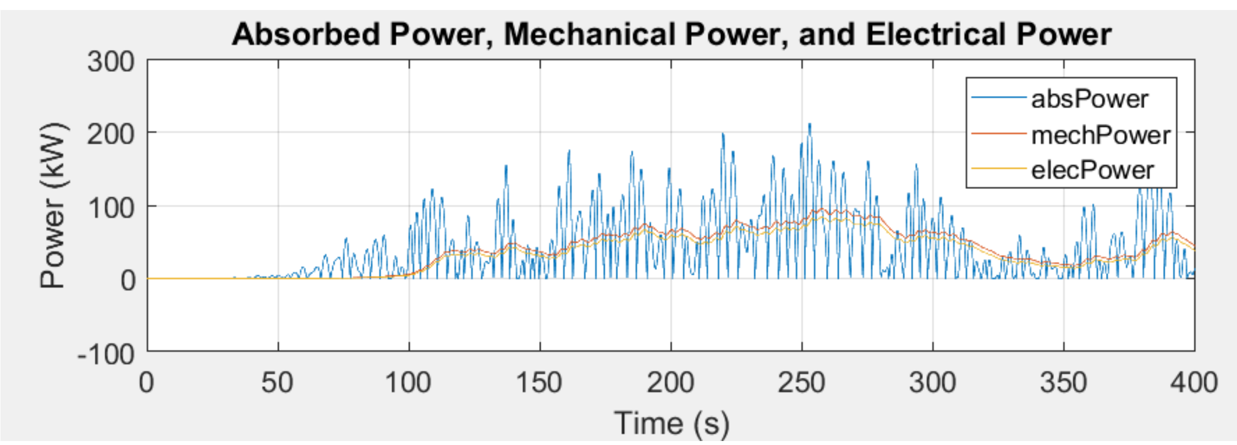


*Figure 20 Oyster output power*

## Attenuator (Pelamis)

Having two structures with a large meshing size and three joints affected the solving time of the whole project, we first solve hydrostatics and then start a full solve of the project.

The hydrodynamic response analysis with regular wave input result is shown in the form of the position of each structure on the z-axis.

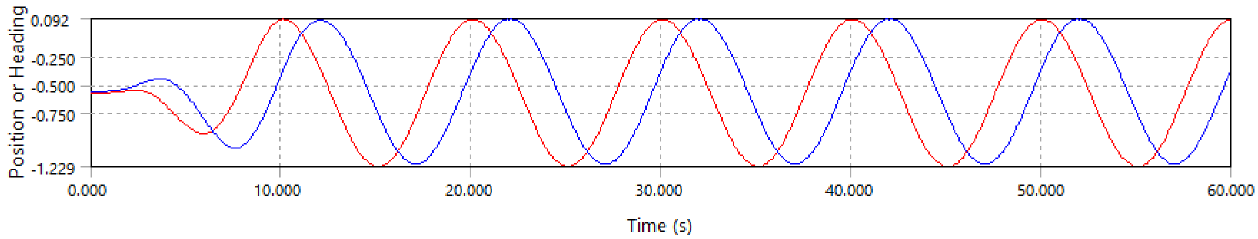


*Figure 21 Pelamis position result with regular wave*

In the figure each line represents a structure body, structure 1 is the first body to meet the incident wave so we have the red line in the lead. As we see the two curves are uniform sinusoidal curves in which the uniformity represented in the graph form and we can see that the curves have taken the same alignment as the structures.

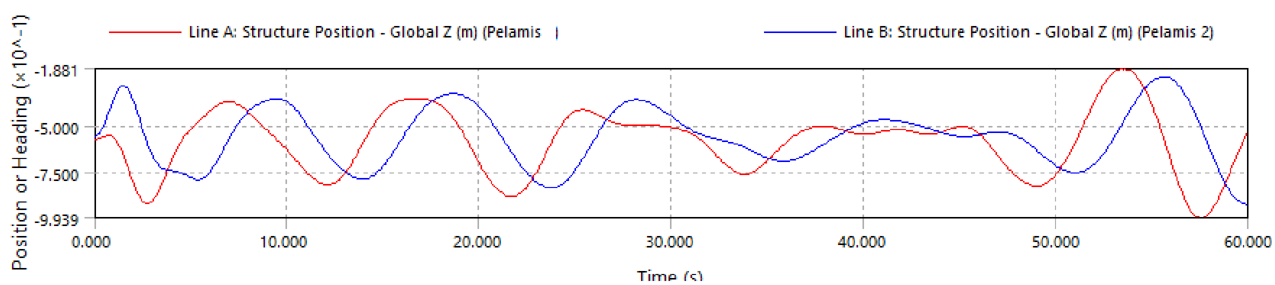


*Figure 22 Pelamis position result with irregular wave*

The irregular waves are a series of regular waves with different frequencies, we can see that in the above graph as it may not be clear which structure comes first, there is an non uniformity on the overall view of the graph, but if we cut the graph in a small time periods we may see a somehow uniformity.

Pelamis consisting of one joint and two hydrodynamic structures have shown its electrical and mechanical characteristics, it did passed through the transitional phase and then it started its stable power generation phase after 144 seconds. The Pelamis reached a maximum of absorbed power of 60 kW during the transitional phase and of 42 kW during the stable phase. Also a maximum of 5 kW of electrical power as shown in the following figure:

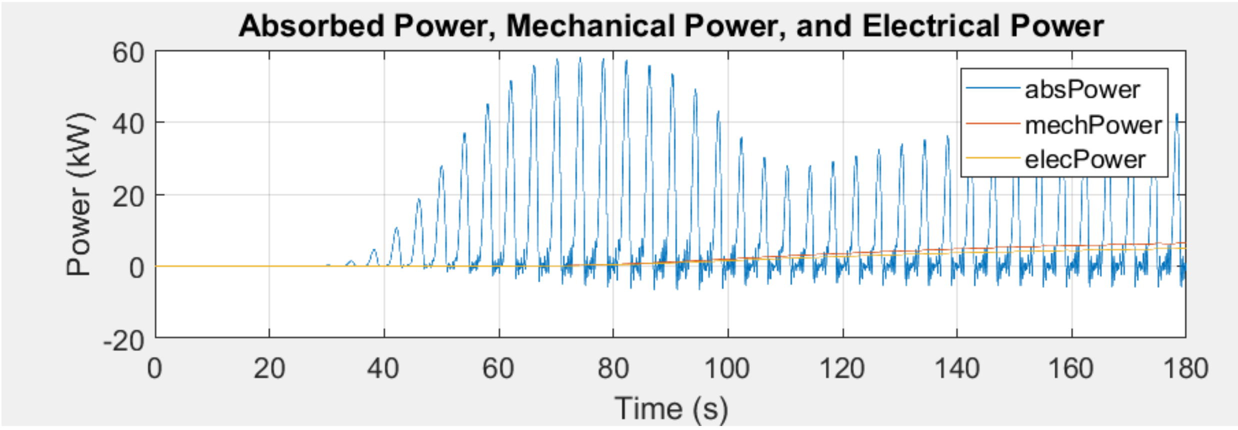


*Figure 23 Pelamis output power*

# Chapter 5: Conclusion

A comparison must take place between all three case studies, although they are not similar and each one has its own functionality and its own characteristics.

*Table 5 Comparison between the three technologies*

<table>
<tr><th colspan="2" rowspan="2">Model</th><th colspan="5">Geometry</th><th colspan="2">Max. Power (KW)</th></tr>
<tr><th>Dimensions (m)</th><th>Area ($m^2$)</th><th>Mass (kg)</th><th>Depth</th><th></th><th>Abs.</th><th>Elec.</th></tr>
<tr><td colspan="2">Buoy</td><td>Diameter= 4<br>Height= 1</td><td>36.201</td><td>6700</td><td>50</td><td></td><td>0.61</td><td>0.59</td></tr>
<tr><td rowspan="2">Oyster</td><td>Flap</td><td>1.8x18x8.9</td><td>423.02</td><td>127000</td><td rowspan="2">10</td><td rowspan="2"></td><td rowspan="2">210</td><td rowspan="2">90</td></tr>
<tr><td>Base</td><td>1.8x18x1.7</td><td>136.68</td><td>fixed</td></tr>
<tr><td rowspan="2">Pelamis</td><td>Structure 1</td><td>Diameter=3.5<br>Legnth= 30</td><td>349.11</td><td>155000</td><td rowspan="2">50</td><td rowspan="2"></td><td rowspan="2">59</td><td rowspan="2">5</td></tr>
<tr><td>Structure 2</td><td>Diameter=3.5<br>Legnth= 31</td><td>349.11</td><td>155000</td></tr>
</table>

Clearly we can't compare the three types directly as they are extremely different, also each type functions in its own way. But we may compare the output power with relation to their size and mass. That means that we compare the output power according to the technology complexity and the structural characteristics.

In the comparison can be noticed that the buoy has the smallest dimensions and the smallest output power, although its power generation is notable in relation with its size.

On the other hand the Pelamis didn't generate the estimated power compared to its size, compared to the buoy, the buoy showed a great success in our simulation due to its small size and amount of output power generated.

While the oyster has the most generated power output, but as seen in results reaching its stable phase would take a lot of time, which means it's complexity in simulation and complexity in achieving a fine result.

After comparing the power generation, we should take in account that choosing a WEC depends also on the location of the project and depends on the environment that it will be produced in. For example the oyster must be installed nearshore as it only functions in low depths with approximately 12 m maximum.

In this thesis we explained some basic concepts of the wave energy and some test cases that proved that the wave energy might have a great potential in the future. Considering the wave energy for power generation would be a great revelation, and it's a great loss that up till now it's not a fully developed source of energy.

# Appendix

## Appendix 1: Wave Energy projects

### Appendix 1.1: Pelamis (Portugal)

Pelamis Wave Power's Agucadoura Wave Farm is the world's first commercial wave energy project located five kilometre off the Agucadoura coast in Portugal. It took 10 years of design and testing. The farm started delivering 2.25MW produced by three Pelamis generators in September 2008.

Pelamis Wave Power, earlier known as Ocean Power Delivery (OPD) supplied the first three Pelamis P-750 "advanced wave energy conversion technology" machines. Another 28 machines were planned as a part of phase 2 to generate 22.5MW for state-run power company Energías de Portugal (EDP) (15).

The first three generators, however, had to be towed back to the port after four months of commissioning because of technical problems.

The Pelamis is cylindrical, with four main tube segments linked by hinged joints and by three power conversion units. Each segment 120m long and 3.5m wide, and weighs 750 tons when fully ballasted. Pelamis machine lays semi submerged on the surface of water that has a depth greater than 50m. The motion of each section flexing relative to one another results in high pressure oil passing through hydraulic motors driving electrical generators which are linked to the grid through cables along the seabed.

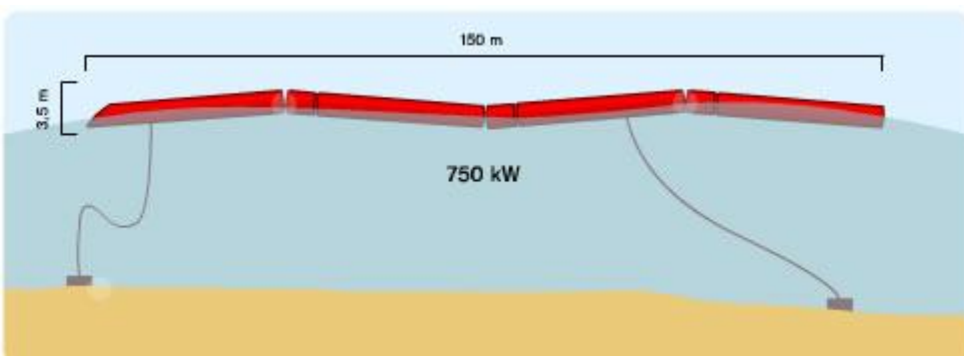


*Figure 24 Pelamis Project (16)*

Efforts were taken to minimize the impact on local marine flora and fauna through, for example, a mooring system of embedment anchors, chains and ropes rather than more permanent gravity based systems (17).

### Appendix 1.2: CETO (Australia)

The CETO 6 Project, located offshore of Garden Island, Western Australia is supported by the Australian Federal Government through a $11m Australian Renewable Energy Agency (ARENA) grant as well as a debt facility from the Commonwealth Bank of Australia.

This next generation CETO unit has a targeted 1MW capacity, representing some four times the output of the previous generation CETO 5 unit (demonstrated as part of the Perth Wave Energy Project) [18].

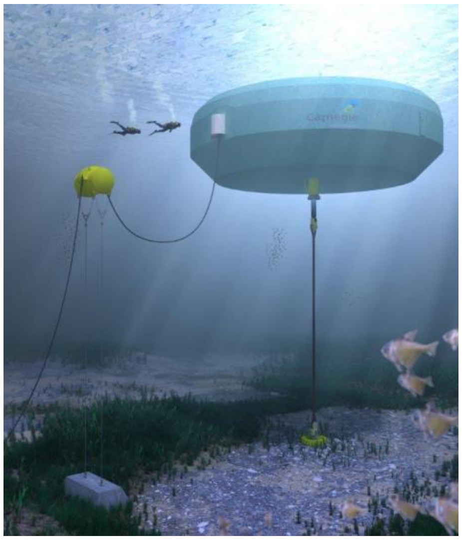

*Figure 25 CETO in Australia [18]*

## Appendix 1.3: SEAREV (France)

Based on 25 years of research in this domain, the “Laboratoire de Mécanique des Fluides (LMF) of Ecole Centrale de Nantes” launched in 2003 a project called “SEAREV” which stands for “Système Autonome Electrique de Récupération de l'Energie des Vagues”.

The SEAREV wave energy converter is a floating device enclosing a heavy horizontal axis wheel serving as an internal gravity reference. The center of gravity of the wheel being off-centered, this component behaves mechanically like a pendulum. The rotational motion of this pendular wheel relative to the hull activates a hydraulic Power Take Off (PTO) which, in turn, set an electric generator into motion [19].

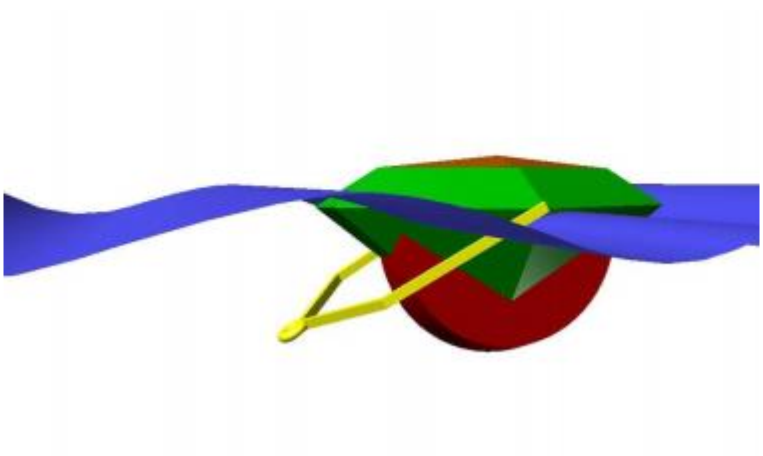

*Figure 26 Searev [19]*

Two major advantages of this arrangement are that, first: all the moving parts (mechanic, hydraulic, electric, components) are sheltered from the action of the sea inside a closed, waterproof shell; and secondly that the choice of a wheel working as a pendulum involve neither stop nor any security system limiting the stroke [19].

## Appendix 1.4: Oyster (UK)

The Oyster concept is an oscillating wave surge converter: a buoyant, hinged flap attached to the seabed at around ten meters depth, around half a kilometer from shore. This flap, which is almost entirely underwater, moves backwards and forwards in the near-shore waves. The movement of the flap drives two hydraulic pistons which push high pressure water onshore to drive a conventional hydroelectric turbine.

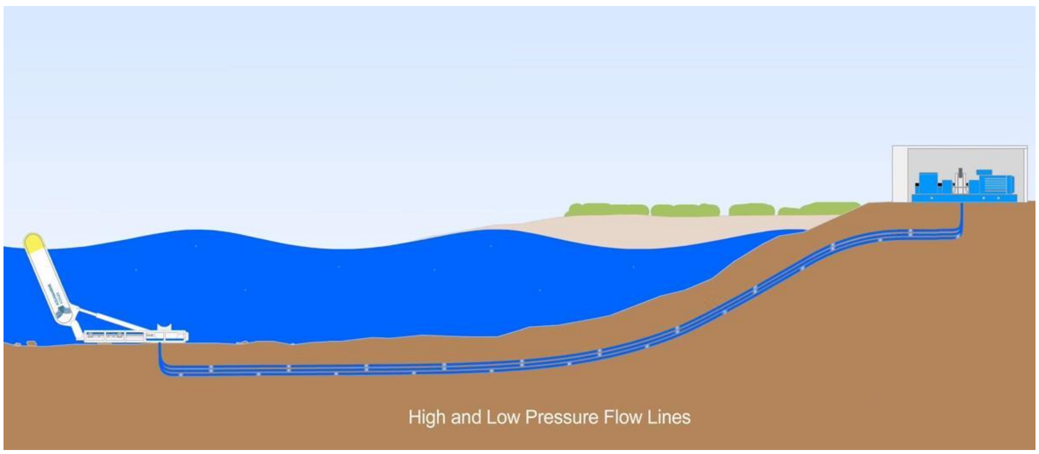


*Figure 27 Oyster* [20]

Aquamarine Power deployed and tested two full-scale Oyster devices at EMEC: the 315kW Oyster 1 and the second-generation 800kW Oyster 800, spending in excess of £3m in Orkney. Oyster 1 wave power device was installed at the EMEC in Orkney (Scotland) in the summer of 2009 and was connected to the grid in November later this year. Oyster 800 was grid-connected in June 2012 at EMEC's Billia Croo test site until the test program ended in 2015 [13].

## Appendix 1.5: OCEANLINX (Australia)

The Oceanlinx commercial wave energy demonstrator is a 3,000 ton structure measuring approximately 21 meters wide by 24 meters long. The device was designed to sit in shallow water, using oscillating water column (OWC) technology to generate 1MW peak output.

The Oceanlinx patented OWC and air turbine technologies were combined in Oceanlinx's greenWAVE device, designed to be a highly efficient energy converter with no moving parts under water. As waves rise within the OWC, it was designed to drive a column of air ahead and through a turbine to generate electricity.

In February 2014, construction of the device was complete and it was intended to transport the device from Port Adelaide to Port McDonnell for grid connection and 12 months operation and testing. Transportation occurred on 1 March 2014 and was expected to take approximately four days.

On 2 March 2014, complications were experienced during transportation of the device, 24 hours into the operation. The device was set down in shallow waters off the Fleurieu Peninsula in South Australia. As a result of the transportation complications, the device was damaged beyond repair [21].

## Appendix 1.6: LIMPET (UK)

LIMPET (Land Installed Marine Powered Energy Transformer) is a shoreline WEC ideally placed to generate electricity in areas exposed to strong wave energy. It is placed on the island of Islay, off Scotland west coast. The current LIMPET device (LIMPET 500) was installed in 2000 and produces power for the UK grid [22].

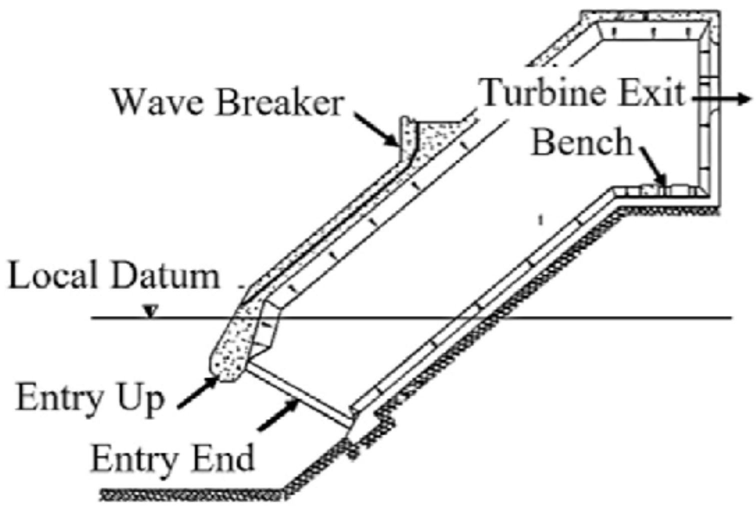


*Figure 28 LIMPET [23]*

## Appendix 1.7: Wave Dragon (UK)

Wave Dragon is a floating, slack-moored energy converter of the overtopping type that can be deployed in a single unit or in arrays of Wave Dragon units in groups resulting in a power plant with a capacity comparable to traditional fossil based power plants.

The Wave Dragon technology is a wave energy converter with a rated capacity of 4MW. Wave Dragon Ltd have been working toward commercialization of the device for 16 years, and had a 1:4.5 scale prototype deployed in Denmark from 2003 to 2007 where reliable power production has already been demonstrated [24].

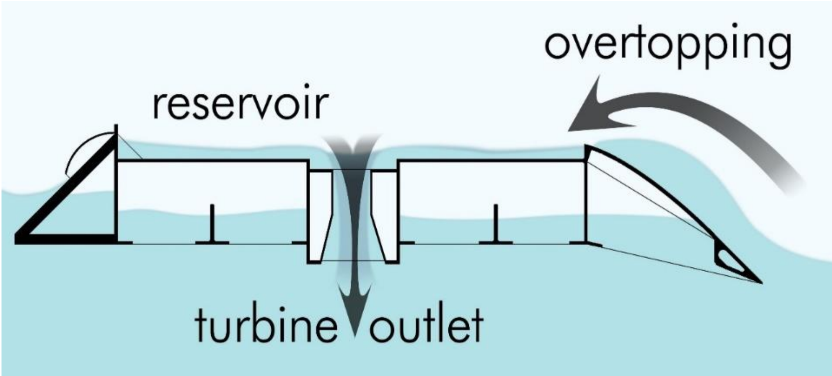


*Figure 29 Wave Dragon (24)*

## Appendix 1.8: AWS

AWS (Archimedes Waveswing) is a submerged wave power buoy designed to provide reliable and affordable power for maritime communities and offshore applications.

The system is suitable for deployment in water depths in excess of 25m and can be configured for ratings between 25kW and 250kW by selecting the appropriate scale [25].

*Figure 30 AWS [25]*

The technology was tested offshore Portugal in 2004 and narrowly missed a world first for delivery of offshore wave power to a national electricity grid, being beaten by Pelamis by some 6 weeks. Since that time, the Waveswing has been refined and developed to focus on customer needs in an emerging market.

In the middle of 2017 the company “AWS” intend to offer their 25kW Waveswing on a pre-commercial basis.

# Appendix 2: Wave types

## Appendix 2.1: Stokes 2nd Order Wave Theory (26)

Stokes wave is a non-linear and periodic surface wave on an inviscid fluid layer of constant mean depth. Stokes' wave theory is of direct practical use for waves on intermediate and deep water.

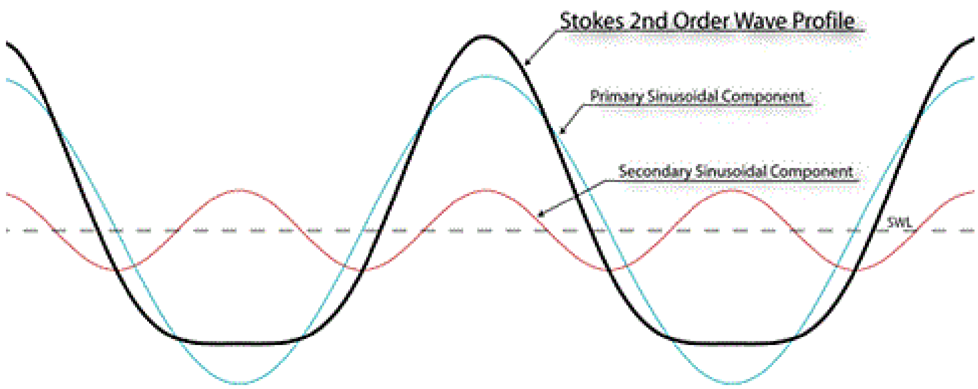


*Figure 31 Stokes Waves*

The surface elevation η and the velocity potential Φ are, according to Stokes' second-order theory of surface gravity waves on a fluid layer of mean depth h:

$$
\begin{aligned}
\eta(x,t) =& a \left\{ \cos\,\theta + ka\,\frac{3-\sigma^2}{4\,\sigma^3}\,\cos\,2\theta \right\} \\
& + \mathcal{O}\left((ka)^3\right), \\
\Phi(x,z,t) =& a\,\frac{\omega}{k}\,\frac{\cosh\,k(z+h)}{\sinh\,kh} \\
& \times \left\{ \sin\,\theta + ka\,\frac{3\cosh\,2k(z+h)}{8\,\sinh^3\,kh}\,\sin\,2\theta \right\} \\
& - (ka)^2\,\frac{1}{2\,\sinh\,2kh}\,\frac{g\,t}{k} + \mathcal{O}\left((ka)^3\right), \\
c =& \frac{\omega}{k} = \sqrt{\frac{g}{k}\,\sigma} + \mathcal{O}\left((ka)^2\right), \\
\sigma =& \tanh\,kh \quad \text{and} \quad \theta(x,t) = kx - \omega t.
\end{aligned}
$$

## Appendix 2.2: JONSWAP Wave (27)

The Jonswap wave spectrum can be used to describe a wave system where there is an imbalance of energy flow.

The JONSWAP spectrum is similar to the Pierson-Moskowitz spectrum except that waves continues to grow with distance (or time) as specified by the “a” term, and the peak in the spectrum is more pronounced, as specified by the “g” term. The latter turns out to be particularly important because it leads to enhanced non-linear interactions and a spectrum that changes in time according to the theory of Hasselmann 1966.

Parameterization of the classic form of the Jonswap spectrum (with parameters of fetch and wind speed) was undertaken by Houmb and Overvik (BOSS Trondheim 1976,Vol 1).These empirical parameters (which you must enter) are termed Gamma (γ), Alpha (α) and Peak Frequency (ωp) (the frequency at which the spectral energy is a maximum).The peak frequency together with empirical parameters termed Gamma and Alpha are used in this formulation

The spectral ordinate (S) at a frequency (ω) is given by:

$$S_j(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^r$$

$$r = exp\left[\frac{\left(\omega - \omega_p\right)^2}{2\sigma^2 {\omega_p}^2}\right]$$

Where α = a constant decided by Hs, ωp, and γ

g = acceleration due to gravity

ωp = peak frequency

γ = peak enhancement factor

In ANSYS AQWA, there are two types of JONSWAP: Jonswap (Hs); Jonswap (Alpha). If you choose Jonswap (Hs) as the Wave Type, Significant Wave Height will be used in the calculations rather than the parameter Alpha, (which is used when the Wave Type is set to Jonswap (Alpha)).

# Appendix 3: Three buoy study

## Appendix 3.1: Functioning

There are many ways to arrange and align the three buoys, in which they may be arranged in a straight line but in this case we won’t reach our goal. In which our main goal is to investigate in how the arrangement may affect the other buoys.

Finally after investigation and searching we reach to the main concept design of this section, by connecting or aligning the three buoys in a triangle form, by which one buoy takes the lead in front of the other two buoys.

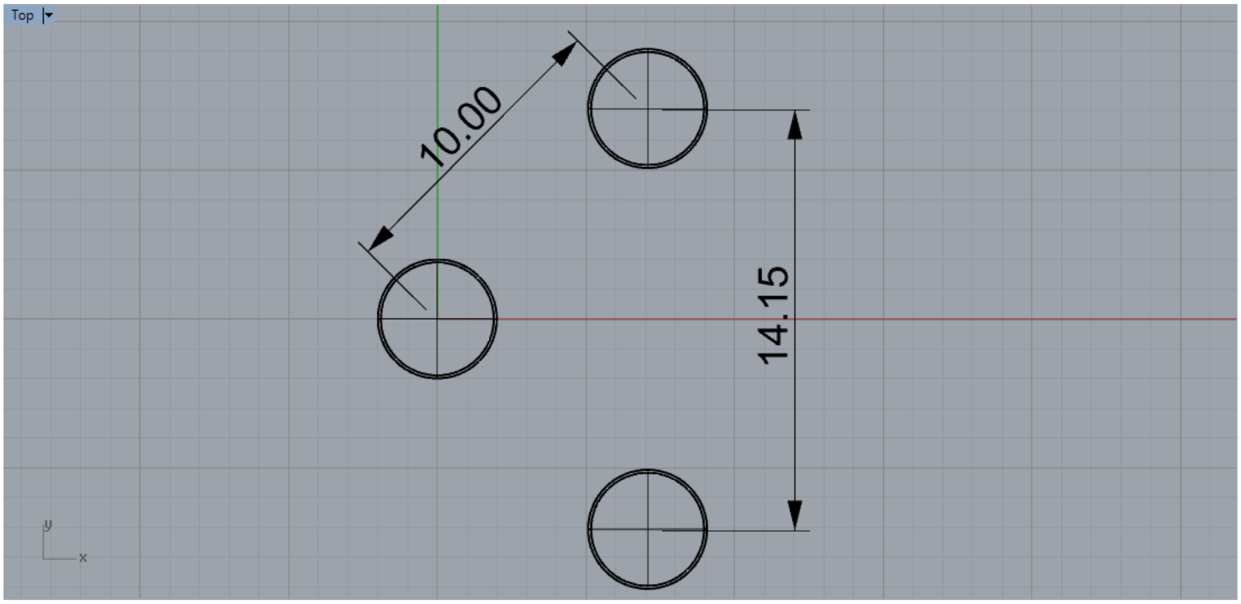


*Figure 32 three buoys*

Having three buoys arranged as seen in the previous may propose some changes in the outcome of the simulation, for example the first the buoy may affect on the wave propagation reaching the other two.

The generated wave power of the three wave energy converters can be transmitted onshore via an underwater power cable and then can be connected to the network.

## Appendix 3.2: Design

As explained in the previous case study, the buoy used here is the same as the one used before. But in this case we are going to add two more buoys, so in total three buoys.

The first buoy is in the plane (0,0,0) which means the center of the buoy is at the mentioned point,  it's in the lead and in the starting point. The second buoy is in the plane (7.071,7.071,0) which means the center of it behind the center of the first one by 7.071 meters and is moved 7.071 in direction of y-axis. The third and the last buoy is the same as the second but at the other side having the axis points at (7.071,-7.071,0). With this alignment the three buoy are forming a right angled triangle with two equal sides.

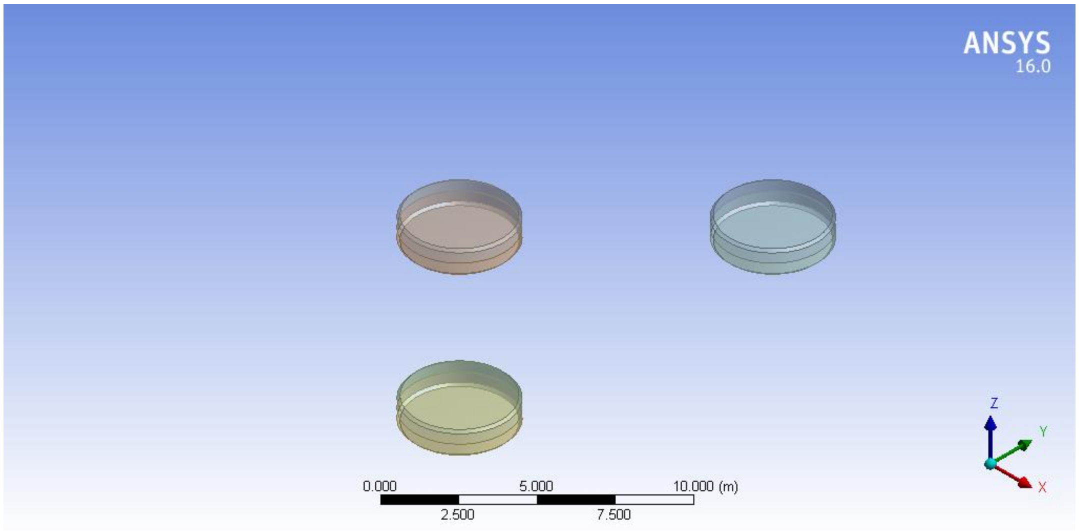


*Figure 33 Three buoys ANSYS*

The above picture is from ANSYS Design Modeler after the completion of the three buoys design which was achieved by dimensions mentioned in the following table:

*Table 6 Three buoys dimensions*

| Three Buoys | |
|---|---|
| **Plane** | XY ( 0,0,0) - (7.071,7.071,0) - (7.071,-7.071,0) |
| **Diameter/Width (m)** | 4 |
| **Length (m)** | 1 |
| **Surface Area ($m^2$)** | 36.201 |
| **Number of Bodies** | 2 |
| **Number of Faces** | 6 |
| **Number of Edges** | 6 |
| **Number of Vertices** | 0 |
| **Fluid/Solid** | Solid |

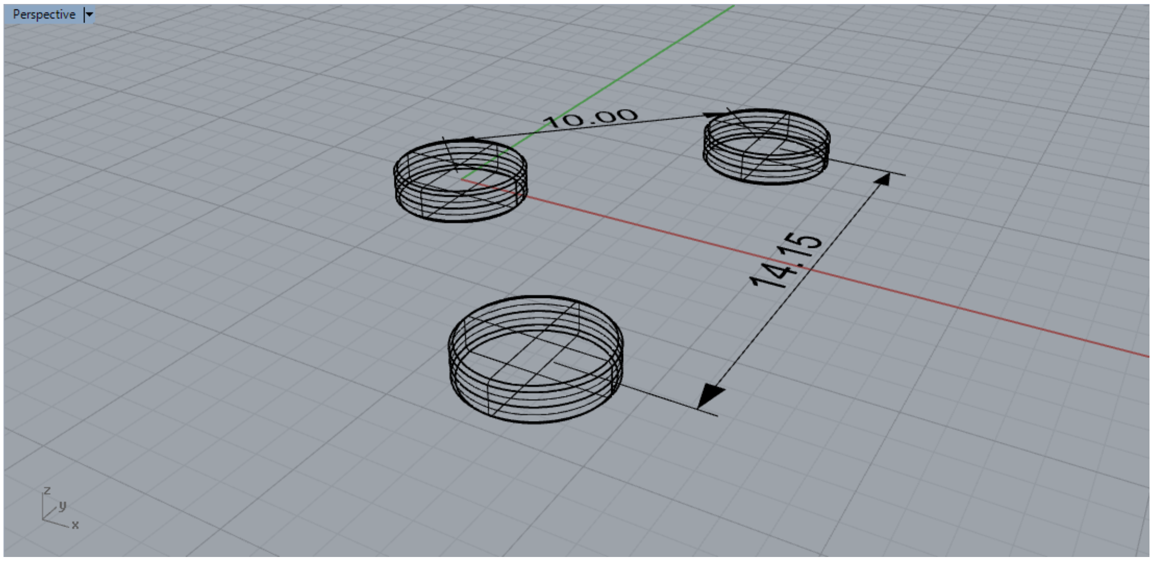


*Figure 34 spacing between buoys*

## Appendix 3.3: Simulation

### *Appendix 3.3.1: Mechanical (ANSYS)*

For starting the simulation we have to define the parameters of the environment. By defining the parameters of the sea depth and the simulation area dimensions.

*Table 7 Simulation environment*

| Three Buoys | |
|---|---|
| **Water Depth (m)** | 50 |
| **Water Density (kg/m³)** | 1025 |
| **Water Size X (m)** | 100 |
| **Water Size Y (m)** | 100 |

According to the above table, the simulation environment parameters are the same to the one of the buoy simulation as our goal is to maintain the same environment in both simulations, for the purpose of studying the main effect of one buoy on the other two.

Next, we will define the moments of inertia in the same way as defined before in the previous case study of the buoy, by the direct input of the moment of inertia values into the AQWA application using the same formulas.

The difference this time that we will have to introduce the moments of inertia three times. We have to set the structural mass of each body and then define the moment of inertia of each body separately, because each body has its own center of gravity.

*Table 8 Structural properties*

| Three Buoys |
|---|

| | |
|---|---|
| **Total Structural Mass** | 6700 |
| **X Position of COG** | 0 |
| **Y Position of COG** | 0 |
| **Z Position of COG** | -0.1 |
| **Structure Fixity** | Structure is free to move |
| **Ixx ($kg.m^2$)** | 7816.666667 |
| **Iyy ($kg.m^2$)** | 7816.666667 |
| **Izz ($kg.m^2$)** | 13400 |

Also, the same steps of the setting the linear cable mooring lines in the simulation. Connecting each buoy to a fixed point in a specific depth to act as our imaginary power takeoff device.

*Table 9 Cables and Joints*

| Three Buoys | |
|---|---|
| **Number of fixed points** | 3 |
| **Number of Connection points** | 3 |
| **Number of Joints** | 0 |
| **Number of Cables** | 3 |

We can now start our meshing as we have achieved setting all the needed settings and parameters to start the meshing and to choose the adequate mesh size.

Mesh size won't differ from the previous case study, the only difference will be in the number of nodes and number of elements. This difference is due to having three buoys, so the outcome number will be three times bigger than the previous case.

*Table 10 Mesh parameters*

| Three Buoys | |
|---|---|
| **Defeaturing Tolerance (m)** | 0.055 |
| **Max Element Size (m)** | 0.11 |
| **Max Allowed Frequency (Hz)** | 1.743 |
| **Number of Nodes** | 30888 |
| **Number of Elements** | 30882 |
| **Number of Diff Nodes** | 15732 |
| **Number of Diff Elements** | 15441 |

### *Appendix 3.3.1.1: Hydrodynamic Diffraction*

Moving on to the next which is the hydrodynamic diffraction analysis, the most important part is to include all the structures in the simulation. Meaning that we have to make sure to select all three buoys in the project.

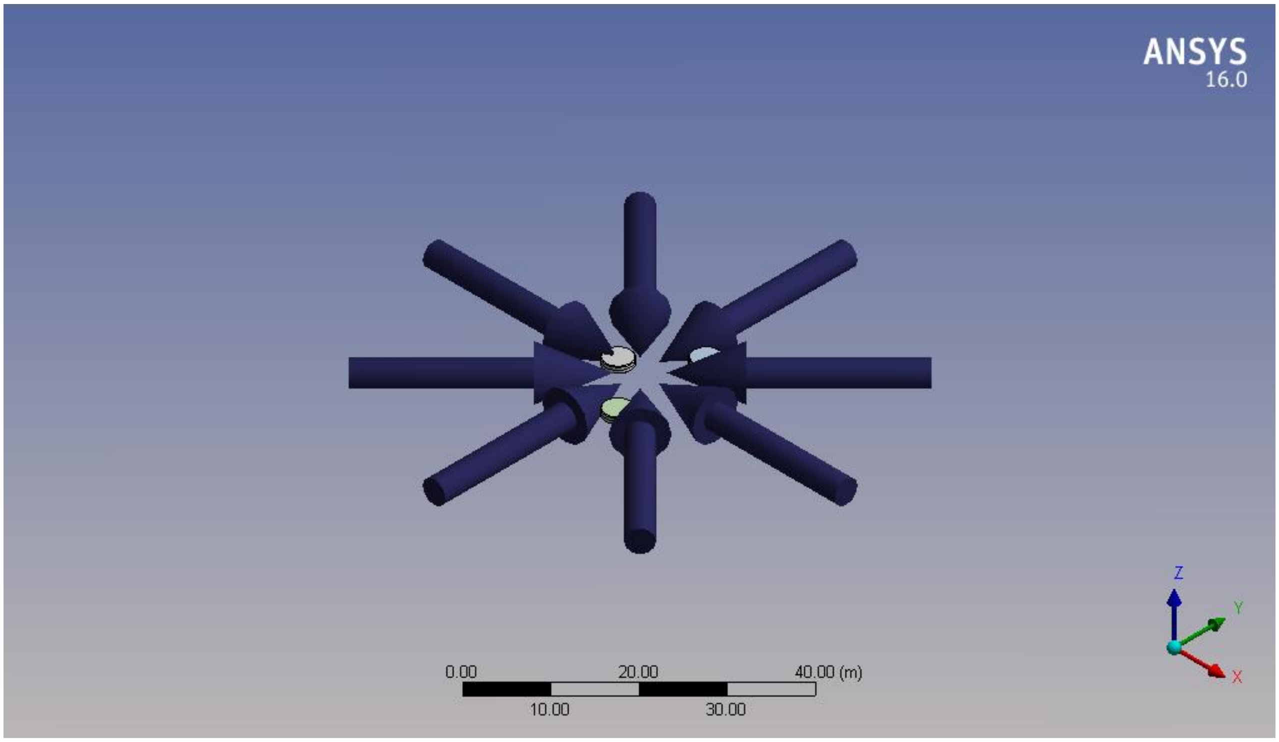


*Figure 35 Wave directions*

In the previous case study we mentioned that the direction won't matter as the buoy has a circular shape, but in this case it's important to choose the right direction as there is only one right direction.

Choosing the right direction depends on our goal, as our goal is to study the effect of the first buoy on the other two, so we will have to choose the direction were the wave meets the first buoy before the other two, which means the wave direction in this case is 0 degrees as seen in the following figure.

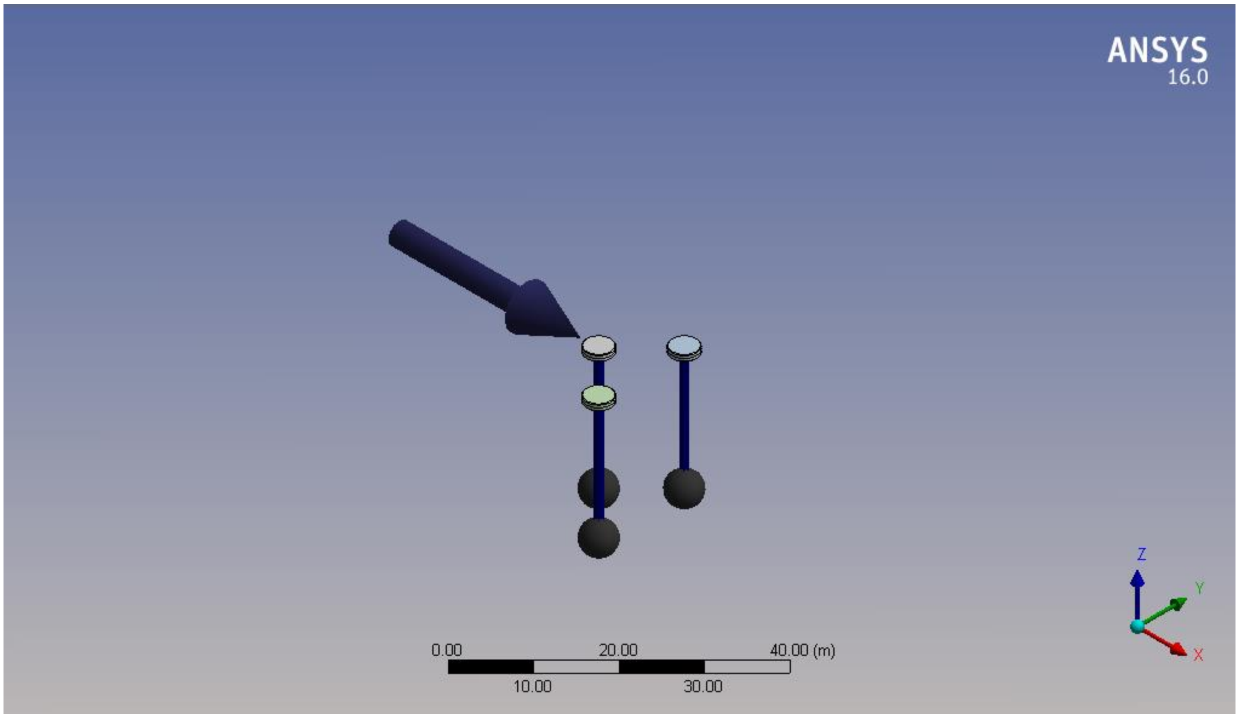


*Figure 36 Wave direction*

## *Appendix 3.3.1.2: Hydrodynamic Response*

In the previous case study we added two hydrodynamic time response analysis, to study the behavior of the buoy in the regular wave environment and the irregular wave environment. In this case we will also follow the same steps of the buoy simulation and maintain the same analysis settings and environment.

In our opinion choosing only the regular waves permits us to study the exact effect of one buoy on the others due to the uniformity of the waves and the uniformity of the sinusoidal graph. With this uniformity it will be easier to get the exact results and reach our main goal in this part of the thesis.

In the irregular wave environment it will help as assure results we will get from the regular wave analysis, irregular wave sinusoidal graph won't be uniform as seen before but will show us the slight difference between each and every buoy, meaning that will show us the effect of the first buoy on the other two, and the effect of the second on the third one and vice versa. A theory that won't be noticed in the regular wave environment.

The steps of configuring the analysis settings are the same in all case, it doesn't differ from the previous section. The values of the start time, duration and number of steps are equal to the previous case which will explained in the following table:

*Table 11 Analysis Properties*

| Three Buoys |
|---|

| | |
|---|---|
| **Analysis type** | Time Response Analysis |
| **Start Time (s)** | 0 |
| **Time Step (s)** | 0.1 |
| **Duration (s)** | 60 |
| **Number of Steps** | 601 |
| **Finish Time (s)** | 60 |

After setting all the analysis settings, now will have to set the wave inputs of the regular and irregular waves. Copying the same wave types and parameters from the previous simulation might be more helpful to get more accurate results.

The regular wave parameters will be as follows:

*Table 12 Regular wave*

| Three Buoys | |
|---|---|
| **Wave type** | Stokes 2nd Order Wave Theory |
| **Direction (Degree)** | 0 |
| **Amplitude (m)** | 0.5 |
| **Period (s)** | 2.5 |
| **Frequency (Hz)** | 0.4 |

And now introducing the irregular wave parameters as the last step before the full solve.

*Table 13 Irregular Wave*

| Three Buoys | |
|---|---|
| **Wave type** | JONSWAP (Hs) |
| **Significant Wave Height (m)** | 1 |
| **Gamma** | 3.31 |
| **Peak Frequency (Hz)** | 1.4 |
| **Start Frequency (Hz)** | 0.82051 |
| **Finish Frequency (Hz)** | 5.64018 |

It's recommendable from ANSYS to solve hydrostatics in the hydrodynamic diffraction analysis before applying a full solve on the entire project.

## Appendix 3.4: Results

Solving time of this simulation may take triple the time of the one buoy simulation, as the number of structure is tripled and the number of nodes of the mesh is tripled. The simulation took from 7 to 8 hours approximately.

Setting the direction 0 degrees as explained before, the same frequency and wave amplitude of the previous simulation to get the pressures and motions result graph.

*Table 14 Frequency*

| Three Buoys | |
|---|---|
| **Frequency (Hz)** | 0.497 |
| **Direction (Degree)** | 0 |
| **Incident Wave Amplitude (m)** | 0.5 |
| **Result Type** | Phase Angle |
| **Wave Position (Phase)** | 1 |

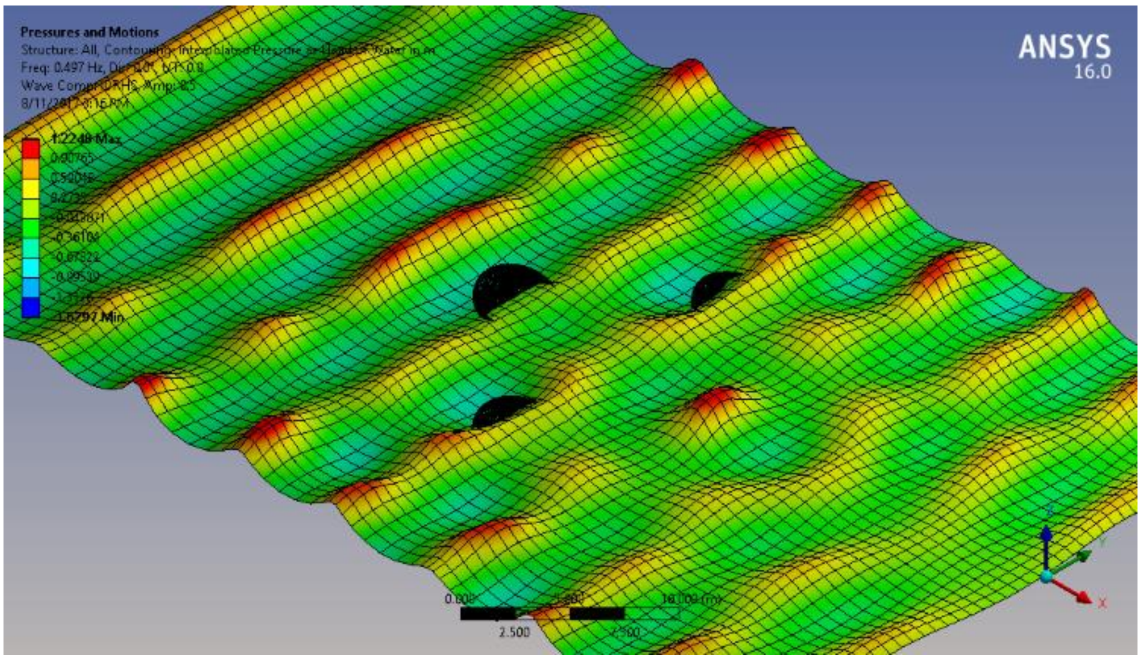


*Figure 37 Wave motion*

Above image from ANSYS solver, shows the pressures and motions at head of water, it may be noticed that the Buoy 2 and Buoy 3 are having the same position, and the wave form acting on Buoy 1 differs than that acting on Buoy 2 and Buoy 3.

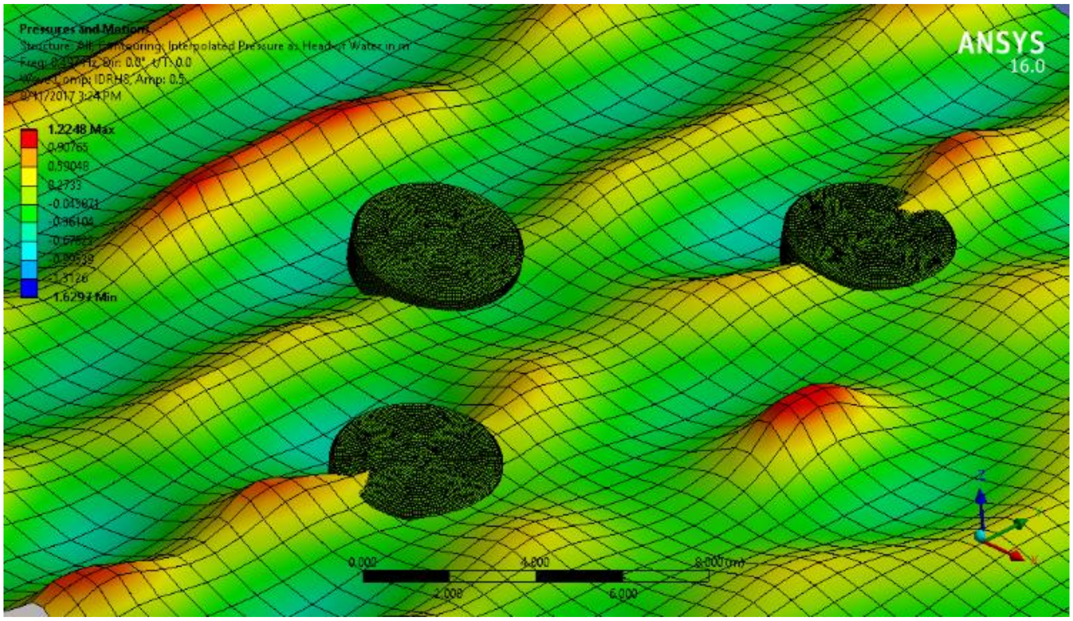


*Figure 38 Wave motion 2*

Another image from the same result and same plane but more focused on the buoys as to demonstrate the buoys position with respect to the waves.

Hydrodynamic time response analysis has two result files, starting with the regular wave simulation result. We will view the position of the three buoys in one graph, with each buoy curve has its own color as seen in the following graph:

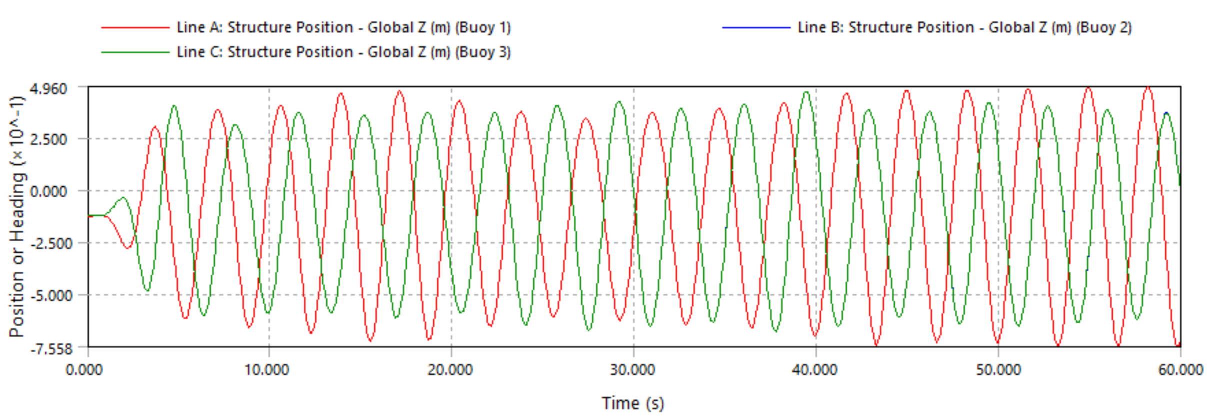


*Figure 39 Buoys position with regular wave*

The Red line corresponds to Buoy 1, the blue line corresponds to Buoy 2 and the green line to the third buoy. It may be noticed that only appears red and green line, the explanation to this is that the second and the third buoy share the same position as they are on the same plane, the same y and x axis. Which makes their reaction to the wave in the z-axis equal.

It's noticeable also that there is a difference between the position of buoy 1 and the other two, there is approximately a period difference between the two lines (red and green). This difference uniformly extends all through the simulation taking in account the uniformity of both lines

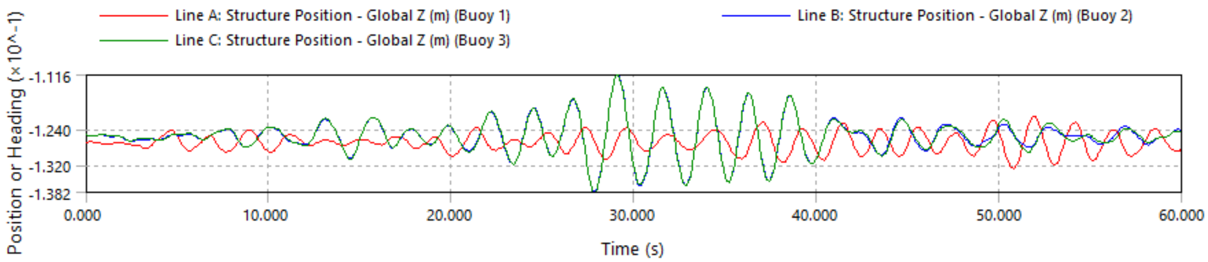


*Figure 40 Buoys position with irregular wave*

Next the irregular wave analysis result, as we can see in the above figure now the three lines can be seen. First, the comparison between the second and the third buoy or in other words the blue and the green line, there is a slight difference between these two lines in which it can be noticeable in some parts but in other parts it's not noticeable, this difference may be estimated in a 0.001 meter structure position at first, and between the 42 second and the 58 second this difference increases than the mentioned value and is very noticeable.

Second, the comparison between the first and the other two buoy, in the previous case was a uniform period difference and a uniform position difference, in this case there is a huge position difference between the first buoy and the other two, which can be explained as the first buoy affects on the wave propagation reaching the other two buoys and with the irregularity of waves this effect is increased leading to the position difference between the structures.

## Appendix 4: WEC-SIM Input File Code

### Appendix 4.1: Buoy Code

```
%% Simulation Data
simu = simulationClass();
simu.simMechanicsFile = 'Buoy2.slx';     % simMechanicsFile is case sensitive
simu.startTime = 0;
%simu.rampTime = 40;                      % Wave Ramp = 5T
simu.endTime= 160;                       % End Time = 20T
simu.dt = 0.001;                         % We recommend a WEC-Sim dt<T/100,
                                         % for PTO-Sim it needs to be even
smaller
simu.CITime = 10;                        % Specify CI Time [s]

%% Wave Information
% Regular Waves with convolution integtral calculation
waves = waveClass('regularCIC');         % Initialize waveClass and Specify
Type
```

```
waves.H = 2;                              % Wave Height [m]
waves.T = 8;                              % T, Wave Period [s]

%% Body Data
% Float
body(1) = bodyClass('ANALYSIS.h5');
body(1).geometryFile = 'buoy.stl';
body(1).mass = 'equilibrium';
body(1).momOfInertia = [7816.666667 7816.666667 13400];


%% PTO and Constraint Parameters
%% Floating (3DOF) Joint - This constraint was causing the error:
    % ['Buoy/Floating (3DOF)/CONSTRAINT (Planar Joint)']: 'Buoy/Floating
(3DOF)/CONSTRAINT
    % (Planar Joint)' has a degenerate mass distribution on its follower
side.
% You cannot have a joint and a contraint connected directly to one another,
% there must be a mass between

% constraint(1) = constraintClass('Constraint1'); % Initialize
constraintClass for Constraint1
% constraint(1).loc = [0 0 -12.5];                   % Constraint Location
[m]

%% Translational PTO
pto(1) = ptoClass('PTO1');                % Create PTO Variable and Set PTO
Name
pto(1).k = 0;                             % PTO Stiffness [N/m]
pto(1).c = 0;                             % PTO Damping [N/(m/s)]
pto(1).loc = [0 0 -12.5];                     % PTO Location [m]
```

## Appendix 4.2: Oyster Code

```
%% Simulation Data
simu = simulationClass();
simu.simMechanicsFile = 'oyster.slx'; % Specify Simulink Model File with PTO-
Sim
simu.startTime = 0;
%simu.rampTime = 100;
simu.endTime=400;
simu.dt = 0.01;
simu.CITime = 30;

%% Wave Information
%Irregular Waves using PM Spectrum
waves = waveClass('irregular');
waves.H = 2.5;
waves.T = 8;
waves.spectrumType = 'PM';
waves.randPreDefined=1;

%% Body Data
% Flap
body(1) = bodyClass('ANALYSIS.h5');
```

```
body(1).geometryFile = 'flap.stl';
body(1).mass = 127000;
body(1).momOfInertia = [1.85e6 1.85e6 1.85e6];
body(1).linearDamping = [0, 0, 0, 0, 1*10^7, 0];    % Specify damping on body

% Base
body(2) = bodyClass('ANALYSIS.h5');
body(2).geometryFile = 'base.stl';
body(2).mass = 'fixed';

%% PTO and Constraint Parameters
% Fixed Constraint
constraint(1)= constraintClass('Constraint1');
constraint(1).loc = [0 0 -10];

% Rotational PTO
pto(1) = ptoClass('PTO1');                        % Initialize ptoClass for
PTO1
pto(1).k = 0;                                     % PTO Stiffness Coeff
[Nm/rad]
pto(1).c = 0;                                     % PTO Damping Coeff [Nsm/rad]
pto(1).loc = [0 0 -8.9];
```

## Appendix 4.3: Pelamis Code

```
%% Simulation Data
simu = simulationClass();
simu.simMechanicsFile = 'pelamis.slx'; %Location of Simulink Model File with
PTO-Sim
simu.startTime = 0;
%simu.rampTime = 100;
simu.endTime=180;
simu.dt = 0.001;
simu.CITime = 10;

%% Wave Information
%Irregular Waves using PM Spectrum
waves = waveClass('regular');
waves.H = 2;
waves.T = 8;
%waves.spectrumType = 'JS';
waves.waveDir = -180;
%waves.randPreDefined=1;

%% Body Data
% Float
body(1) = bodyClass('ANALYSIS.h5');
body(1).geometryFile = 'pelamis.stl';
body(1).mass = 155000;
body(1).momOfInertia = [11743671.88 11743671.88 237343.75];

% Spar/Plate
body(2) = bodyClass('ANALYSIS.h5');
body(2).geometryFile = 'pelamis.stl';
body(2).mass = 155000;
```

```
body(2).momOfInertia = [11743671.88 11743671.88 237343.75];

%% PTO and Constraint Parameters
% Floating (3DOF) Joint
constraint(1) = constraintClass('Constraint1');
constraint(1).loc = [15 0 0];

% Translational PTO
pto(1) = ptoClass('PTO1');              % Initialize PTO Class for PTO1
pto(1).k = 0;                           % PTO Stiffness [N/m]
pto(1).c = 0;                           % PTO Damping [N/(m/s)]
pto(1).loc = [15 0 0];                   % PTO Location [m]
```

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