EXPERIMENT AND SIMULATION BASED SELECTION OF OSCILLATING BUOYS FOR RACK & PINION POWER TAKE-OFF WAVE ENERGY CONVERTORS

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Thesis submitted in partial fulfilment of the requirements for the
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ABSTRACT

Wave Energy Converters (WECs) are explored on finding solutions to the energy sector as a renewable energy source for electricity and trying to convert the immense power available with ocean waves in the most efficient way. Many researches have been undertaken to improve varieties of WECs. However researchers have paid less attention towards the improvements of Rack & Pinion Power Take-off (PTO) WECs. Oscillating buoys are the most important part in most of the mechanical WECs which are used to absorb initial power from ocean waves. The aim of this thesis is to select the best performing oscillating buoys for Rack and Pinion PTO WECs by fulfilling the three objectives: (1) To identify Oscillating buoys suitable for Rack and Pinion PTO WECs, (2) To carry out simulation analysis to select the best performing oscillating buoys for Rack and Pinion PTO WECs, and (3) To conduct experimental analysis to select the best performing oscillating buoys for Rack and Pinion PTO WECs. The DMAIC (Define, Measure, Analyse, Improve & Control) cycle was used as the basis for the methodology. Six buoy types were selected based on the commonly available other types of WECs and this thesis focussed on simulation & experimental analysis to select the best performing oscillating buoys for Rack and Pinion PTO WECs. Simulations of all buoys were carried out with the help of Computational Fluid Dynamics (CFD) software X-Flow and three parameters, namely: Static Pressure, Vorticity & Liquid Phase, which were compared with each other. Proto type Rack and Pinion PTO WEC with regular wave making facility in a testing tank and six types of buoys in equal weight with the height to width ratio as 1 were fabricated and experimental testing were undertaken by creating four different wave heights for each buoy. Simulation and experimental results were analysed carefully and the best performing buoys for the proto type model of oscillating buoy operated, Rack & pinion PTO WEC were selected.

Key Words: ***Wave Energy Converter, Oscillating Buoy, Power Take-Off, Simulation, Experimental Analysis and Optimization***

TABLE OF CONTENTS Page

LIST OF FIGURES Page

LIST OF TABLES **Page**

LIST OF ABBREVIATIONS

Abbreviation	**Description**
CAD	Computer Aided Design
CCD	Coastal Conservation Department
CEB	Ceylon Electricity Board
CFD	Computational Fluid Dynamics
LCOE	Levelised Cost of Energy
LHI	Lanka Hydraulic Institute Ltd
NWW	Noaa Wave Watch
OWC	Oscillating Water/Wave Column
PTO	Power Take Off
RAO	Response Amplitude Operator
RPM	Revolutions per Minute
UK	United Kingdom
WCD	Wave Converting Devices
WEC	Wave Energy Converter

1. INTRODUCTION

1.1 Content of the Research Work

While searching for comforts, the entire world is moving forward with new sophisticated technology. At present, electricity is the mostly and widely used energizing source of systems. Nothing could beat the point that functioning of the entire world would stop if there happens to be an electricity failure, as almost all the major requirements of mankind such as industries, communication, transportation etc. now depend upon electricity. But, the question is, whether the world has enough electricity to fulfil the demand, and even if we have whether it is economical and environment friendly. In Sri Lanka 58% of the country's electricity requirement is fulfilled by hydroelectricity, including both the main hydro power plants and the mini hydro power plants and 2% of the requirement is fulfilled by renewable energy sources such as wind [1]. But the problem is, the rest of the 40% of requirement is generated by thermal power plants which cause negative impacts on both the environment and the economy of the country. Apart from that, fossil fuel, crude oil, natural gases and coal are energy resources, but they are non-renewable. Therefore, the usage of these fuels is limited in quantity. Though proposals are being made for nuclear power plants, Sri Lanka is yet to start such projects mainly due to its requirement of huge investments and technology which Third World developing countries like Sri Lanka do not possess [1] to achieve them easily.

There are many on-going researches in various countries in order to develop several renewable energy power plants such as the Plamis Wave Farm which uses wave energy to generate electricity [2]. These methods are basically called Wave Energy Converters (WEC) which are capable of contributing considerably towards the global electricity demand with no cost for fuel. Therefore, being an island surrounded by the Indian Ocean it is very beneficial to use WEC around Sri Lanka. Implementation of these project with developments by continuous researches, will lead to the reduction of environment pollution and expansion of job opportunities. Furthermore, WEC will help to reduce the usage of non-renewable power sources which are currently being used in Sri Lanka and it will directly help the economy of the country as a Third World developing country. Unfortunately, though the country enjoys this renewable energy resource, Sri Lanka has tried it yet. Therefore, it is required to introduce the WEC technology to Sri Lanka. Mr. Amarasekara [3] has clearly proven that the use of WEC in Sri Lanka's national grid is very beneficial. However, the available sources of information are limited, since this is a new technology as far as Sri Lanka is concerned. But, a pre-feasibility study has been carried out on this technology with the available information [3] by proving the fact that the generation of a considerable amount of energy is possible with the available wave energy around Sri Lanka.

Oscillating buoy is used to collect the energy in the sea and there by this buoy oscillates up and down. In most cases this oscillating buoy is used to build point absorber type wave energy convertors. As a renewable energy product, the wave energy concept is economical than other concepts. The WEC is designed so that it can be easily installed and maintained along the coast line. With reference to the literature survey, it was observed that the researchers have given very less consideration for mechanical type power take-off wave energy converters. The mechanical method which is used in this analysis is the rack and pinion method to transmit power generated by waves to the shaft through the oscillating buoys which cause the linear movement in upward and downward directions which are subsequently converted into a rotational motion at the end shaft which will then be utilized in generating electricity. Further, only very few researches have been completed for selecting the best performing oscillating power buoys for different categories of wave energy converters except the rack and pinion type power take-off wave energy convertor. Therefore, the scope of this thesis will cover the design and analysis of six types of oscillating buoys and select the best performing buoys for rack and pinion power take-off wave energy convertor based on simulation and experimental analysis.

1.2 Aim and Objectives

1.2.1 Aim

To select the best performing oscillating buoys for Rack and Pinion Power Take-off Wave Energy Convertors.

1.2.2 Objectives

a. To identify Oscillating buoys which are suitable for Rack and Pinion Power Take-off Wave Energy Convertors

b. To carryout simulation analysis to select the best performing oscillating buoys for Rack and Pinion Power Take-off Wave Energy Convertors.

c. To conduct experimental analysis to select the best performing oscillating buoys for Rack and Pinion Power Take-off Wave Energy Convertors.

1.3 Methodology

The Literature Survey was done by referring to research papers, journals, relevant books and articles to find out various relevant information and system specifications relevant to the topic. The study was conducted by an experimental analysis with the help of six types of fabricated buoys and proto type Rack and Pinion Power Take-off Wave Energy Convertor, and a simulation analysis using Computational Fluid Dynamics simulation software. Six types of buoys were selected based on commonly available buoys in different categories of point absorber type wave energy convertors and commonly used buoys by other researchers for performance analysis. Analysing systems, components and parameters of the simulation study and the experimental study were undertaken with the assistance of all facilities available in the Sri Lanka Navy. Assistance was obtained from a few researchers who had conducted similar analysis related to wave energy convertors and their performances in various aspects. The intention of this whole project is to find solutions and implement them practically based on the DMAIC cycle. The philosophy of the DMAIC cycle is the development of a process/product while eliminating defects through prevention and process improvement. The project purpose and scope will be defined in the Define phase.

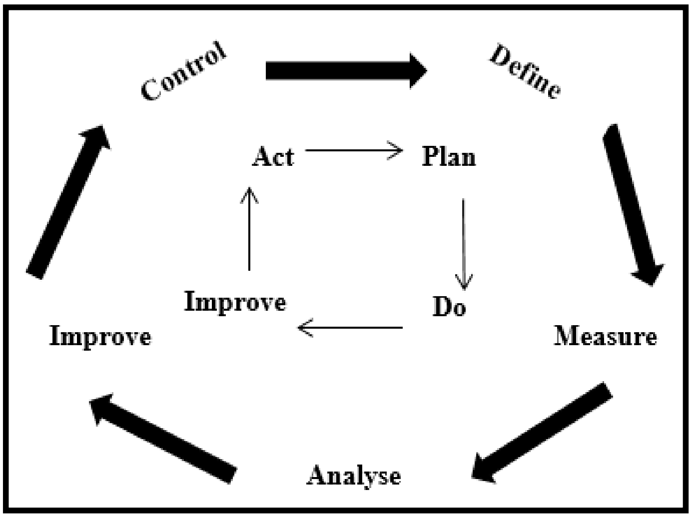


Figure 1.1: DMAIC Cycle

During the measuring phase, measuring the essential parameters of different categories which are required to carry out the experimental analysis by utilising Rack and Pinion Power Take-off Wave Energy Convertor and tabulating relevant data by commencing the simulation of buoys have been completed to focus on the achievement of the aim. Further, the measuring of the varieties of data was carried out to its utmost condition by changing the different operating conditions.

During the analysis phase, collected data on the experimental testing and the simulation were analysed to find the best performing buoys. During the improvement phase, the best performing buoys were selected for efficient functioning of the Rack and Pinion Power Take-off Wave Energy Convertor and successes/drawbacks will be discussed. During the Controlling as the last phase, the successful findings from the research work were discussed to implement this pilot project into actual practice by using efficient and effective buoys.

1.4 Introduction to Chapters

Chapter 2 explains the Literature Review done for this research and it covers the different types of wave energy convertors, power take-off methods, design and hydrodynamic characteristics of wave energy convertors and buoys and performance evaluation of different types of wave energy convertors and buoys. Chapter 3 describes the Theoretical Background and includes buoys interaction in a coordinated system, wave equations, power in waves, energy efficiency concepts, hydrodynamic forces acting on buoys and control methods in energy absorption. Fabrication of Proto Type Wave Energy Convertor and Buoys are covered in Chapter 4 and it explains the fabrication of a supportive structure and fitted components, wave generating tank and six types of buoys which are attached with the Rack and Pinion Power Take-off Wave Energy Convertor. Chapter 5 describes the Analysis and Results and includes the graphic representation of data gathered from simulation of buoys and experimental testing. Finally, the best performing buoys are selected based on the simulation and experimental analysis. Chapter 6, 7 and 8 respectively cover the Discussion, Conclusion and Future Works.

2. LITERATURE REVIEW

2.1. Types of Wave Energy Convertors

Wave energy converters can be classified into three categories and presently there are many varieties around the world depending on the concepts and designs. [4].

2.1.1 Attenuator

Attenuator structure is oriented parallel to the wave, and this is called as a linear absorber. The structure is composed of multiple sections in pitch and yaw components connected together into one continuous arrangement. Finally, a hydraulic turbine or a generator is used to generate electricity by using the above motion and pressurizing the hydraulic piston unit.

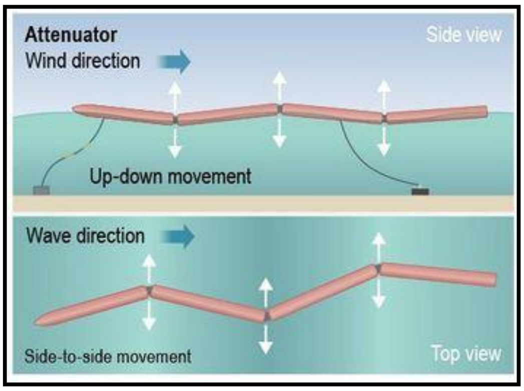


Figure 2.1: Attenuator WEC [5]

2.1.2 Point Absorber

This device is manufactured with small dimensions compared to the wave length of the incident wave. A point absorber depends on the pressure differential and will work as a floating arrangement or bottom mounted structure. This operates in the heaving up and down motion on the water surface or submerged condition. This does not depend on the wave direction due to the small size of the structure. Power buoy technology is one of the point absorbers which is used presently to fabricate wave energy converters.

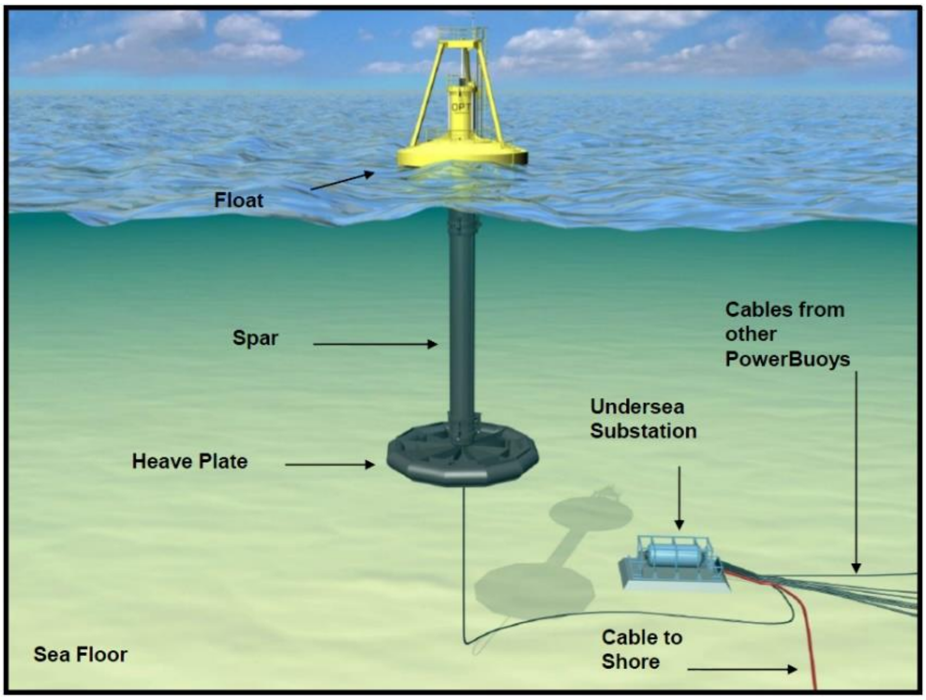


Figure 2.2: Point Absorber WEC [5]

2.1.3 Terminator

A terminator is also a WEC and mostly fitted perpendicular to the wave direction. This comprises two sections, and one part of the terminator stays stationary while the other part moves as a response to the incident waves. The Stationary component is fitted to the sea bed or shore and it does not move when compared to the moving part. The moving part works like a piston and pressurizes air or oil to drive a turbine.

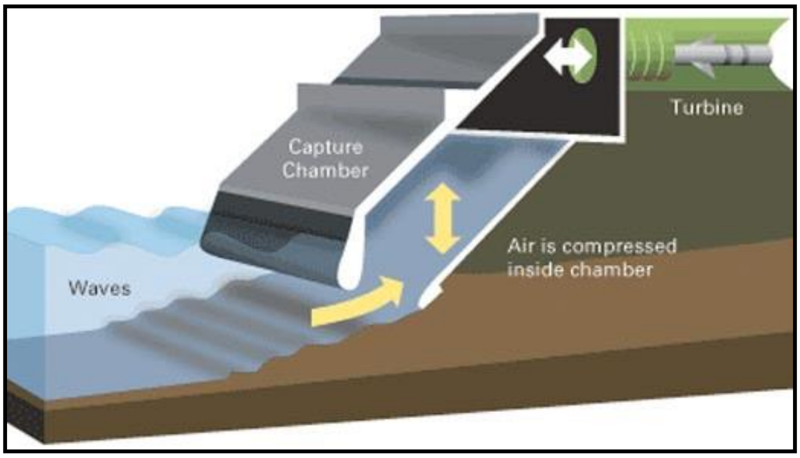


Figure 2.3: Terminator WEC [6]

An overtopping device is also called a terminator device and it collects water into a reservoir from the rising incident waves. This water passes through an opening in the middle of the device and it drives a turbine while passing through this opening.

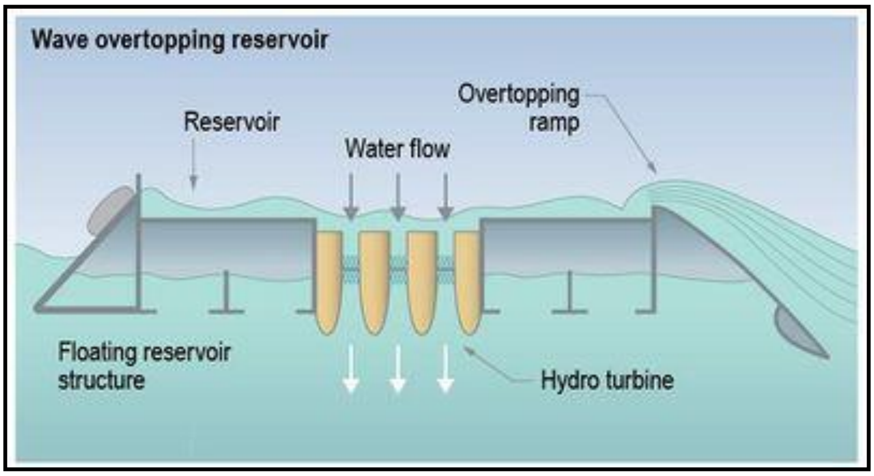


Figure 2.4: Overtopping Device [7]

2.2 Regions Where Wave Energy Converters are Sited

The Regions where Wave Energy Converters can be installed are categorized into three regions [4]. Selecting a place to install the wave energy converter is the most important point because the performance and efficiency of the output totally depends on the region selected to install a particular WEC.

2.2.1 Offshore

It is generally corresponding to deep waters, typically greater than 50m. Because of the water depths involved most offshore WECs are moored floating devices. Increasing the depth of the sea is proportional to the energy of the wave.

2.2.2 Near Shore

While strict boundaries for the Near Shore do not exist, this region is generally considered to have water depths between 10 and 25 metres. Due to the shallow or intermediate water depths in this region the few WECs that occupy such locations tend to be mounted on the seabed rather than being moored.

2.2.3 Shore Line

These areas are sited on the land and typically operate in water depths of less than 10 metres. These shore based devices generally make use of the local topography to form the main body of the converter.

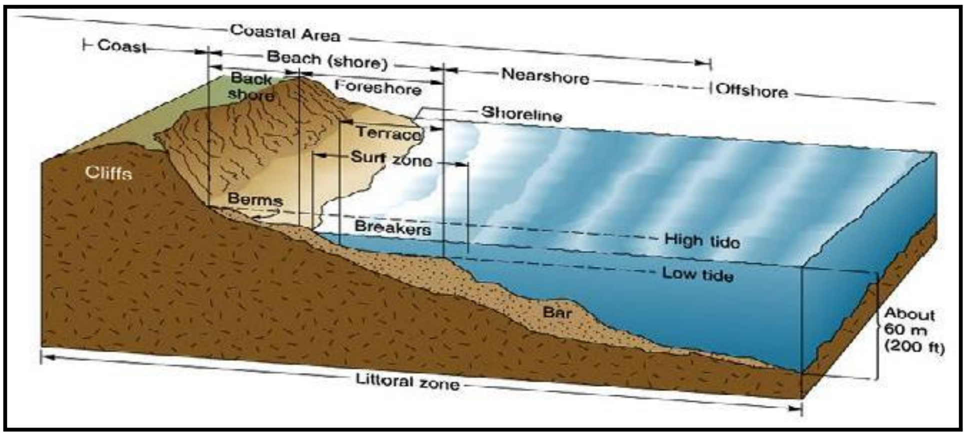


Figure 2.5: Shore Levels [5]

2.3 Power Take Off (PTO) methods

Initially the energy of the incident waves are absorbed by the primary converter and then it is transformed into electrical energy. Power-Off (PTO) methods are used for the above purpose. The PTO system is the most important part of a WEC and the correct selection of a PTO system will affect the efficiency of the wave power absorption and how accurately it converts into electricity. Furthermore, the selection of a PTO system has to be done while paying attention to good structural stability, the correct size and mass. An enclosed chamber is used as a primary convertor in many of the WECs [8].

2.3.1 Electrical Method

In the electrical method, mostly synchronous generators are used with approximate constant speed and ensuring that the frequency is the same as the grid connection to generate electricity in WECs. However, generators with different speeds are utilized depending on the converting concept. The primary convertor of a PTO system transforms the wave energy into mechanical energy and then transfers directly into linear electrical generator which ends up as electrical energy. This concept of electricity generating method has further developed with the development of power electronics and with the discovery of the permanent magnet concept. Alternate polarity magnets are coupled to a buoy in this method of PTO system. A heaving motion is created by the buoy with the interaction of the coming incident waves and electrical current is induced in the stationary part of the linear electrical generator, which is the starter of the generator equipped with coils.

2.3.2 Mechanical Method

Mostly wave energy converters which are equipped with oscillating water column and overtopping device are connected with this method. Initially these mechanical type PTO systems are connected with the oscillating body and the oscillating body interacts with the incident waves which capture the wave energy. This mechanical arrangement is directly connected to drive a rotary electrical generator. Normally these systems comprise a gear box, pulleys and cables. Further, a flywheel is connected to the systems which are in turn incorporated with a rotary motion to store excess energy which thus ensures a smooth operation of the WEC. The best example for this type of mechanical method is the buoy operated rack and pinion power take-off wave energy converter which is facilitated with a ratchet system.

2.3.3 Hydraulic Method

The hydraulic method is used in WECs with oscillating motions of the body dealing with large forces at low frequencies. Hydraulic systems are best suitable methods to absorb wave energy in waves with large forces moving with slow speeds. Normally conventional rotary electrical generators cannot be used in the systems where the wave energy absorbing mechanism comprises a movement of a body which interacts with the incident waves. For example, in some point absorbers and attenuators, it is not efficient to use normal rotary electrical generators directly coupled with the system and the best suitable method is hydraulic operated mechanisms which will act as the interface of converting wave energy into electrical energy. The movement of the body after interacting with the incident waves, transport the pressurized hydraulic to drive the hydraulic motor which in turn operates the generator.

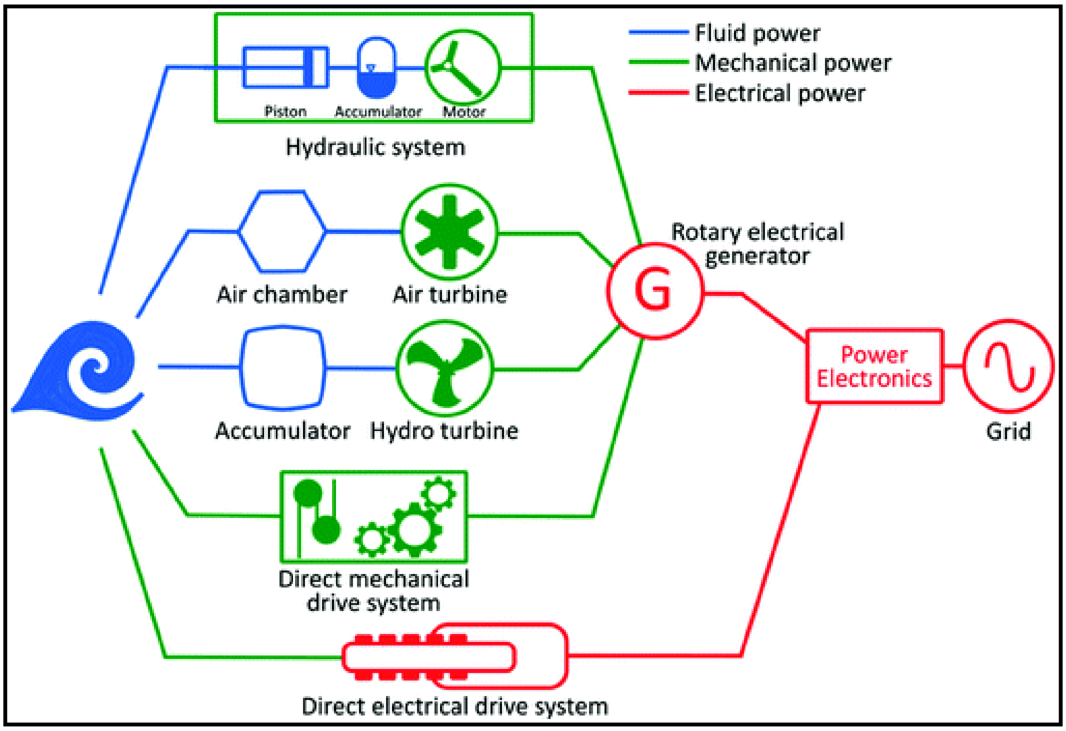


Figure 2.6: Power Take off (PTO) methods [8]

2.4 Modes of Operation

The wave energy converters could be further categorised based on the different modes of the operations of wave energy converters.

2.4.1 Submerged Pressure Differential

A submerged point absorber is used in this method and this submerged pressure differential method incorporates the pressure difference on top of the arrangement between the wave crest and troughs. Normally these are fitted on the sea bed closer to shore.

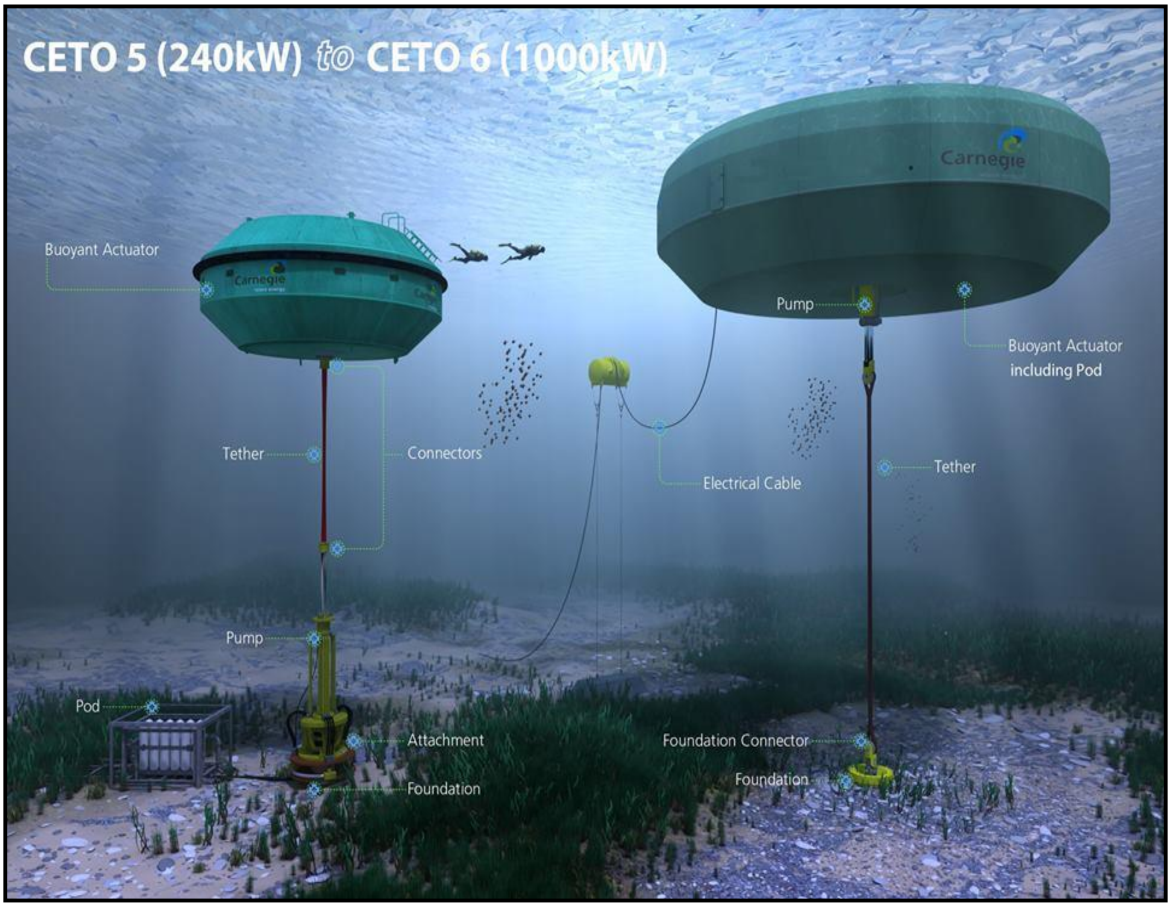


Figure 2.7: Submerge Pressure Differential Device [8]

2.4.2 Oscillating Wave Surge Converter

This type of converter is fitted to a deflector which is hinged at the bottom and placed in a perpendicular direction against the incident waves. With the interaction of the velocity of horizontal particle of the waves, this arrangement will move back and forth.

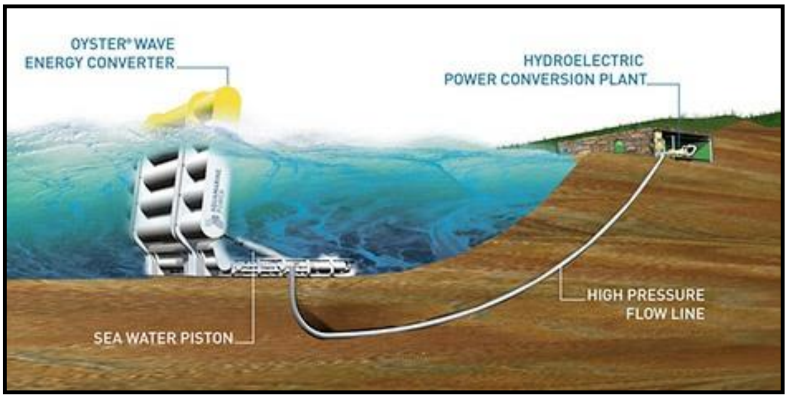


Figure 2.8: Oscillating Wave Surge Converter [8]

2.4.3 Oscillating Water Column

In this method, a water column is used inside the chamber of the WEC to move trapped air upward like a piston moving in the cylinder and increases the air pressure inside the chamber. This pressurised air is used to drive a turbine to generate electricity. While the water column is moving down, the air will be drawn from the atmosphere through the turbine unit which ensures continuous rotation of the turbine and ultimately production of electricity throughout the operation. In both conditions, the turbine should rotate in a single direction and the low pressure wells turbine is the most appropriate unit.

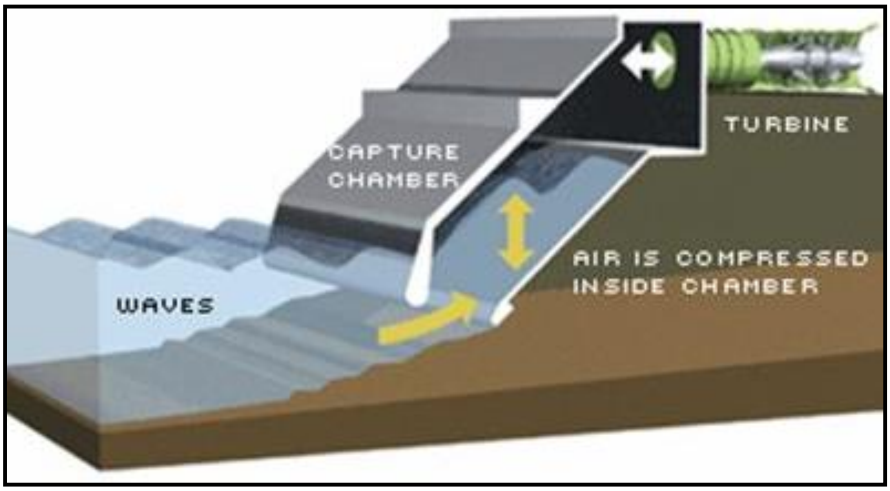


Figure 2.9: Oscillating Water Column [6]

2.5 Wave Energy Conversion Techniques

Many wave energy converting concepts were patented during the past years in America, Japan and Europe. Large numbers of new concepts are explored by the researchers. Normally these concepts are divided mainly considering the location of installation and the type of WEC.

2.5.1 Method of Oscillating Water Column (OWC)

Normally the OWC consists of a chamber which is built near the shoreline coast. Installation of WECs near shore facilitates easy maintenance and it is profitable as there are not many under water cables or mooring arrangements. This type of device consists of a partly submerged steel or concrete dam. The motion of the sea wave pushes air through the turbine or impeller. Again, sea wave returns to the sea while the air pushes down through the turbine or impeller. However, the turbine has been designed to rotate in the same direction. In 1976 Alan A. Wells introduced the axial flow wells turbine (1924 – 2005) for use in this method.

2.5.2 Method of Oscillating Power Buoy (OPB)

Oscillating body is used to collect the energy in the sea and thereby this buoy oscillates up and down. In most cases this oscillating buoy is used to point absorbers. Most of the systems use this power buoy connected with linear generator and taking as power take off method. By combining these two existing methods energy of the waves can be enhanced and electricity can be produced. As a renewable energy product the wave energy concept is economical than other concepts. The WEC is designed so that it can be installed along the coast line for easy installation and maintenance.

2.6 Power Take-off Systems for wave energy converters

Amelie Tetu and two editors [8] of this section of Ocean engineering and oceanography explained many varieties of PTO systems, controlling methods of these systems, the criticality of operating of PTO systems and how different PTO systems are connected with WECs. Construction of WECs directly uplifts the annual energy production and efficiency of those will depend on the correct selection of the PTO system for the particular WEC. Initial cost of the WEC and the maintenance cost are the main concerns while selecting suitable WEC with an efficient PTO system. It is of paramount importance to select a trouble free and reliable PTO system to achieve cost effective operation. Figure 2.9 shows the PTO efficiency and reduction in PTO cost (%) against the Levelised Cost Of Energy (LCoE) [8].

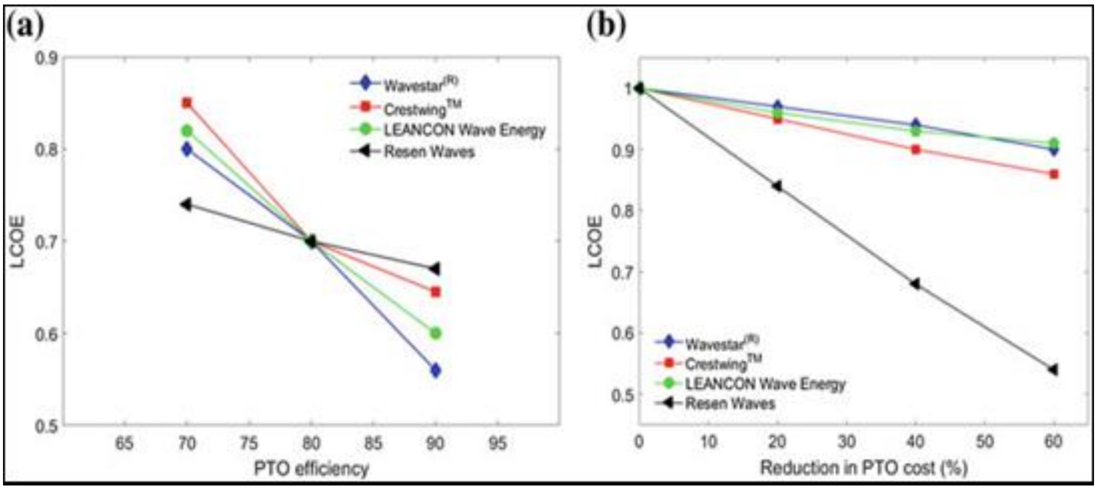


Figure 2.10: PTO Efficiency and Cost [8]

There are three main power take off methods used in WECs. They are mechanical power, electrical power and fluid power. In the oscillating water column PTO method of WECs, air turbines are mostly used to convert wave energy into electrical energy. When incident waves reach this type of PTO system then the oscillating water column in the chamber creates oscillating air pressure which drives the turbine. The criticality of the operation is that the turbine operation is in bi-directional in the WEC. One way is to use a conventional turbine with a non-return valve. However, this method is not cost effective due to high maintenance cost and the size of the non-return valve involved in the unit. A self-rectifying air turbine is the next option and this enables the turbine to rotate in unidirectional for both operation modes. Many varieties of self-rectifying turbines were explored during the recent past and many researchers are still in the process of finding trouble-free and efficient PTO system for WECs. The main three categories of self-rectifying turbines are as follows:

a. Wells type turbine
b. Impulse turbine
c. Dennis-Auld turbine

Efficiency comparison of the aforementioned three categories of self-rectifying turbines when faced with irregular flow of incident waves is shown in Figure 2.11 below.

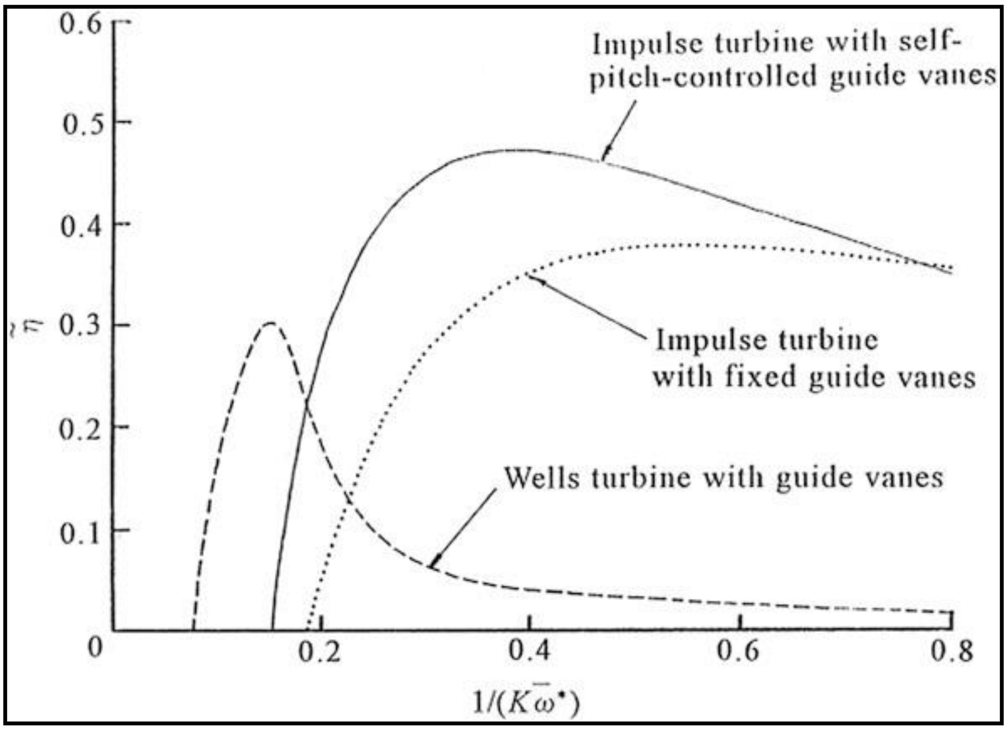


Figure 2.11: Different self-rectifying efficiency [8]

Normally the optimum control can be categorized as reactive control, since part of the energy is returned to the sea during a very low fraction of time interval of the oscillating cycle. This is a major consequence of using an optimum control technique. To widen the frequency band of operating WECs, it is required to use reactive control techniques around the natural frequency of a particular WEC. When the submerged sphere heaves with optimum level, the absorbed power from given sinusoidal wave technique were compared under different control strategies and explained in Figure 2.12.

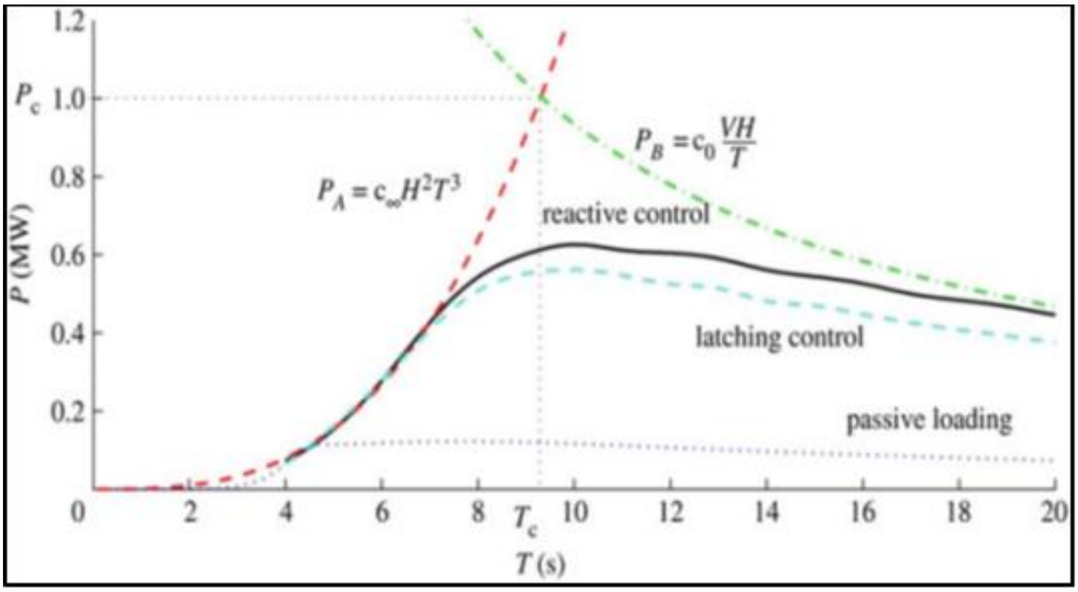


Figure 2.12: Control Strategies [8]

2.7 Model Study of a Pendulum type Wave Energy Converter to utilize Wave Energy around Sri Lanka

Gunawaradane and his team [15] have developed a WEC in Sri Lanka. According to them, Sri Lanka being an island, it is very useful to use wave energy convertors. But Sri Lanka has a low wave energy density oceanic climate. High performing WECs with good hydrodynamic characteristics should be developed, to capture the maximum amount from the waves. The economic feasibility of this type of sustainable energy plant is related to the construction costs. Therefore, by considering those factors, they have modified an existing method of WECs. And any sustainable system should be ecologically viable and economically feasible and socially accepted.

By considering the above factors they have developed the following WEC as a model. The “pendulum” device had been first invented in Japan. The device consists of a flap hanged inside a caisson which faces the ocean waves (See Figure 2.13). The flap is operated by motion of horizontal water particle of the waves. Standing waves were directed towards the device which is a composition of the superposition of many incident waves and waves which were reflected from the back wall. A rotary vane pump is driven by this pendulum and it drives an oil motor which in turn drives a generator.

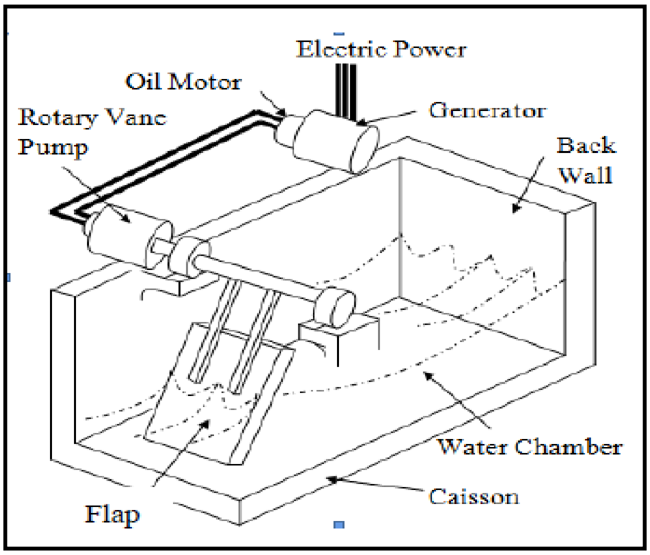


Figure 2.93: Caisson [15]

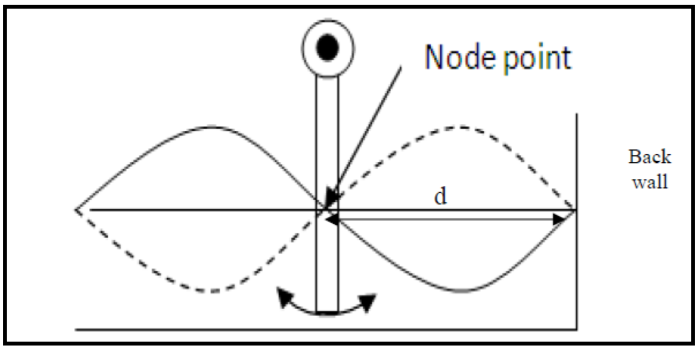


Figure 2.14: Node point [15]

The flap is kept at the node point of standing waves (See Figure 2.14), and the water particles are fully horizontal. The node point is away from the distance d from the back wall. Where d = λ/4 for a wave inside a straight caisson, (λ = wave length). Therefore, the chamber length depends on the wave length. With the oceanic climate of Sri Lanka, the swell wave length is around 100m and according to that, the node point will occur 25m before the back wall.

Therefore, it required a lengthy Caisson. Then they have done a modification to Caisson to reduce the node point length from the back wall as shown in Figure 2.15.

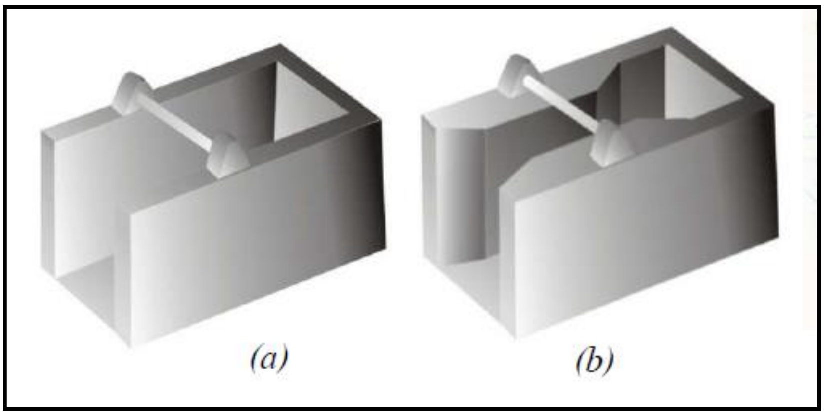


Figure 2.15: Modification to caisson [15]

(“(a)” is the previous Caisson and “(b)” is the modified Caisson.)

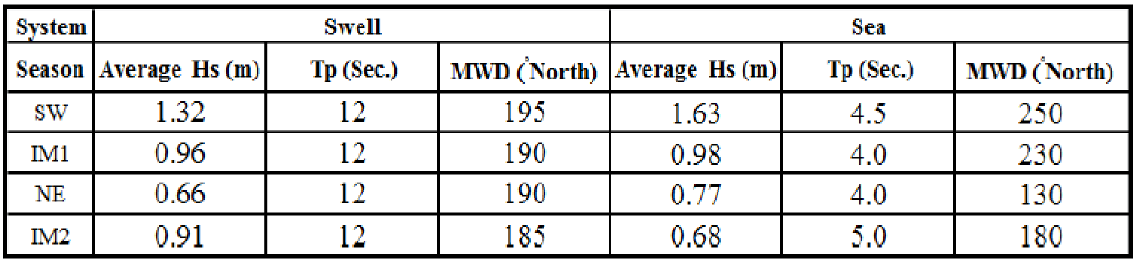
2.8 Assessment of near shore wave climate in southern coast of Sri Lanka

Ranasinghe and his partner [16] have done a study on the wave climate of the southern coast area. According to them, the reasons for a good energetic wave climate is, the availability of swell waves approaching from a southerly direction and sea waves mainly influenced by monsoonal weather pattern and occasionally vulnerable for cyclonic wave conditions [16]. With the diversity of wave patterns being heavy, it should clearly filter. But due to lack of data recordings, the assessment of wave climate had been limited to some extent. Therefore, they have done a mathematical simulation based on limited data available and they have done a study on wave propagation from offshore to near shore with the use of mathematical equations. A numerical model was developed by considering the wave energy conservation equation and the model of “Battjes” and “Jonssen (1978)”. That model was capable of simulating propagation of waves from offshore to near shore.

2.8.1 Wave data availability

Since the 1980s wave measurements were taken in the southern coast and this was done by the Coastal Engineering Research Centre of the Coast Conservation Department, currently known as Lanka Hydraulic Institute Ltd (LHI). Initially the measurements have been taken by a device called Wave Rider Buoy which is only capable of measuring the wave height but not the direction of the flow. Later the directional wave data have been collected by the German Technical Assistance Programme on the request of the Coast Conservation Department in 1989 [16]. As per their simulation, they obtained the following results for wave climate around Galle.

Table 2.1: Wave Climatic Data [16]



System	Swell			Sea		
Season	Average Hs (m)	Tp (Sec.)	MWD (°North)	Average Hs (m)	Tp (Sec.)	MWD (°North)
SW	1.32	12	195	1.63	4.5	250
IM1	0.96	12	190	0.98	4.0	230
NE	0.66	12	190	0.77	4.0	130
IM2	0.91	12	185	0.68	5.0	180

2.9 A pre-feasibility Study on Ocean Wave Power Generation for Southern Coast of Sri Lanka

Amarasekara and his team [3] have said that global environmental deterioration has occurred during the past years and that is based on excessive consumption of energy sources such as fossil fuel, crude oil and coal. As a result, people have been forced to use clean and renewable energy sources such as hydro, solar, wind, waves, biomass and geothermal. Among these renewable sources, the hydro, wind and solar power generation technology is at its peak development point whereas sources such as wave, tidal and biomass power generation are relatively immature. [17] [18].

Thought the utilization of wave energy resources have long a history dating back to 1799, recorded practical utilization of wave energy was in 1910 by Bochaux-Praceique [19]. By this paper, they have done a study on suitable methods for wave climates and electrical feasibility. To investigate a most suitable place, long term measurements related to wave climates are required. Due to unavailability of such data, they have used wind data, which is an alternative way of predicting the wave climate. Apart from that, they have investigated the geographical position of Sri Lanka and the weather condition throughout the year. Therefore, since we have open sea towards the south and subjected to both monsoons, they have predicted the southern coast as the most energetic coast around Sri Lanka [20].

As mentioned above, Sri Lanka has only a limited data. Amerasekara has found the directional wave climate study done by the CCD-GTZ Coast Conservation Project in the southern coast area and those few data were also limited to some locations only. With that research they have obtained wave climatic data of the southern coast. According to CCD-

GTZ data, moderately high waves are common along the south to south west coast throughout the year [21]. Specific wave climatic data are required to estimate the wave characteristics for a proposed site and due to the absence of such data they have use alternative ways to simulate the wave climate by using NWWIII (Noaa Wave Watch III) [22]. This model required wind and ocean depth, and minimum depth of 25m deep sea approximation have been used [23]. Then, data has been modelled for every three hours from 1997 to 2006. With that process, they have calculated the significant wave height, the peak periods and wind strengths. The variation of seasonal wave height data and peak periods data with time are shown in Figure 2.16 and Figure 2.17.

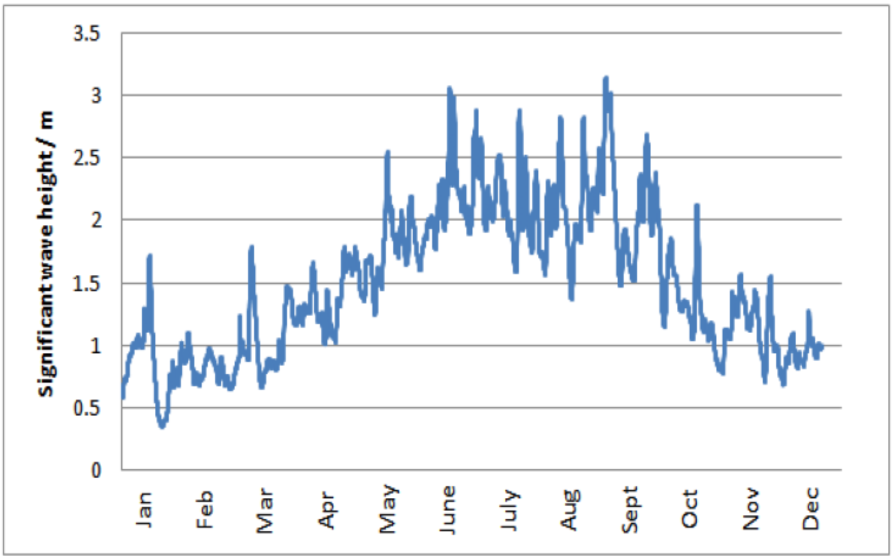


Figure 2.16: Wave height vs Time [3]

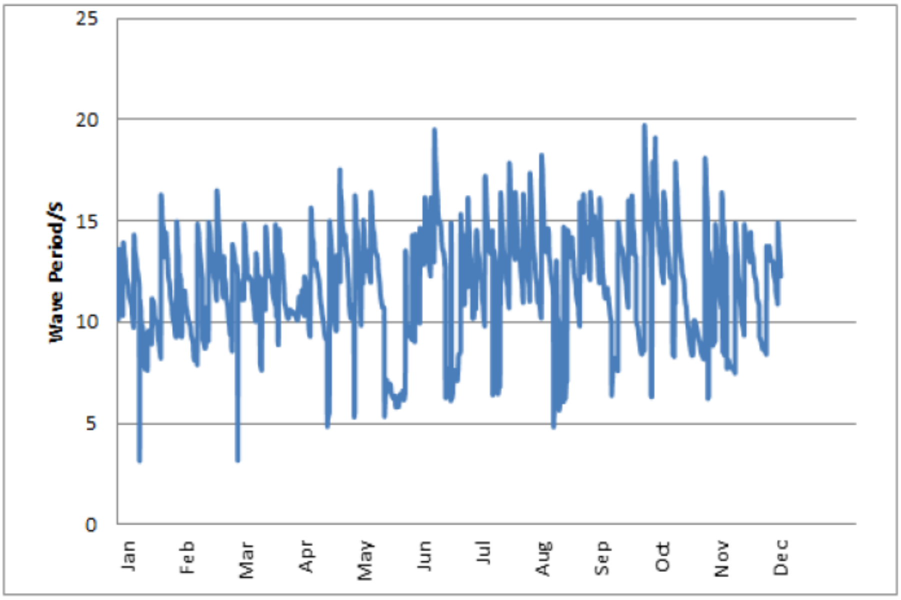


Figure 2.17: Wave Periods [3]

2.9.1 Suitable WECs for Sri Lanka

Around the world, the wave characteristics change from region to region. Therefore, as per the wave climate around Sri Lanka, most of the tropical seawater has an average power level below 20kW/m [24]. Because of that, it is essential to have more efficient methods to have an economically viable power plant.

2.9.2 Oscillating Wave Column Method

OWCs are the world's most widely researched and tested method of WECs [25] and there are many operating practical power stations at present. This method use sea water waves to pressurize the air trapped inside a chamber, allowing it to pass through a uni-directional air turbine (Wells turbine). However, due to low efficiency in energy conversion in the air turbine, these types of plants are not suitable for low energetic waves.

2.9.3 Oscillating Bodies

These are mainly of two types, namely swing flaps or heaving buoys. These WECs are much more capable of converting energy due to the use of mechanical systems to generate electricity. In the heaving buoy method, the buoy will go up and down with the incident wave. But, in Pendulum, it swings with the wave. In both cases, a hydraulic system is used for the PTO system, since it has the ability to store energy as hydraulic pressure. Though the energy of the waves is less in near shore than that of offshore waves, it has inherent maintenance simplicity as a promising aspect and also lesser initial investments are required.

2.9.4 Electrical Feasibility

According to the Ceylon Electricity Board and the power utility of Sri Lanka, CEB allows maximum of 10MW grid connection power under a distributed generation category to the 33kV network. If someone contributes more than 10MW, then they have to connect to the 132kV or 220kV network which is not cost effective for a wave energy convertor. Therefore, it is restricted to a maximum of 10MW output from a single power station. The following graph shows how the power outputs vary with the time.

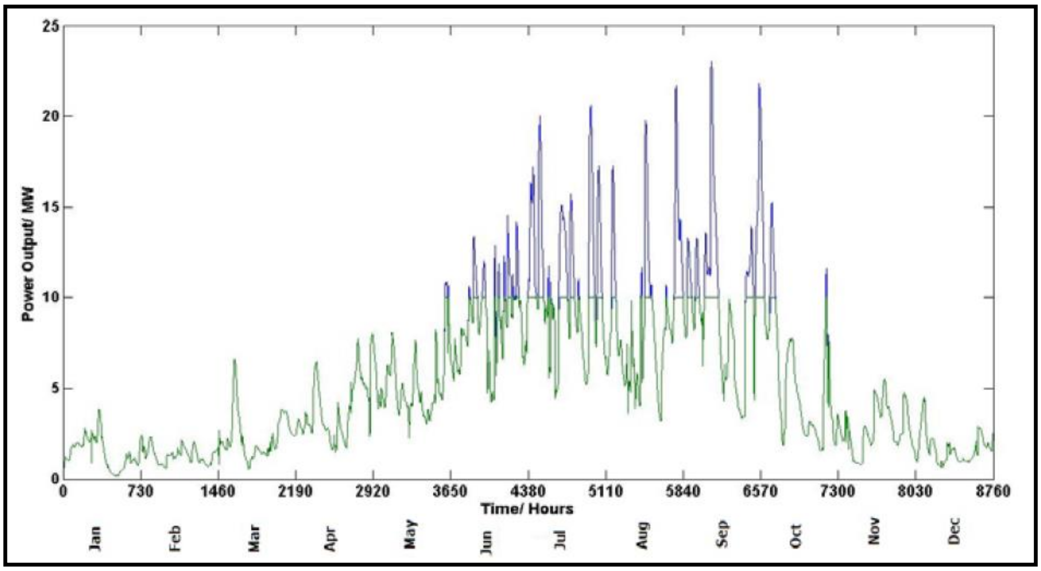


Figure 2.18: Power Output vs Time [3]

In this study, they have only concentrated on long term wave power fluctuations. But in order to do more precise short term power fluctuations, more precise wave data is essential, which are not available at present. Therefore, a study on more precise data is required prior to implementing a project to address the issue of voltage flicker and voltage sag. While giving due consideration to the above factors, they have proposed six different places which have minimum voltage fluctuations and situated along the CEB transmission and distribution network.

Figure 2.19: Proposed Sites [3]

2.9.5 Social and Environmental concerns

Prior to implementing such a project, it is required to carry out an assessment on the impact on social, environment, marine biology, water pollution and land uses. Selecting a suitable site should be done by considering all the above factors and it may not meet the exact requirements. But, it is necessary to minimise the negative impacts and also justify the importance of implementing such a project over the negative impacts.

2.9.6 Final Results

Their study has proved that 10MW Wave Energy Power Plants can be implemented and they have also suggested the sites. Finally, it is recommended and proposed to carry out a few studies prior to the implementation of such a project.

a. Wave climate of site throughout the year
b. Environment and social assessment around site area

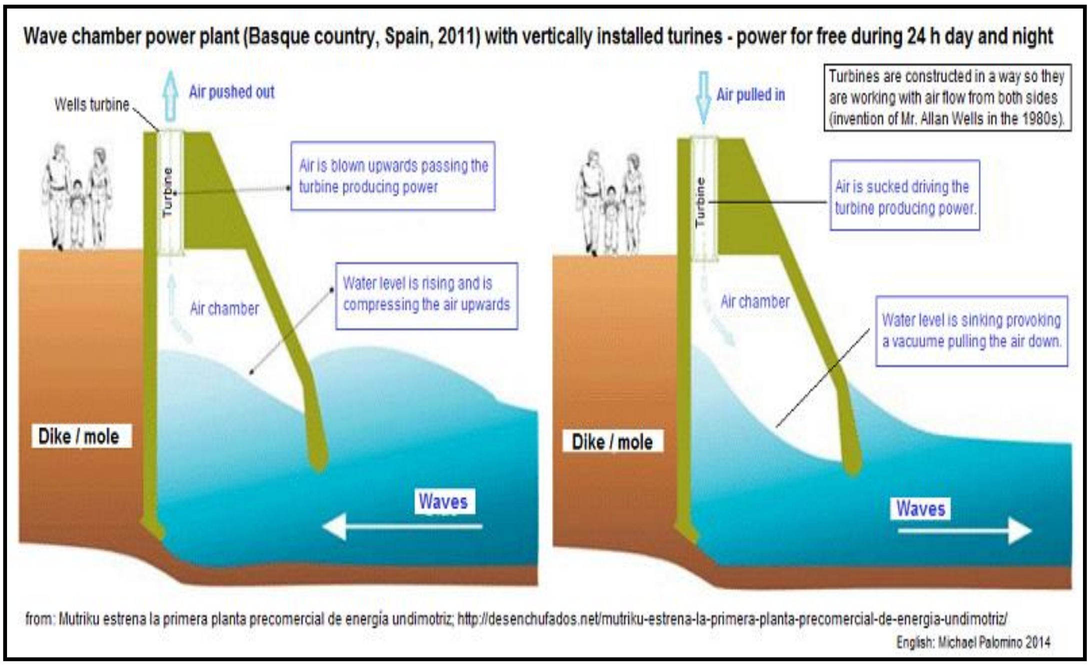
2.10 Design considerations for a WEC for Sri Lankan coast

Before undertaking any WEC projects, it is essential to study the previous methods and which are currently used in the world and implement the best unit which is most suitable for the country. For example, the method of oscillating water column which is used in the Spain wave energy chamber in Mutriku, Basque port. [30]

Figure 2.20: Wave Chamber Power Plant [32]

Mutriku harbor is located in the Bay of Biscay in Spain. Because of the strong storms, the boats were damaged and hence the government constructed the breakwater project to protect the boats. After that, the government proposed to construct the wave energy converting plant to use the breakwater and after examining several methods, the government finally selected the OWC method because of its simple and non-disruptive design [31]. Construction of the Mutriku plant covers the area alongside the pier with a distance of 100m at the outer wall of the breakwater. It has 16 chambers within the sea wall. A hollow structure of trapezium shape was constructed for the plant. A submerged underwater front opening has been built at the structure of the plant. Each chamber has one turbine which is operated only with air. When waves enter the chamber, the air pushes up and drives the turbines. Also, when the waves recede [33], the air sucked out through the turbine rotates the turbines. The turbines connected to the turbo generator add an average annual production of 600,000 kWh of electricity to Spain's energy grid. This plant enables to protect the harbour and also produces power. Also, sea water never enters the system, thus reducing the maintenance cost of the plant.

Figure 2.21: Basque harbour, Spain [34]



Wave chamber power plant (Basque country, Spain, 2011) with vertically installed turines - power for free during 24 h day and night

Turbines are constructed in a way so they are working with air flow from both sides (invention of Mr. Allan Wells in the 1980s).

Air is blown upwards passing the turbine producing power

Water level is rising and is compressing the air upwards

Air is sucked driving the turbine producing power.

Water level is sinking provoking a vacuume pulling the air down.

from: Mutriku estrena la primera planta precomercial de energía undimotriz; http://desenchufados.net/mutriku-estrena-la-primera-planta-precomercial-de-energia-undimotriz/
English: Michael Palomino 2014

Figure 2.22: Wave Chamber Power Plant [34]

The next example is the German technology company which developed the wave energy converter. The module installed at the end of the breakwater wall of the Heraklion’s port at Crete in Greece [35] has a floating body which moves up and down according to the motion of the waves. Individual models were connected through the generator unit and electricity is generated when the floating buoys move up and down through the generator unit. By using a series of units, the complete grid will generate the electricity.

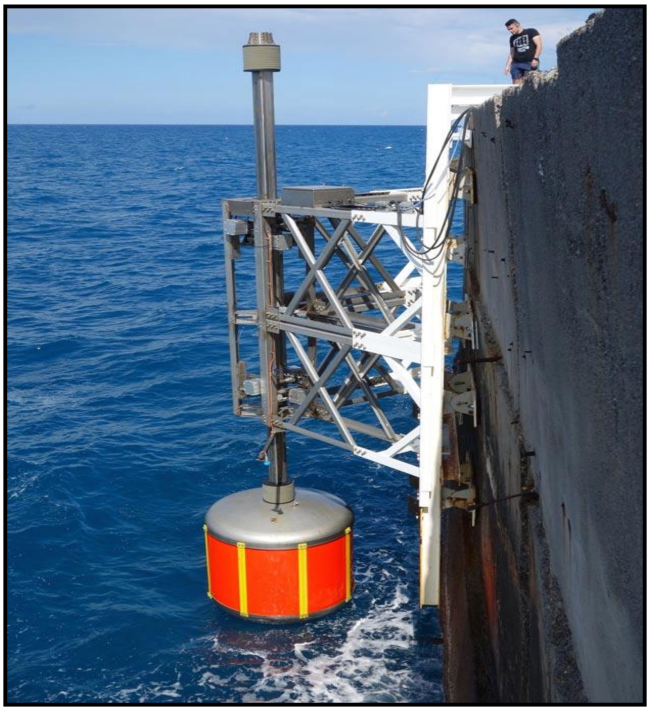


Figure 2.23: SINN power team testing buoy with linear generator [35]

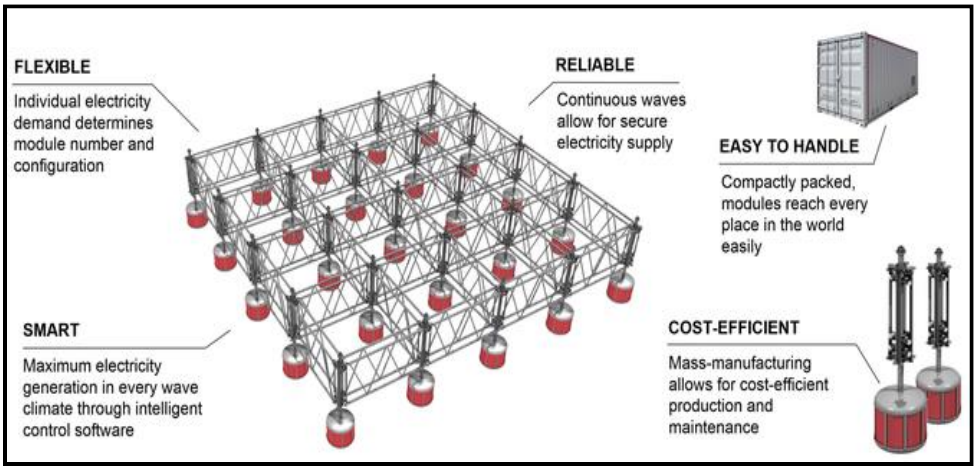


Figure 2.24: SINN power project [36]

2.11 Performance evaluation of wave energy converters

To generate power commercially and more accurately with efficient WECs, it is essential to develop the existing standards and guidelines into more common, transparent, robust and with less restriction for any development stage of existing WEC and newly discovered concepts related to WECs [26]. In this research, firstly, it is mentioned how the development stages of a WEC are continuing up to the level of commercialization. For that, they mainly considered the proof of concept which is planned to verify and prove the working of the model. The design and feasibility study are usually done, including structural or hydrodynamic numerical investigations, functional prototype to testing, demonstration to commercialization by in near shore and giving due consideration to economic aspects. Then the data of wave climates are analysed for significant wave weight **(H_s)** and energy period **(T_e)** in four locations related to Western Europe. Next, it is required to look for the sea states selection and, for that they used BilliaCroo at EMEC and scatter diagrams and wave contribution diagrams were used to represent the data. Then they carried out tank testing and sea trials to assess the performances. From tank testing, they analysed the hydrodynamic behaviour of the body which interacted with the waves, the performance of the PTO system in non-dimensional nature and changes of the scaling ratio on **η** for selected waves for small to large devices. For the sea trials, varieties of subsets of performance data were formed and those subsets were selected based on the abundance of performance data, area of coverage on the scatter diagram and performance data zoning. Finally, the end results gave the efficient PTO methods by using the calculations.

2.12 The Performance of a Wave Energy Converter in Shallow Water

This paper investigates the power capture of a point absorber-type wave energy converter moving in surge/pitch when in deep and shallow water [27]. Significant interest was attained in recent developments of WECs due to hydrodynamic stability and the performance of point absorbers. If WEC is mounted in near shore location, then the cost involvements and power losses can be decreased [28] due to low costs of installation and maintenance; a shorter distance from the harbour to device reduces travelling time and increases plant availability by utilization of smaller weather windows for repair and maintenance [29]. Surge wave force on small bodies are analysed by using effect of water depth on horizontal water particle motion and comparison of approximation with surge wave force ratio for a hemisphere. Effect of water depth on incident wave power was analysed by reduction in incident wave power from the 40 meter contour to the 10 meter contour influenced by the incident wave power for the Islay data set. The combined effect of an increase in the wave force and a reduction in incident wave power can be investigated by comparing the predicted power capture of a nominal surface-piercing flap-type WEC when deployed in deep (h = 50m) and shallow (h = 12m) water and analyses data relative performance of a flap-type WEC in deep and shallow water, effect of water depth on optimum amplitude of motion in deep and shallow water, effect of water depth on optimum damping coefficient motion in deep and shallow water, power capture of a flap-type WEC with a reduced drag coefficient in deep and shallow water, power capture of a flap-type WEC with complex conjugate control in deep and shallow water, relative performance of a flap-type WEC with a 50% wave power loss between deep and shallow water.

2.13 Hydrodynamic characteristics of buoy

As per the reviewed papers, it was found that there were various factors to be considered before developing suitable and efficient WECs. In the article by Hui Liang and his team [10] they have done their research on selecting and optimization of the buoy. In their research they have addressed the other optimize process such as the PTO system. But in Ke Sun's research they have done optimization on the PTO system of the WECs. When referring to both researches together we can have 60th optimized buoy and PTO system.

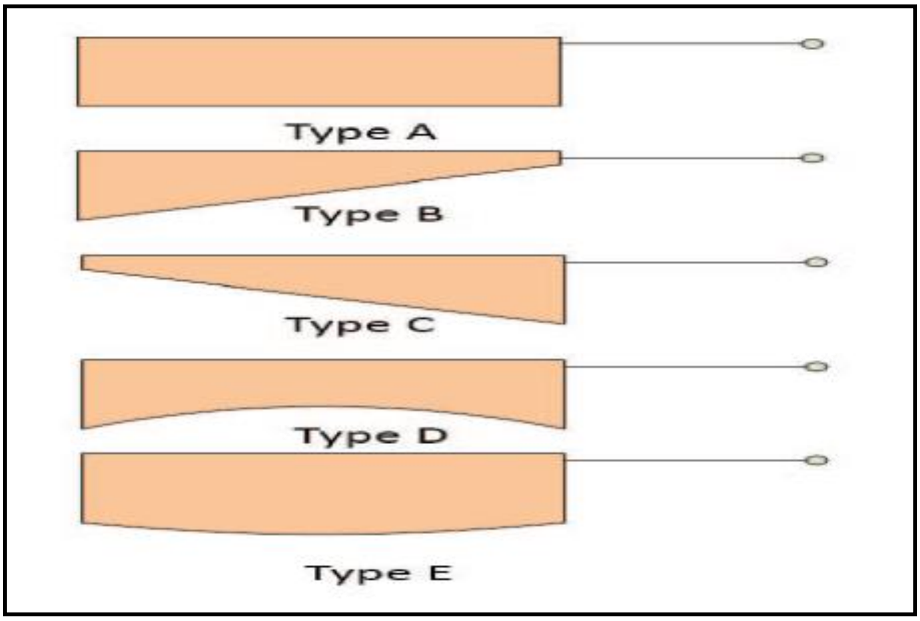


Figure 2.25: Types of Buoys selected [10]

Hydrodynamic characteristic is one of the crucial factors in increasing the efficiency of WECs. Therefore, Hui Liang [10] and his team have done a research to find an optimum shape for pendulum type WECs. They have taken five different types of shapes and each having the same mass and moment of inertia. Then, they have individually done the simulation with the same conditions for each shape. From the results, they have found that the shape "C" has the best performance. Further, they have done the optimization for the shape "C" by fine tuning the shape of the buoy with five different types. Same as above, they have done the simulation for each type with the same conditions and from the results they have found that type “4” is the best performing shape.

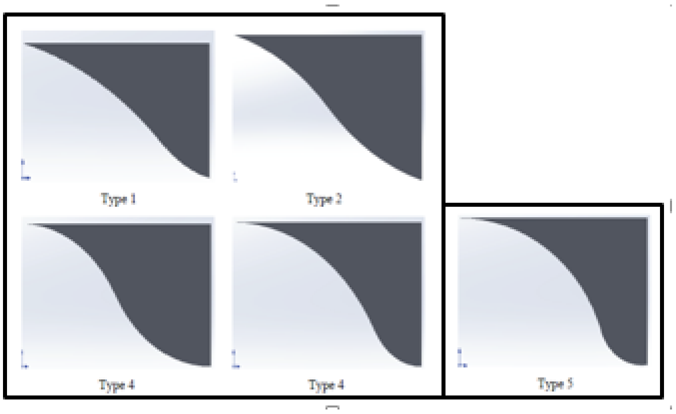


Figure 2.26: Shapes of Buoys [10]

2.14 Hydrodynamic Research of a Novel Floating type Pendulum Wave Energy Converter based on Simulations and Experiments

As per Hui Liang and his team [10], the estimated energy consumption for the following decades is considerably high. Since the ordinary energy extraction methods remain the same and contribute to serious environment problems such as reduction of the Ozone layer, reduction of fossil fuel and crude oil and natural gasses. Many governments around the world have seen this problem and have identified the necessity for renewable energy. Therefore, people are now focusing on renewable energy resources [11]. Most parts of the world are covered by sea and people have identified the sea as a very good promising energy resource. Therefore, people have invented various techniques for the extraction of wave energy and among all these methods and techniques, the floating type WCDs are the most effective due to their high wave energy conversion efficiency. Apart from that, these types also have shock resistance abilities in rough sea conditions [12].

Researches based on hydrodynamics of floating type WECs have been continuously done since its first study in the 1980s by the Muroran Institute of Technology, Japan. In the earlier stages the efficiency of these wave energy converters had been as low as 40% but the efficiency has significantly improved with the development of technology. Also, it has been proven that the hydrodynamics of the system is affected by the shape of the buoy. Wang [13] has studied the effect of the width of the buoy on this WEC. When comparing the hydrodynamics of the WEC and the final results, it is proved that the wave energy conversion efficiency decreases with the width of the buoy for short wave periods. Shuji Ogai and his team have discovered a new method for pendulum WECs to extract wave energy efficiently. Air is compressed by using wave energy and this air has the ability to avoid the irregularities of output and at the same time it is safe to use compressed air in shore operations [14].

2.15 Research Gap

The uneven distribution of sunlight over the earth creates wind patterns that blow from high pressure zones to areas of low pressure. Friction between the wind and the sea surface creates waves. This is an ascending chain in energy conversion where the energy density increases from sunlight to waves, giving the world’s oceans a renewable source of free energy on the order of terawatts that has to this date not been utilized commercially in an effective manner. When the wind stops to blow, the wave energy will continue to travel with low losses as swells. Thus, wave energy can be expected to have smaller power fluctuations over longer periods of time than the other fast developing two energy sources; wind and solar power.

While the wind energy industry has seen a continuously exponential growth during the last decades, the pattern has not been the same for wave power since the research begun in the 70’s. In 2002 there existed 340 patents explored for wave energy conversion and the first patent came around the year 1799. But it was not until the oil crisis of the 70’s that researches started on a large scale. At that time, several research programmes started with both private and public support by Portugal, Norway, UK, Denmark, Sweden, Ireland and mainly by European countries. The last few years have seen a large increase in activity. In Europe and other international countries, several wave power concepts are advancing into full-scale offshore level testing and implementation.

Different varieties of researches are stepping into the first viable WEC of commercial nature or large demonstration pilot plants and different approaches of wave energy conversion had been forwarded and investigated into in recent years, which transform energy produced by ocean waves into electrical energy. These converters can be grouped into five categories: point absorbers, attenuators, terminators, oscillating water columns and overtopping devices. Further, there are three main versions of Power Take-Off configurations which are connected with the WECs: Hydraulic method, Mechanical method and Direct Electrical.

Wave energy converter design ideally involves experimental and numerical modelling in order to get a suitable prediction of the converter performance. Different numerical model techniques had been utilized to predict the power performance and the wave structure interaction such as linear wave diffraction theory in time and frequency domains for regular and irregular waves and Computational Fluid Dynamics (CFD) models. Further, some researchers have used numerical simulation techniques by using MATLAB to analyse the performance without going for fabrication of actual prototype models.

Further, there are a few researches that have been carried out to optimize the oscillating power buoy/body arrangements for other types of wave energy convertors except the rack and pinion power take-off wave energy convertor. Therefore, the gap of this thesis will be the design and analysis of six oscillating power buoys/bodies and to select the optimum arrangement for rack and pinion power take-off wave energy convertor. Tank based oscillating power buoy/body connected rack and pinion operated WEC model fabricated and used for the practical analysis and CFD analysis will be carried out with the support of software.

3. THEORETICAL BACKGROUND

3.1 Buoy Interaction in Coordinate System

The coordinate system for a buoy in interaction with waves has 6 degrees of freedom, where the **x** and **y** are for the horizontal motions, **x** is surge and **y** is sway and the **z** direction is for the heaving motion (up and down). The angular motion around **x** is roll, around **y** is pitch and around **z** is yaw.

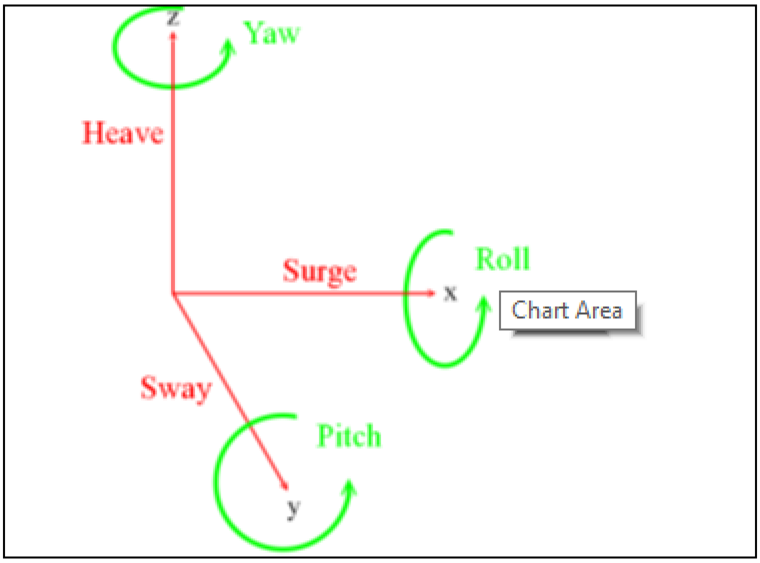


Figure 3.1: The axis for the coordinate system [44].

3.2 Waves

The waves formed by winds blowing across the surface of the water can be categorized while based on the waves with different characteristics, different height, length and period. These waves are used by WECs for power generation. Other kinds of waves can be formed by tides due to astronomical gravitational forces or due to moving (floating) structures such as ships. Tidal waves are very large but slow for most WECs and carry an enormous amount of energy. Tsunami waves due to earthquakes or landslides are not that common and also carry a lot of energy [44]. The wind waves are the waves formed by winds blowing across the surface of the water and the fetch is the length that the wind affects the water. The waves form as per the length of the fetch and the wind speed. Swells are the waves that travel out of the area they were created and can travel long distances without losing much energy [45]. Ocean waves interact by merging and combining and travel all over the open seas. These waves are combinations of many frequencies and wave heights and create different sea states [46].

The real sea waves or irregular waves are the waves that are present in the ocean. The waves are very irregular due to the variable wind energy and can be seen as a superposition of many varieties of irregular harmonic waves [47]. To analyse a complicated sea state, it is essential for their own set of parameters, such as height, period, wave length and direction and these parameters, or sum of them to be defined and characterized by an energy spectrum. The JONSWAP, Bretschneider and Pierson-Moskowitz spectra are the main mathematical models used to describe the frequency distribution of the energy in a real sea state [48].

3.2.1 Wave Height

The wave height is defined from the wave's crest (top) to the trough (bottom) and half of that is called the wave amplitude. Sea spectrum can be complicated as it consists of different heights and different waves and **H_s** is the significant wave height and express the height of the spectra. "The average value of the highest one-third waves in a wave spectrum" or the mean value of the highest 33% of the waves is the other meanings for the same [49].

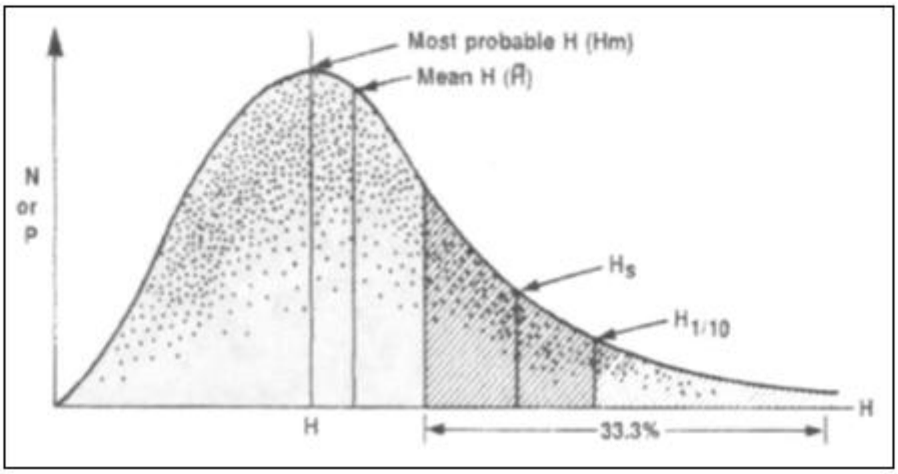


Figure 3.2: The significant wave height as the average value of the highest one-third of the spectra [46].

The **H_s** is defined by using the spectral analysis and calculated from the spectral moments, where **m_0** is the zero moment of the spectral density function [50].

$$\boldsymbol{H_s = H_{m0} = 4 * \sqrt{m_0}} \tag{3.1}$$

3.2.2 Wave Period

A wave period is defined as the time for a whole wave to pass from a certain point in the wave till the next wave corresponding point occurs and the peak of a crest or the bottom of a trough is used as the corresponding point. The zero crossing period **T$_z$,** which is the time period between the wave elevation to cross the zero or the average surface position is used as one meaning [50] [51].

$$\boldsymbol{T_z} = \sqrt{\frac{\boldsymbol{m_0}}{\boldsymbol{m_2}}} \tag{3.2}$$

The peak period **T$_p$** is also used as the wave period where is the most energy or the most energetic waves come with the total wave spectrum and used as a parameter to describe an irregular sea state [52] [53]. Further, the energy period is the regular wave period which comprises the amount of an actual sea state. **T$_e$** is the energy period and defined as follows from spectral moments:

$$\boldsymbol{T_e} = \frac{\int_0^{2\pi}\int_0^{\infty} f^{-1} S(f) df\, d\theta}{\int_0^{2\pi}\int_0^{\infty} S(f) df d\theta} \tag{3.3}$$

The energy period has to be estimated when the spectral shape is unknown and the method used is to multiply the peak period with a coefficient. For example, the coefficients are **T$_e$ = 1:2T$_z$** and **T$_e$ = 0:857T$_p$** for a Pierson-Moskowitz sea spectrum [54] [55].

3.2.3 Wave Length

The horizontal distance between wave crests is defined as the wave length. This can be found for any corresponding points in the wave for regular waves and the distance is equal to the zero crossing time **T$_z$**. Given by the equation **λ = (2π/k)** where **k** is the wave number.

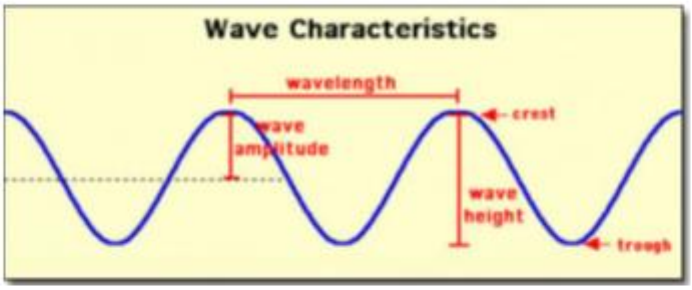


Figure 3.3: The main parameters for waves [52]

3.3 Wave equations

The mathematical part of waves and the energy, power and forces that are present in waves can be discussed by using the parameters of waves. The surface elevation or wave profile of a wave moving can be expressed as follows in the positive **x-** direction.

$$\boldsymbol{\zeta = \zeta a \cos(kx - \omega t)} \tag{3.4}$$

Where **k** is the wave number **ω** is the angular frequency and ς_a is amplitude. Irregular waves, can be taken as a superposition of many regular waves and can be written as a sum of harmonic waves.

$$\zeta = \Sigma_{n=1}^{N} \zeta an \cos(k_n x - \omega_n t + \varepsilon_n) \tag{3.5}$$

Where $\mathcal{E}_n$ is a random phase angle component, the dispersion relation for ocean waves is described with the angular frequency and the wave number and can be described as follows:

$$\omega^2 = gk \tanh(kh) \tag{3.6}$$

Where **ω** is frequency, **h** is water depth and **k** is the wave number, which is **k = (2π/λ)** where λ is the wave length. The **tanh(kh) ≈ 1** for deep water where **kh** >> **1** and the equation can be simplified.

$$\omega^2 = gk \tag{3.7}$$

The group velocity is defined as the velocity of a group of waves that travel across the ocean or the propagation of velocity of the energy of the waves **(dω/dk)**. For deep water conditions the group velocity, V_g**=g/2ω**. As in the experimental set up, the approximation **(kh** >> **1)** is not valid, the equation for the group velocity is still found by **(dω/dk).**

$$v_g = \frac{\omega}{2k}\left[1 + \frac{2kh}{\sinh(2kh)}\right] \tag{3.8}$$

3.4 Energy in Harmonic Waves

The total energy stored in waves can be written as the summation of the potential and kinetic energy per square meter.

$$E = E_k + E_p \tag{3.9}$$

3.4.1 Potential Energy

The potential energy of the wave is the energy developed due to the elevation of the water, from the wave's trough up to the crest and indicated as the average potential energy per unit horizontal area [51].

$$E_p = \frac{\rho g}{4}|A|^2 = \frac{\rho g}{16}H^2\left[\frac{J}{m^2}\right] \tag{3.10}$$

Where **ρ** is density of the fluid (At sea, it is 1025 kg/m^3), g is the gravitational acceleration and **A** is amplitude and **H** is the height.

3.4.2 Kinetic Energy

This is expressed as follows per unit horizontal area [51]:

$$E_k = \frac{\rho}{2}\omega^2|A|^2 \int_{-\infty}^{0} e^{2kz}\, dz = \frac{\rho\omega^2}{2.2k}\, |A|^2 \left[\frac{J}{m^2}\right] \qquad 3.11$$

For **ω² = gk tanh(kh)**, if the deep water conditions do not apply and the kinetic equation becomes:

$$Ek = \frac{\rho}{4}|A|^2 g \tanh(kh) = \frac{\rho}{16}H^2 g \tanh(kh) \qquad 3.12$$

The **tanh(kh) ≈ 1**, for deep water conditions and then **ω² = gk**. Therefore the equation simplifies to:

$$E_k = \frac{\rho g}{4}|A|^2 = \frac{\rho g}{16}H^2 \qquad 3.13$$

Finally, the total energy in waves becomes as stated in equation

$$E = E_k + E_p = \frac{\rho g H^2}{16}(1 + \tanh(kh)) \qquad 3.14$$

The **tanh(kh) ≈ 1**, for deep water conditions where results that **Ek = Ep** and equation simplifies to:

$$E = E_k + E_p = \frac{\rho g H^2}{8} \qquad 3.15$$

Where **g** is gravitational constant and $\boldsymbol{\rho}$ is density of the water and **H** is wave height.

3.5 Power in Waves or Energy Transport

The power in the waves or the wave energy transport is obtained by multiplying the group velocity of the wave with the energy in the wave obtaining the power in the wave front i.e. the energy transported per unit crest length or in watts per meter. The waves transport energy when they propagate in a certain direction. The power is obtained by time averaging the work done by the wave [55].

$$P = \overline{W} = v_g E \left[\frac{W}{m}\right] \qquad 3.16$$

The power or energy flux which is transmitted by the regular waves is possible to be fond if the energy in regular waves is multiplied by the group velocity.

$$P = \frac{1}{8}\,\rho g H^2 v_g = \frac{\rho g H^2}{8}\,\frac{\omega}{2k}\left[1 + \frac{2kh}{\sinh(2kh)}\right] \qquad 3.17$$

Where **H** is height of the waves, $\mathbf{V_g}$ is defined as the group velocity, **ρ** is density of the fluid. For deep water conditions, the power in regular (Harmonic) waves can also be found using the equation $\mathbf{V_g=g/2\omega}$ and $\mathbf{\omega=2\ \pi/T}$.

$$\boldsymbol{P = \frac{\rho g H^2}{8}\ v_g = \frac{\rho g H^2}{8}\ \frac{g}{2\omega} = \frac{\rho g^2}{32\pi}\ H^2 T} \qquad 3.18$$

3.5.1 Energy in Real Waves

Real waves or irregular waves can be seen as a superposition of many harmonic waves.

$$\boldsymbol{E = \rho g\ \int_0^{\infty}\ S(f)df} \qquad 3.19$$

Where S(f) is the energy spectrum. Without the deep water approximations, the equation for the energy is more complex and the power will also become a bit more complicated.

$$\boldsymbol{P = pg \int_0^{\infty}\ v_g S(f)df} \qquad 3.20$$

Using the $\mathbf{V_g}$ obtained in equation No. 08 the equation and integral can be rewritten as:

$$\boldsymbol{P = \frac{1}{2} gp \sum_{i=0}^{N}\ \left[S_{n,i}\Delta f\left(1 + \frac{2k_i h}{\sinh(2k_i h)}\right)\frac{\omega_i}{k_i}\right]} \qquad 3.21$$

Δf is spacing of the values of the spectrum and the spectrum is discretized for **N** components. With some approximations, this equation can also be found for deep water conditions [55].

Using $\boldsymbol{H_8 = H_{m0} = 4 * \sqrt{\mathrm{m0}},\ \int_0^{\infty}\ S(f)df = \frac{H_s^2}{16}}$;

$$\boldsymbol{E = pg\frac{H_s^2}{16}} \qquad 3.22$$

The significant wave height $\mathbf{H_s}$ is defined as $H_s = 4 \times \sqrt{m_0}$ i.e. four times the square root of the zero momentum of the spectrum which can be rewritten to $\mathbf{m_0 = (H_s^2/16)}$ for finding the power for deep water waves [51]. From equation No. 3.22 the equation for energy becomes:

$$\boldsymbol{E = \rho g \int_0^{\infty}\ S(f)df = \rho g\frac{H_s^2}{16}} \qquad 3.23$$

$\mathbf{U_g=g/2\omega}$ and $\mathbf{\omega_e= 2\pi/T_e}$ for the wave group velocity for deep water and the power becomes:

$$\boldsymbol{P = Ev_g \approx \frac{\rho g^2 H_s^2}{32\omega_e} \approx \frac{1}{64\pi}\rho g^2 T_e H_s^2} \qquad 3.24$$

3.6 Definitions of some energy efficiency concepts

3.6.1 Absorption Width

This is found by dividing the power absorbed by the device, $\mathbf{P_{device}}$ with the power in the wave front which is interacting with **P**. and defined as a length [m] of a wave front transporting the same amount of power as the WEC would absorb for the same wave conditions.

$$\boldsymbol{Absorption\,Width} = \frac{\boldsymbol{P}\mathbf{device}\ [\boldsymbol{W}]}{\boldsymbol{P}\left[\frac{\boldsymbol{W}}{\boldsymbol{m}}\right]} \qquad 3.25$$

3.6.2 Absorption Efficiency

Absorption efficiency is the ratio of the power absorbed and the power available, transported by the wave front within the width of the device and also referred to as ‘'relative absorption width'', the length would be the diameter of the buoy.

$$\boldsymbol{Absorption\,Efficiency} = \frac{\boldsymbol{P}\mathbf{device}\ [\boldsymbol{W}]}{\boldsymbol{P}\left[\frac{\boldsymbol{W}}{\boldsymbol{m}}\right]\times \boldsymbol{L}[\boldsymbol{m}]} \qquad 3.26$$

3.7 Hydrodynamic Forces Acting on a Point Absorbing WEC

The forces from the external pressures on the buoy and the forces from the PTO are the forces acting on a point absorbing WEC.

$$\boldsymbol{m\,a} = \boldsymbol{F_{pe}} + \boldsymbol{F_{PTO}} \qquad 3.27$$

$\mathbf{F_{PTO}}$ are the reaction forces from the PTO that act on the buoy, **m** is the mass of the system, $\mathbf{F_{pe}}$ are the forces the WEC experiences from the ocean and its waves due to external pressures which can be divided into the gravitational forces, $\mathbf{F_{mg}}$ oscillator is included in the $\mathbf{F_{PTO}}$ and the $\mathbf{F_{mg}}$ buoy in the $\mathbf{F_{hs}}$ and **a** is the acceleration.

$$\boldsymbol{F_{pe}(t)} = \boldsymbol{F_e\ (t)} + \boldsymbol{F_r(t)} + \boldsymbol{F_{hs}(t)} + \boldsymbol{F_d(t)} \qquad 3.28$$

In which $\mathbf{F_e}$ is the excitation force, $\mathbf{F_r}$ is the radiation force, $\mathbf{F_{hs}}$ is the hydrostatic force (buoyancy force), and $\mathbf{F_d}$ is drag force. By multiplying the total force of the system by the velocity of the oscillator, the absorbed power by an oscillating body will be obtained [47].

3.7.1 Excitation Force

Excitation force is created by the incident waves and resulting from the integration of the pressure impinged by the incident waves on the mean wet surface when the buoy is fixed.

With a body interacting with the wave, the incident wave comes with a certain potential and can be called the excitation force.

3.7.2 Radiation Force

When a body oscillates in otherwise calm water it generates waves and the force that generates the waves is known as the radiation force. The radiation force is created with the pressure associated over the mean wet surface, imposed by the fluid moved due to forced device oscillations when there are no incident waves.

3.7.3 Hydrostatic Force

The hydrostatic force is the difference between the gravitational force of the buoy and the buoyancy force discovered by Archimedes and the gravitational force of the buoy and this is due to the buoy being displaced from its natural draft position.

$$\boldsymbol{F_{hs} = pg\nabla - F_{mg\ Buoy}} \qquad 3.29$$

where the submerged volume of the body and $F_{mg\ Buoy}$ is the force due to the weight of the buoy.

3.7.4 Drag Force

Drag force is acting in the direction opposite to the movement of the body on a body moving through fluid. The drag force is calculated with the drag equation:

$$\boldsymbol{F_d = \frac{1}{2} C_d \rho g A s v 2} \qquad 3.30$$

Where $\boldsymbol{\rho}$ is the density of the fluid, $\mathbf{V}$ velocity of the fluid, $\mathbf{C_d}$ is the drag coefficient and $\mathbf{A_s}$ is the reference area or the projected area of the body. This is a dimensionless coefficient and combines both the pressure drag and skin friction on the body.

3.8 Point Absorbers

The oscillating body WECs can be of various sizes, either large or small. When compared to the wave length of the wave it interacts with, if the buoy is small, it is called a point absorber. WECs that have a large horizontal extension are called terminators and attenuators [52]. What determines the power the buoy can absorb is their interaction with the waves. A WEC with a large geometry, large in size can operate in a wider range of frequencies and can work closer to optimal performance at more variable sea states. Similarly, a smaller WEC can operate in a smaller range of frequencies close to its optimum performance. Therefore, a large and a small WEC can absorb an equal amount of energy, as long as the smaller WEC has higher amplitude. To compensate for this, smaller WECs use control methods to bring the motion of the system closer to the resonance and closer to optimum interaction with the wave.

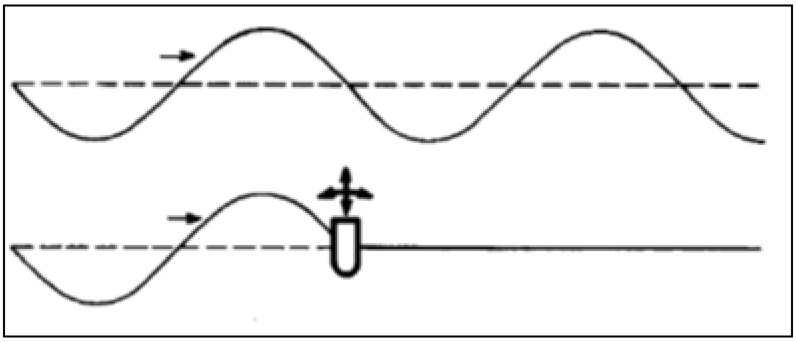


Figure 3.4: Undisturbed wave and how a buoy would absorb the wave energy completely [51].

WEC absorbs energy from waves with the help of oscillating buoy/body by acting against the incident waves, producing waves in the opposite phase or by "generating" waves in the opposite phase to the incident waves and destructively interfering them [56].

3.9 Control Methods

The range of waves where the best performance is achieved is very narrow for small wave energy converters such as point absorbers due to their narrow range of response frequency and they operate rarely close to their optimum conditions which are close to their response frequency, unless a control method is used [57]. By implementing a control method it is possible to maximize the average energy output from the WEC and the device can operate close to its optimum in various sea states. It works close to the optimum conditions with optimum interaction between the incident wave and the body by controlling the oscillations of the system [58]. The devices’ optimum or maximum energy conversion will create when the system oscillates at its resonance frequency. By adjusting the excitation force from the incident wave in phase with the velocity of the oscillatory motion, set the oscillations of the device close to its resonance with the application of the control method. The energy absorption is less when the device is oscillating off resonance as the heaving motion is decreased. By having the excitation force in phase with the velocity and the oscillating with an optimum amplitude, a control method called "reactive control" (Phase and amplitude control or complex conjugate control) aims at obtaining the optimum oscillations of the system [59].

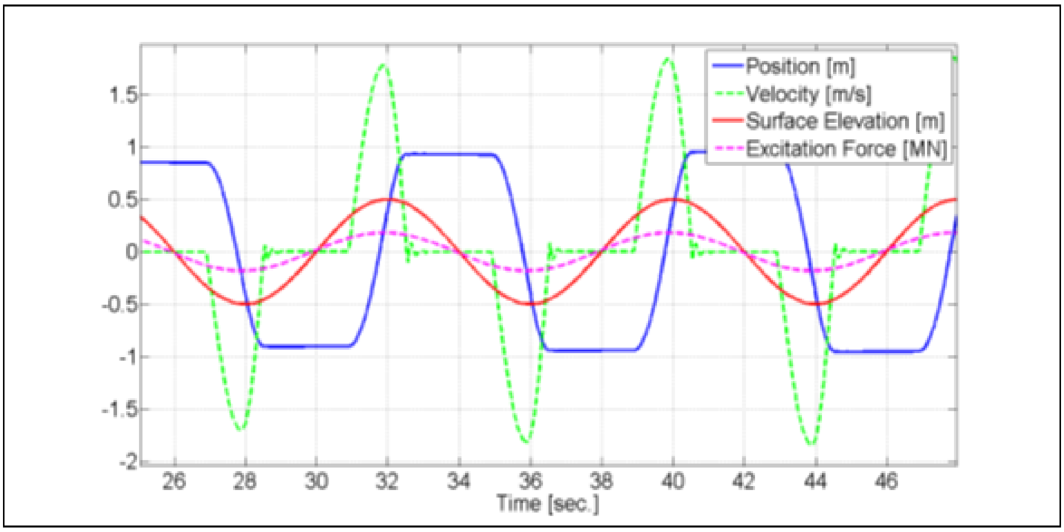


Figure 3.5: The position and the velocity of the buoy in a time series & the surface elevation of the water and the excitation force. If the buoy is released at the right time instance, the peak of velocity is in the phase with the peak in excitation force, giving the most power to the device, obtaining the most velocity [58].

3.10 Latching

Latching is an interesting approach of changing the period of the system, bringing it closer to the optimum of the WEC for various sea states, by ensuring the condition that the wave period is larger than the natural period of the WEC [60]. In that way the body obtains the maximum force from the wave, giving it a maximum velocity for that wave. Latching is done by stopping the motion of the system at the extreme excursion when the velocity is zero and holding it there for a certain time [61]. Subsequently, the device is released at the optimal moment. The main challenges when using latching control, as many other active control schemes, is that the system must be able to predict ahead of time the right moment to unlatch. For a heaving point absorber this "anticipation" time is a quarter of the period of the natural frequency of the system before the maximum peak in excitation force. Therefore it is important to know the natural period of the WEC system, to be able to predict the time it should be released before the peak force [56]. The more complicated challenge is to know when that peak will occur.

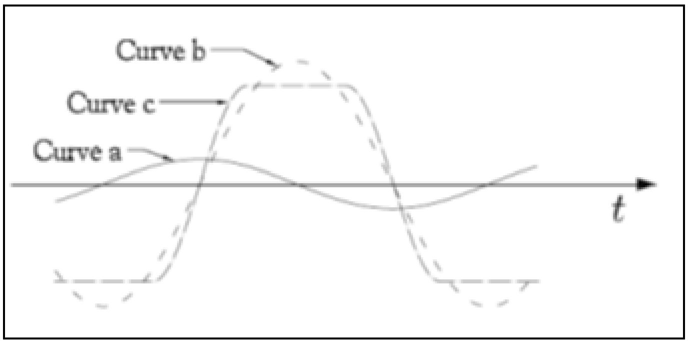


Figure 3.6: Latching works. It shows the wave elevation (a), the movement of a body in resonance with the wave (b) and how a latching body moves through the wave (c) [51].

By latching, it is possible to increase the absorbed power from the wave and can gain up to a factor of 4 compared to a device without control. With the changing of varieties of wave periods and heights, the sea has different sea states, making the prediction complex. Researchers are trying to overcome these difficulties by developing systems to cope with this challenge [62]. There are predictive models that use local or distributed wave sensors to attempt to predict the incoming wave or models using non-predictive methods [63]. A promising approach to provide a robust non-predictive method is to define an amplitude height for the water surface elevation, form the zero position as a threshold value to unlatch the buoy. This is known as "threshold unlatch control". This means, as the buoy is latched its bottom position and the surface of the water reaches a given height (threshold), the buoy unlatches and vice versa for when it is latched at its top position. This is close to the optimal power absorption [64]. The equation for the threshold found by Lopes et. al. is written as;

$$\boldsymbol{\zeta_{th} = \frac{H}{2}\, sin\left[\frac{\pi}{2}\left(1 - \frac{T_n}{T}\right)\right]} \qquad 3.31$$

Where **T** is the period of the wave, **H** is the wave height and $\mathbf{T_n}$ is the natural period of the device, for regular waves. For irregular waves the threshold can be calculated in the same way, where **T** is substituted by the energy period $\mathbf{T_e}$ and **H** is substituted by $\frac{H_s}{\sqrt{2}}$.

3.11 Mass, Spring and Damper System

An oscillating point absorber (WEC) is categorized as a mass-spring-damper system. The hydro mechanical forces and moments due to the oscillations of a rigid body moving in still water and wave exciting forces and moments forces due to the incoming wave that act on the body are represented by the left and right sides of the equation.

$$(\boldsymbol{m}+\boldsymbol{m_a})\ddot{\boldsymbol{z}}+\boldsymbol{b}\dot{\boldsymbol{z}}+\boldsymbol{c}\boldsymbol{z}=\boldsymbol{F} \tag{3.32}$$

Where **m** is the mass and $\mathbf{m_a}$ is the added mass (Hydrodynamic mass coefficient or the radiation), **b** the hydrodynamic damping coefficient and **c** is the hydrostatic restoring coefficient =$\boldsymbol{\rho g A_s}$ and F represent the external forces.

For a body oscillating freely in undisturbed or still water the external forces, F are set to zero. This can be tested with a "decay" test. A decay test is done by moving the body from its equilibrium position and releasing it. It then oscillates in the heaving direction, similar to the mass, spring damper system to its equilibrium point. By setting F to zero and dividing the equation with **(m + a)** it can be rewritten as:

$$\ddot{\boldsymbol{z}}+\boldsymbol{2v\dot{z}}+\boldsymbol{\omega_n^2 z}=\boldsymbol{0} \tag{3.33}$$

Where the natural (Undamped) frequency $\boldsymbol{\omega_n}$ can be found by:

$$\boldsymbol{\omega_n^2}=\frac{\boldsymbol{c}}{\boldsymbol{m+m_a}} \tag{3.34}$$

Which can be re-written to obtain the natural period

$$\boldsymbol{T_n}=\frac{\boldsymbol{2\pi}}{\boldsymbol{\omega_n}}=\boldsymbol{2\pi}\sqrt{\frac{\boldsymbol{m+m_a}}{\boldsymbol{\rho A g}}} \tag{3.35}$$

Where $\boldsymbol{m}$ is the mass of system, $\boldsymbol{m}_a$ is added mass, $\boldsymbol{\rho}$ is fluid density and **g** is gravitational acceleration. Natural period of the system can be used to set the unlatch timing.

4. FABRICATION OF PROTO TYPE WEC & BUOYS

4.1 Buoy

The buoy is one of the major components of the WEC. The requirement of fabricating this is to absorb wave energy and transfer it to the linear motion. The frame of the buoy was designed by using a single mild steel sheet with a thickness of 2mm, angle iron (‘L: shape) were used to design a collar so that this collar supports the buoy to withstand the forces created by the waves. To guide the two racks which are connected to the buoy, there were two pipes installed in the supporting structure. These pipes are supported by steel rods to the supporting structure, so that the two pipes maintain their position even though large forces act upon it.

Figure 4.1: Fabrication of the buoy

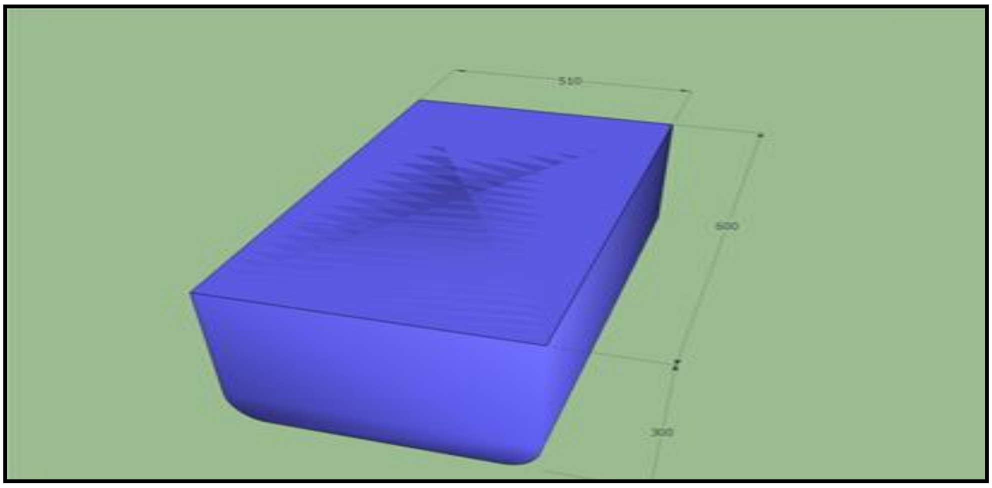


Figure 4.2: CAD design of the buoy

Calculation of data as follows:

Length x Width x Height = 60cm x 50cm x 30cm

Radius at bottom = 10cm

Volume = Volume of the rectangular region + Volume of the curved region

$= (60\times 50 \times 20) + (40\times50 \times10) + 0.5\times \pi\times (10)^2$

$= 80157\text{cm}^3 = 0.8\ \text{m}^3$

Draught = 10cm

Submerged volume = Volume of the rectangular region + Volume of the curved region

$= (40\times50 \times10) + 0.5\times \pi\times (10)^2$

$= 20157\ \text{cm}^3 = 0.2\text{m}^3$

Buoyancy force acting on the buoy and the racks at steady state (without waves)

$= V\times p\times g$

$= 0.2 \times 1000 \times 9.8 = 19600\ \text{Kgm/s}^2$

4.2 Supporting Structure

The supporting structure is designed to mount both the Energy Converting Mechanism (linear and rotational) and Power Generating Mechanism (wave energy collecting) together. The shape of the structure is designed using frames to distribute the forces generated by waves within the whole structure, so that the structure will be protected from excessive forces created by the waves. Two inches angle irons (‘L’ shape) are used to fabricate the supporting structure.

Figure 4.3: Fabrication of the Supporting Structure

Figure 4.4: Final Fabricated Supporting Structure

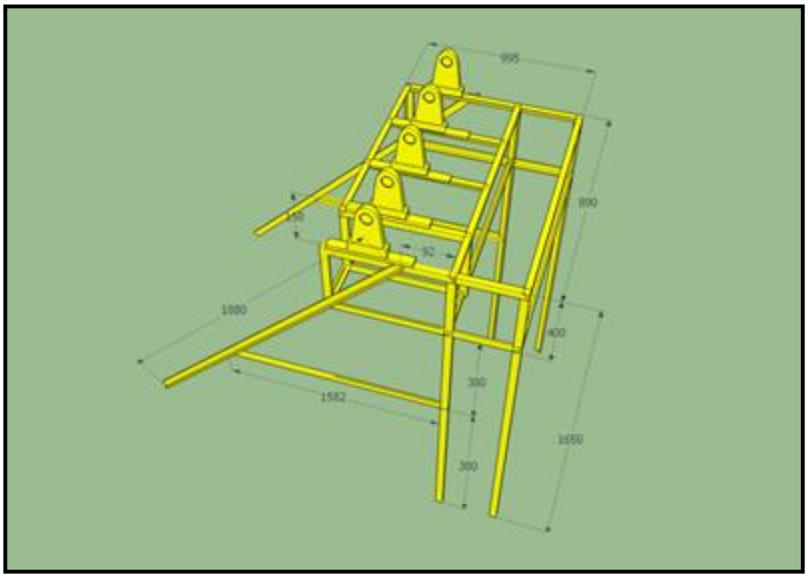


Figure 4.5: CAD design of the Supporting Structure

4.3 Wave Making Water Tank

To test this project, it is essential to have a wave making tank (towing tank) which is used to generate the waves. Unfortunately, such kind of equipment is difficult to find or fabricate due to high cost involvement of the fabrication process. Hence, the water tank was designed according to the minimum requirements of the project. It is built by using 3mm Mild Steel plates and it has been strengthened by adding 2 inches angle irons (“L” shape) collar to the top edge.

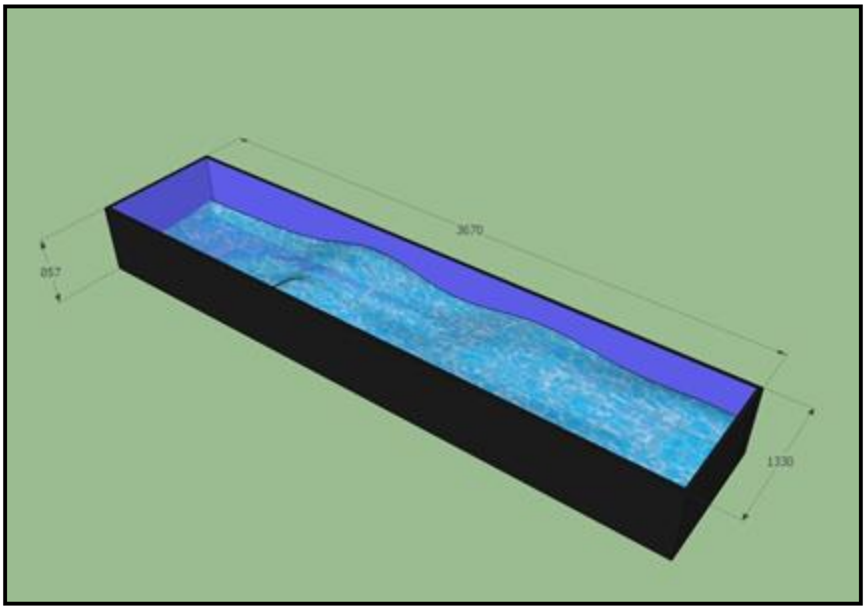


Figure 4.6: CAD design of the wave making tank

4.4 Drive Shaft

Figure 4.7: Gear wheels used for the Drive shaft

The drive shaft is the main component of the system. All the gear wheels and bearings are mounted on to this shaft. The forged steel shaft is machined so that the places where the bearings and gear wheels fit tightly. A key is machined on this shaft where the gear wheel fits, as power to drive the alternator is taken from this gear wheel and a large force acts on this gear wheel, which will make the gear wheel and the shaft slip. The bearings and wheels are mounted on the shaft symmetrically to distribute the forces acting on the shaft and thereby, smooth turning of the shaft can be obtained.

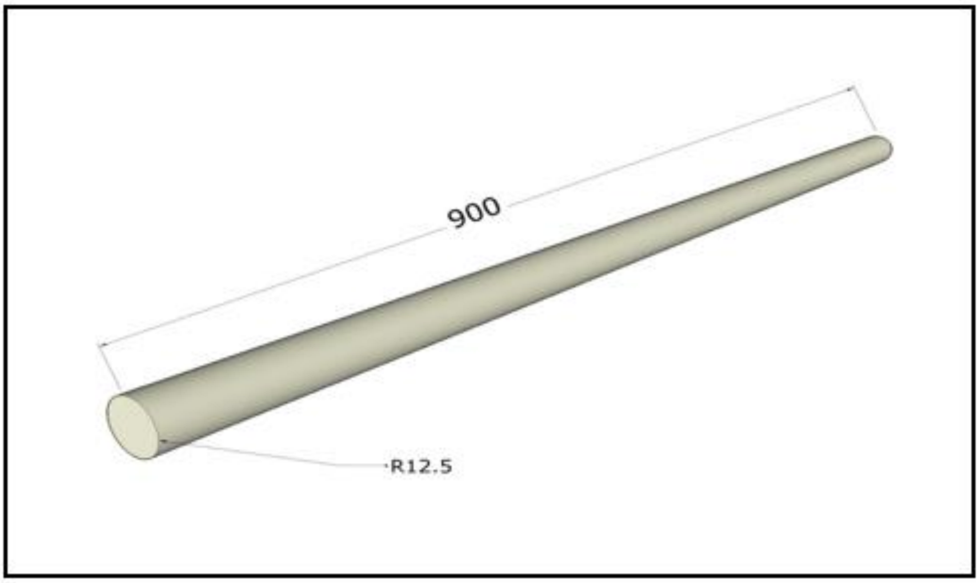


Figure 4.8: CAD design of the drive shaft

Figure 4.9: Accessories used for the prototype model

4.5 Rack and Pinion

The rack is designed to transfer the linear movement of the wave to the shaft via the pinion wheel. The pinion wheel converts the linear movement to the rotary movement. It is very important to have a small pinion wheel to get high rpm of the shaft. Hence, the pinion is designed as small as possible to get this done. The ratchet system is used to drive the shaft according to the movement of the shaft in upward or downward directions.

There are two specially designed assemblies to connect both the ratchet and pinion wheel. The teeth of the ratchet were removed and tightly fitted to this assembly. Both ratchet and pinion wheel rotate as a single part when the buoy is moved upwards due to the wave movement. One set of pinion wheel and ratchet rotate due to the movement of the rack which is connected to that pinion wheel and the other pinion wheel gives a ratchet action as it is connected to the opposite way and hence, due to the weight of the buoy, both racks go down and during this downward movement a second set of pinion wheel and ratchet will rotate due to it being connected to the rack while the other pinion while gives a ratchet action. This will help to create a continuous shaft rotation.

Such a rack and pinion Circular Pitch (P_c) was mathematically calculated by,

$$P_c = \frac{\pi D}{Z} \tag{4.1}$$

Where; D – Diameter of the Pitch Circle (mm)

Z – Number of teeth on the gear wheel

The centre-to-centre distance (α) between the pinion and gear is given by,

$$\alpha = \frac{1}{2}\left(D_p + D_g\right) = \frac{1}{2}\left(mZ_p + mZ_g\right) \tag{4.2}$$

Figure 4.10: Rack and drive shaft

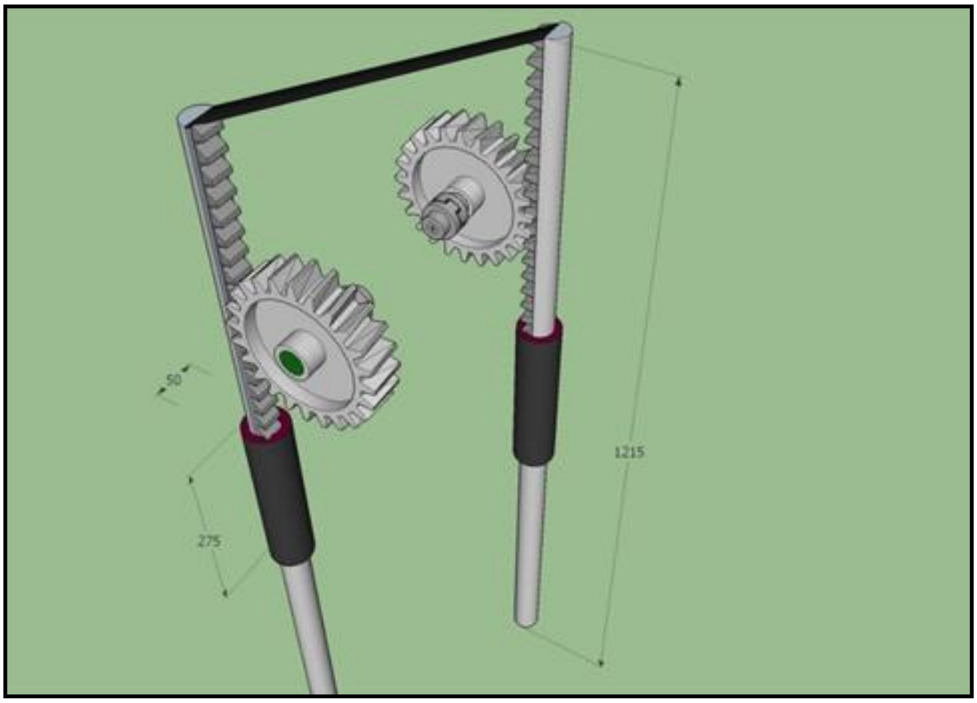


Figure 4.11: CAD design of the two sets of racks and pinions

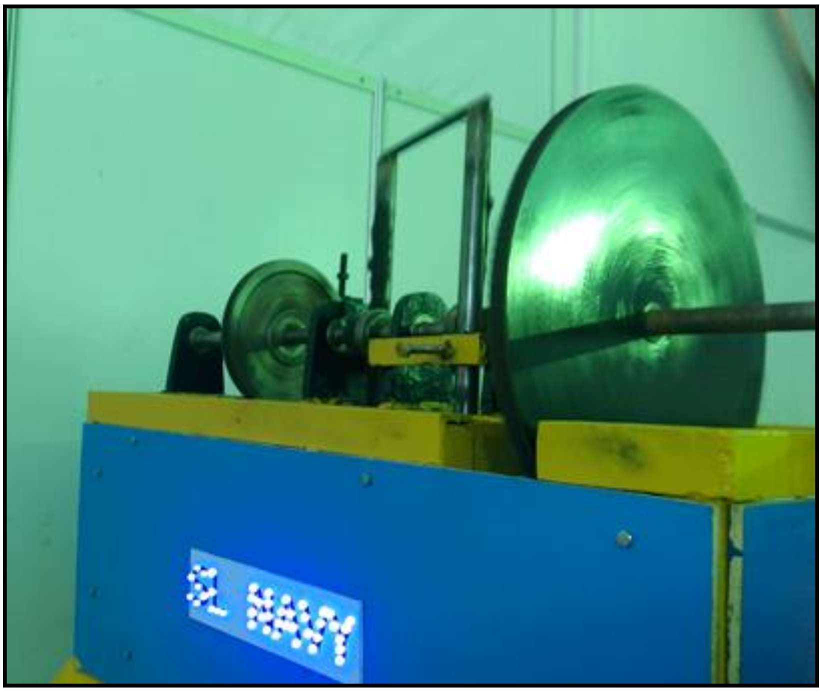


Figure 4.12: Model connected two sets of racks and pinions

To determine the tangential force by using following formulae;

$$a = [m/s^2]$$

$$Fu = (m \cdot g + m \,.\, a)/1000 \ \ (\text{for lifting axle})\ [kN] \qquad 4.3$$

$$Fu = (m \,.\, g \,.\, \mu + m \,.\, a)/1000 \ \ (\text{for driving axle})\ [kN] \qquad 4.4$$

$$Fu\ per\ mtr = Fu\ Tan/\ (K_A .\ S_B \,.\, fn \,.\, LKH\text{ß})\ [kN] \qquad 4.5$$

Where, Fu is Tangential tooth load, m is Mass to be moved, K_A is Load Factor, S_B is the Safety Coefficient (The safety coefficient will be allocated as per the experience and i.e. S_B = 1.1 to 1.4), LKHß is Linear Load Distribution Factor and μ is Coefficient of friction.

4.6 Flywheel

In the technical world, there should be a flywheel to store the rotational energy. Normally in IC engines, the energy is developed during the power stroke only and more power is available than the engine load. Energy will not be developed during the other three strokes; suction, compression and exhaust in four stroke engines and in case of two strokes, mainly in the suction phase. The part of the energy developed at the power stroke will be absorbed by the fitted flywheel and thereafter it will be released to provide energy to work in other strokes where no energy is developed. Thereby, in this fabrication project, the flywheel was used to store the rotational energy created by the rack and pinion which helps to keep the continuous rotation of the shaft because the time delay is created between two waves. With the introduction of the flywheel to the system, the continuous rotation of shaft can be obtained.

Energy stored in a flywheel $(E): \Delta E = m \times R^2 \times \omega^2\, CS = m \times v^2 \times CS$ 4.6

Where **m** is mass of the flywheel in kg, **R** is Radius of gyration of the flywheel in meters, **ω** is Mean angular speed during the cycle in rad and **CS** is Coefficient of fluctuation of speed.

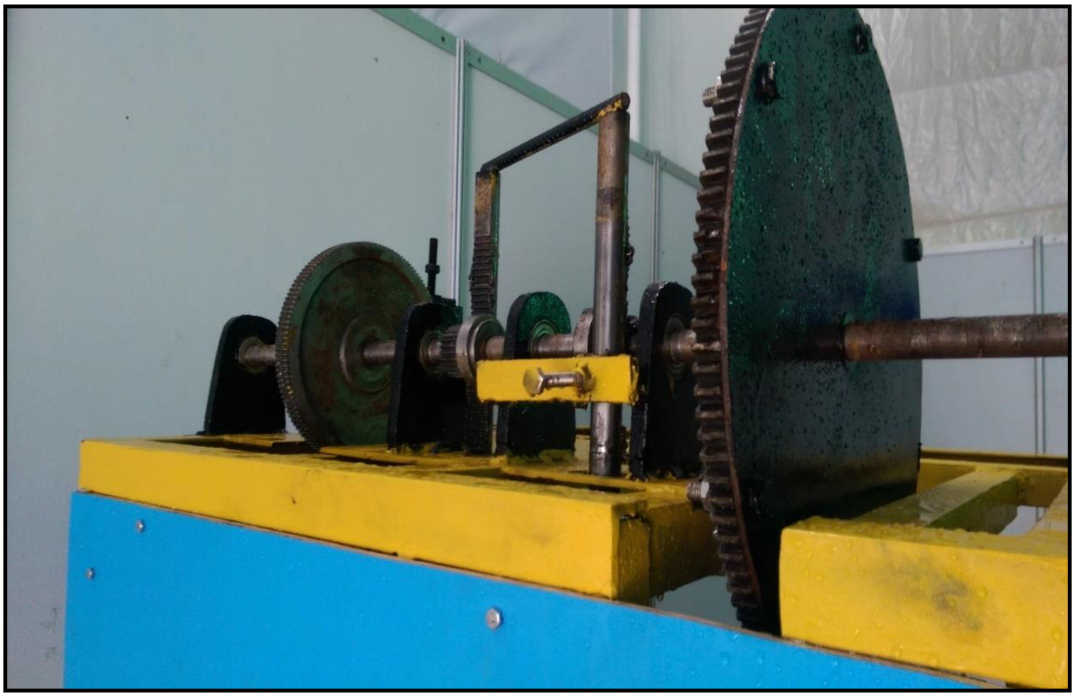


Figure 4.13: Flywheel connected with Drive shaft

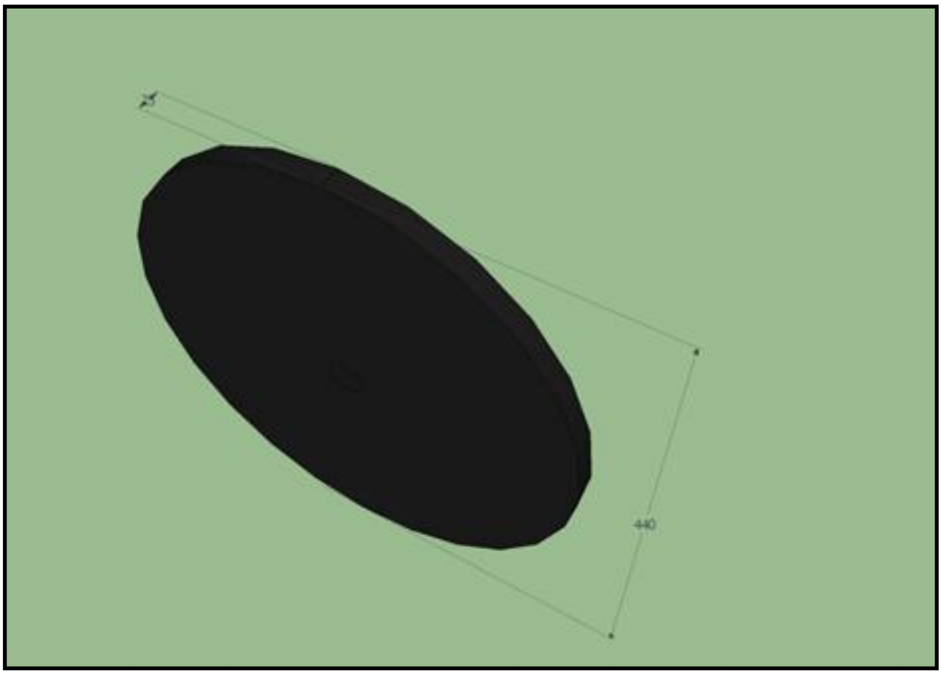


Figure 4.14: CAD design of the Flywheel

4.7 Gear Wheels

Basically, there are two gear wheels in the system; the drive wheel which is mounted to the drive shaft and the driven wheel which is mounted to the alternator. The drive wheel is designed larger than the driven wheel to obtain a high rpm to the alternator. The ratio between two gear wheels is nearly 1:3. The steps of designing the spur gear wheels are as follows;

Design tangential tooth load can be obtained with the help of the power transmitted and the pitch line velocity by using the following formula;

$$\boldsymbol{F = \frac{P}{V} \times C_S} \qquad 4.7$$

Where **F** is Permissible Tangential Tooth Load, **P** is Power Transmitted in Watts, **V** is Pitch Line Velocity and **D** is Pitch Circle Diameter.

$$\text{Pitch line velocity: } V = \frac{\pi.D.N}{60} = \frac{\pi.m.T.N}{60} = \frac{Pc.T.N}{600} \qquad 4.8$$

Where **m** is module in meter and **T** is Number of teeth.

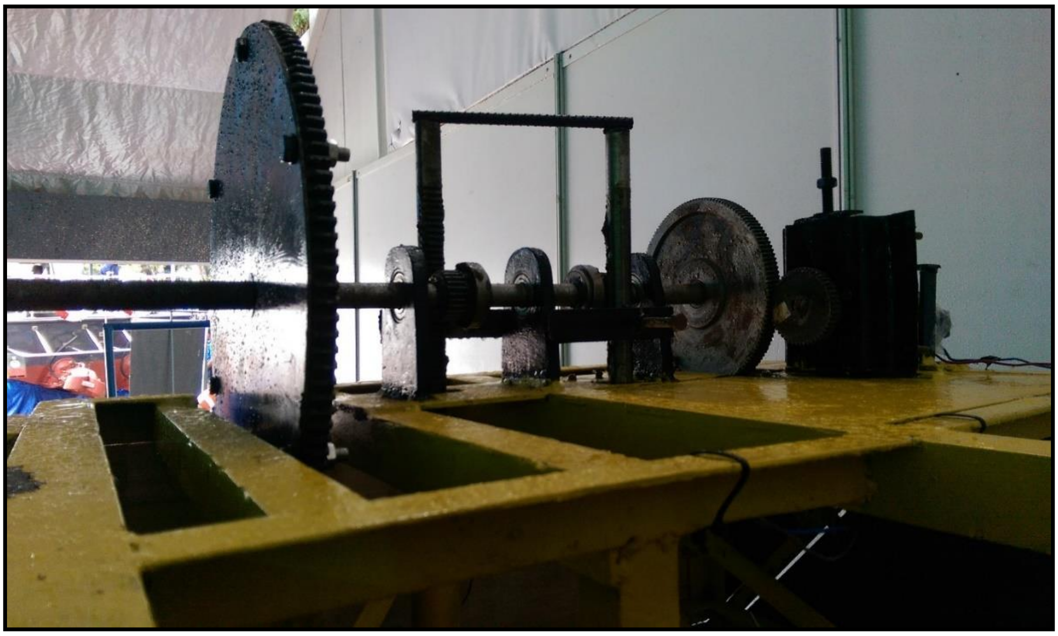


Figure 4.15: Drive & Driven Gear wheels

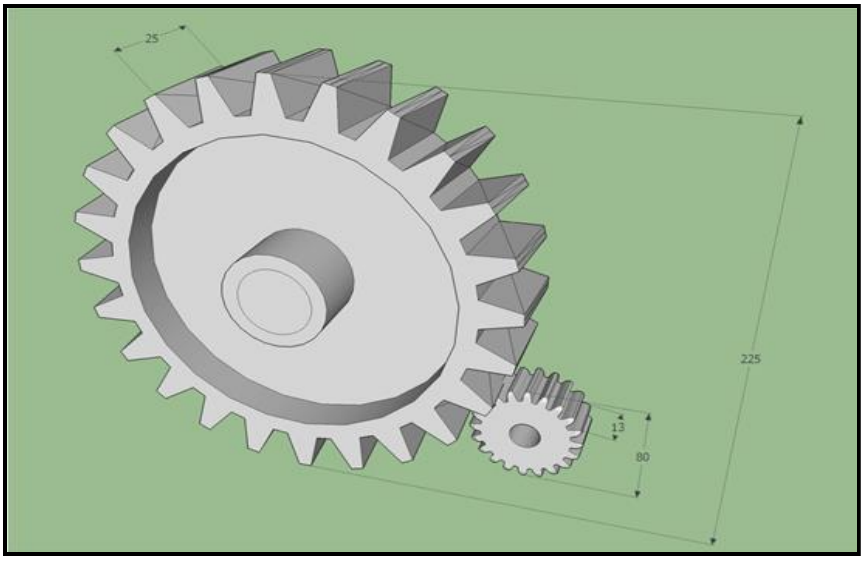


Figure 4.16: CAD design of the Drive & Driven Gear wheels

Diameter of drive gear wheel = 224.5 mm

Number of teeth = 140

Diameter of driven gear wheel = 80 mm

Number of teeth = 48

Gear Ratio = $N_1 / N_2 = 48 / 140 = 0.34$

4.8 DC Motor

A DC motor is used to take the output of the rotary motion created by the wheel. Many methods were experimented, such as using an alternator of a motor bike, alternator of an OBM and a dynamo. Finally, a DC motor which is used in a radar motor was selected to generate electricity. This was selected since the output rpm of the radar motor has been reduced using a special gear wheel arrangement, and the mechanism is also used to produce a lower rpm.

Figure 4.17: Power Distribution of the WEC

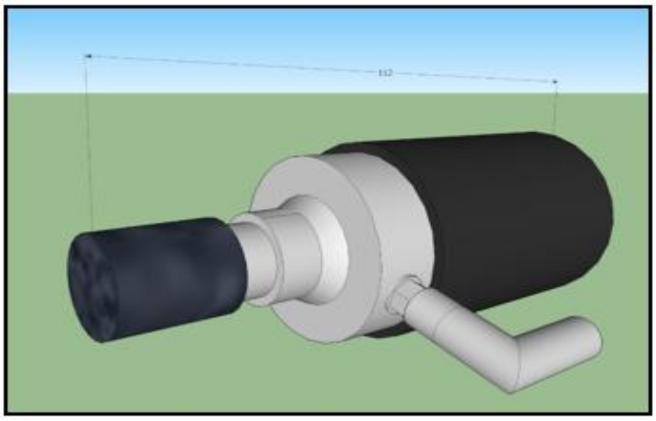


Figure 4.18: CAD Design of the DC Motor

4.9 Dam

A dam was introduced, as this will increase the height of the incoming wave compared to the wave height which is generated. The buoy was placed inside this dam, as it allows more movement of the rack and hence will generate more electricity. Two dams are used, one at the top and one at the bottom which will increase the height of the incoming wave. The dam will also make sure that the unusual horizontal forces acting on the buoy is reduced and this will allow a smooth motion of the rack and the pinion in the vertical direction.

4.10 Final Design

AutoCAD drawings of the final design and final fabricated model are indicted below. Furthermore, the design details 6 types of buoys which are indicated in Table 4.1. All the dimensions are in millimeters.

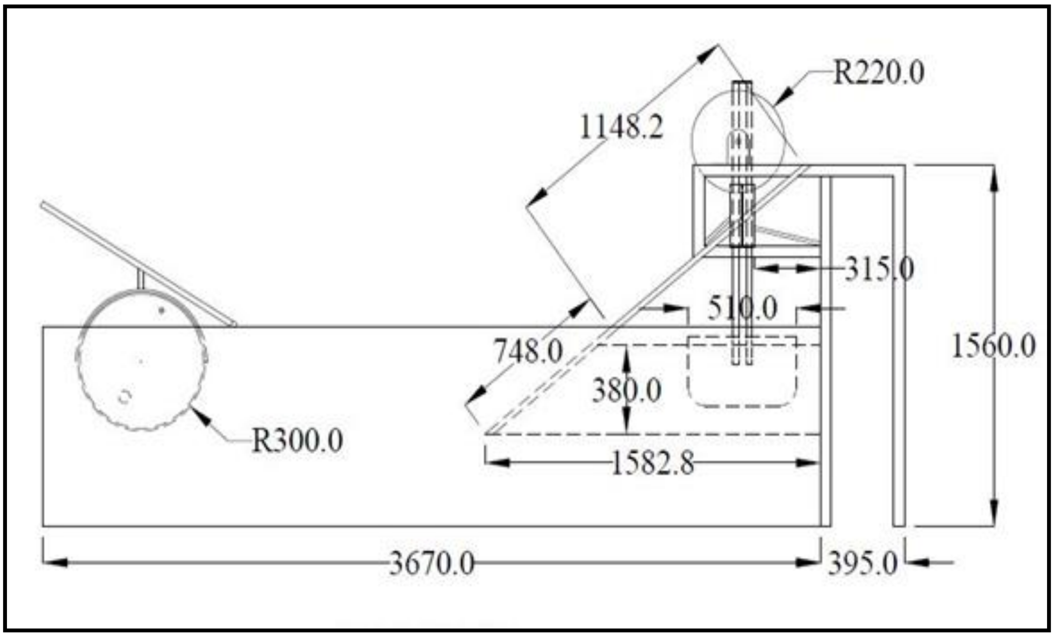


Figure 4.19: CAD drawing of the Final Prototype model of WEC – Front View

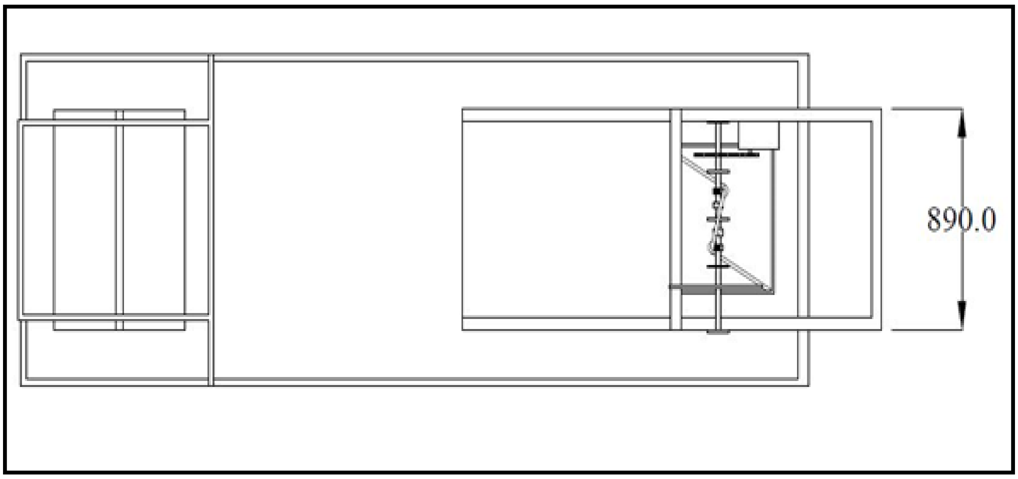


Figure 4.20: CAD drawing of the Final Prototype model of WEC – Top View

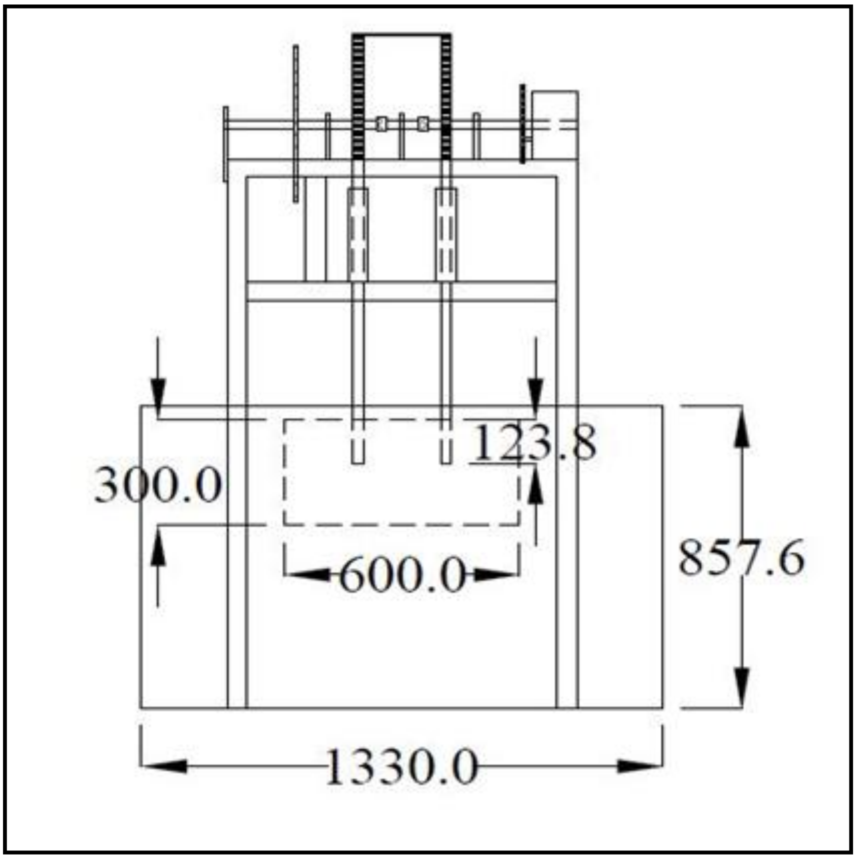


Figure 4.21: CAD drawing of the Final Prototype model of WEC – Side View

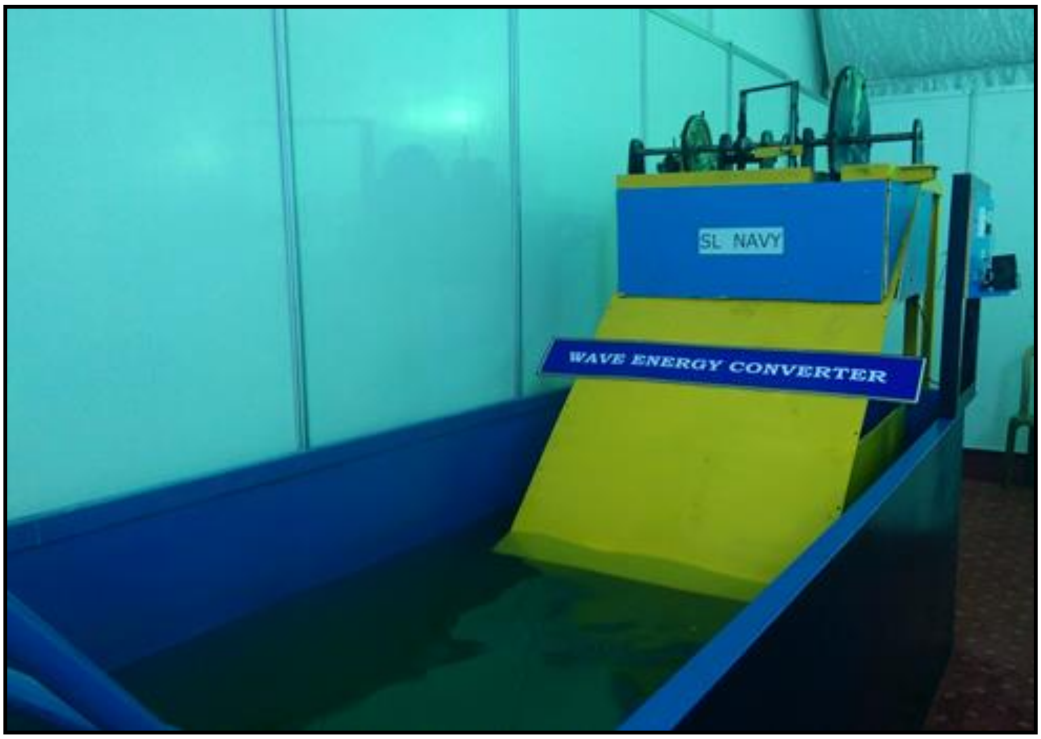


Figure 4.22: Final Prototype model of Oscillating Power Buoy operated Rack & Pinion Power Take-off WEC

Figure 4.23: Wave making facility in Final Prototype model of Oscillating Power Buoy operated Rack & Pinion Power Take-off WEC

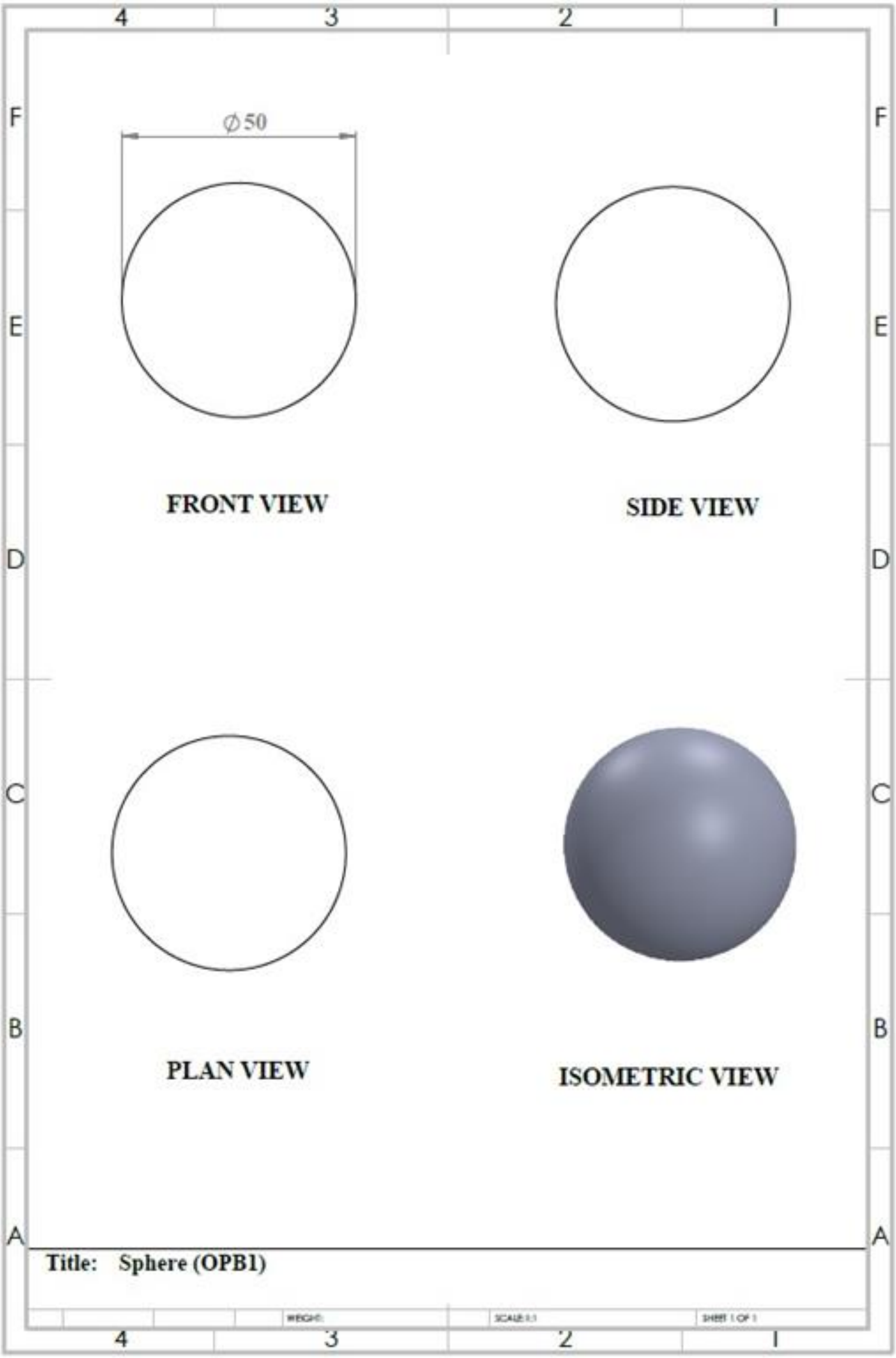


Figure 4.24: Design Parameters of Sphere (OPB 1)

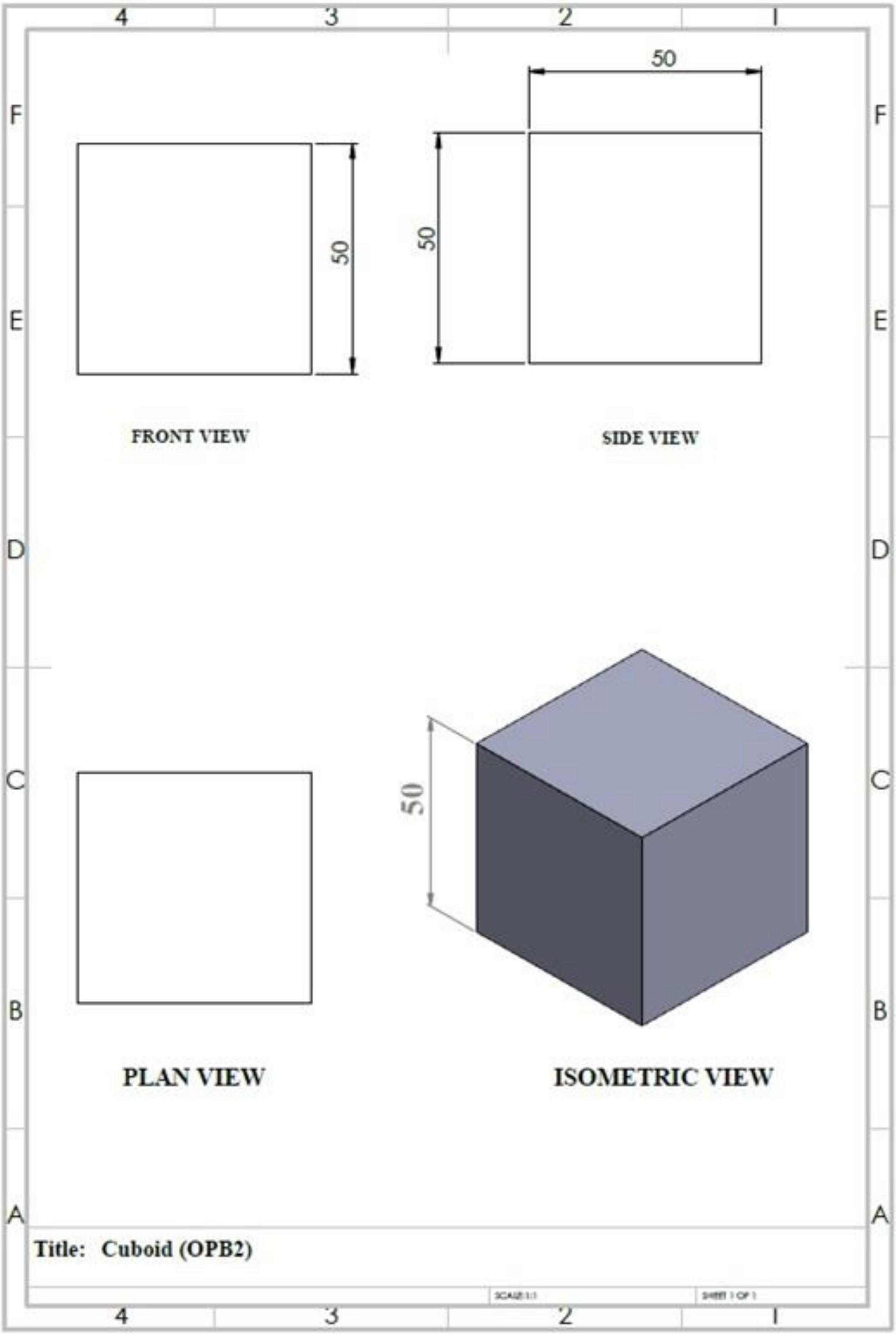


Figure 4.25: Design Parameters of Cuboid (OPB 2)

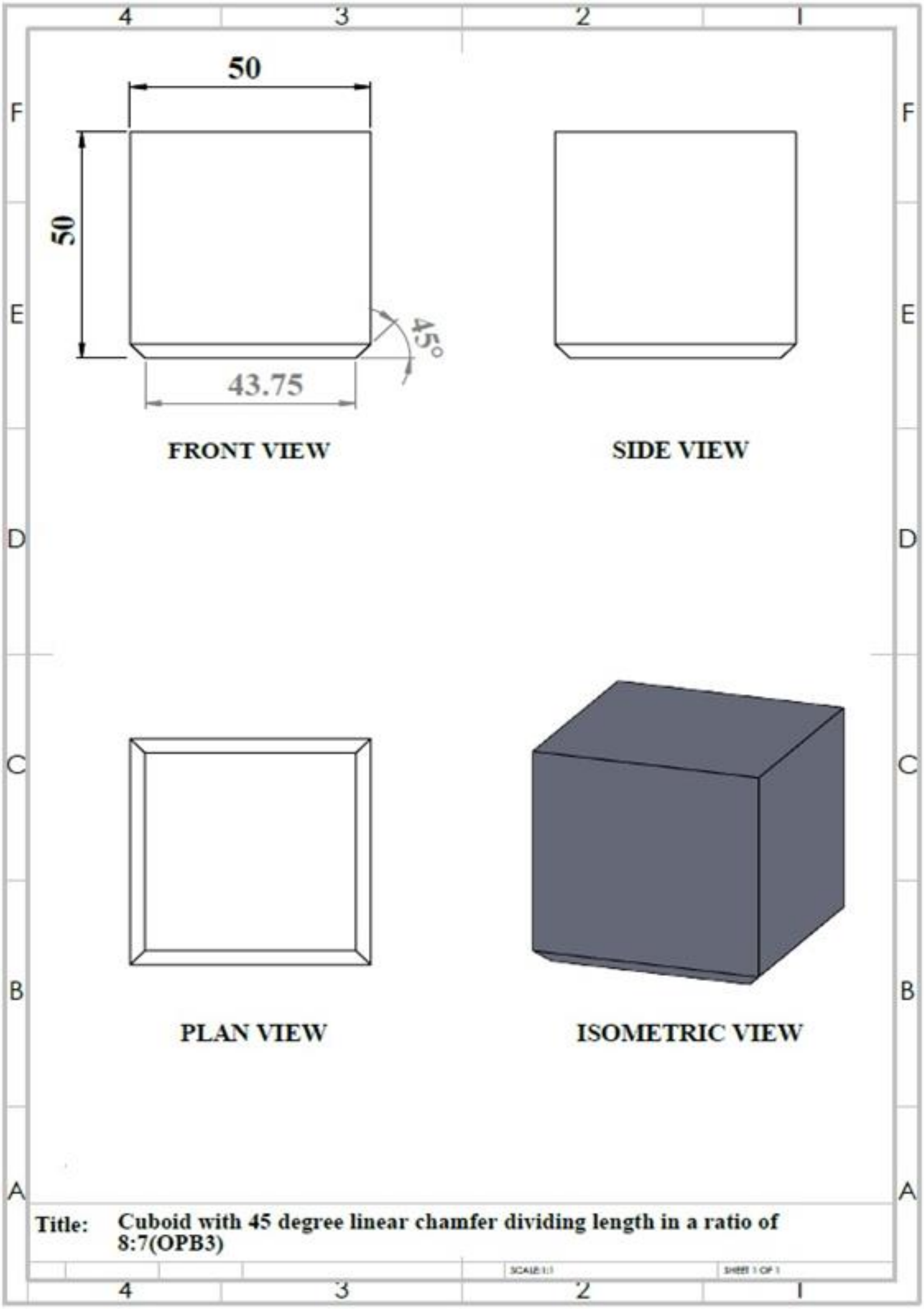


Figure 4.26: Design Parameters of Cuboid with 45 degree Linear Chamfer dividing Length in a Ratio of 8:7 (OPB 3)

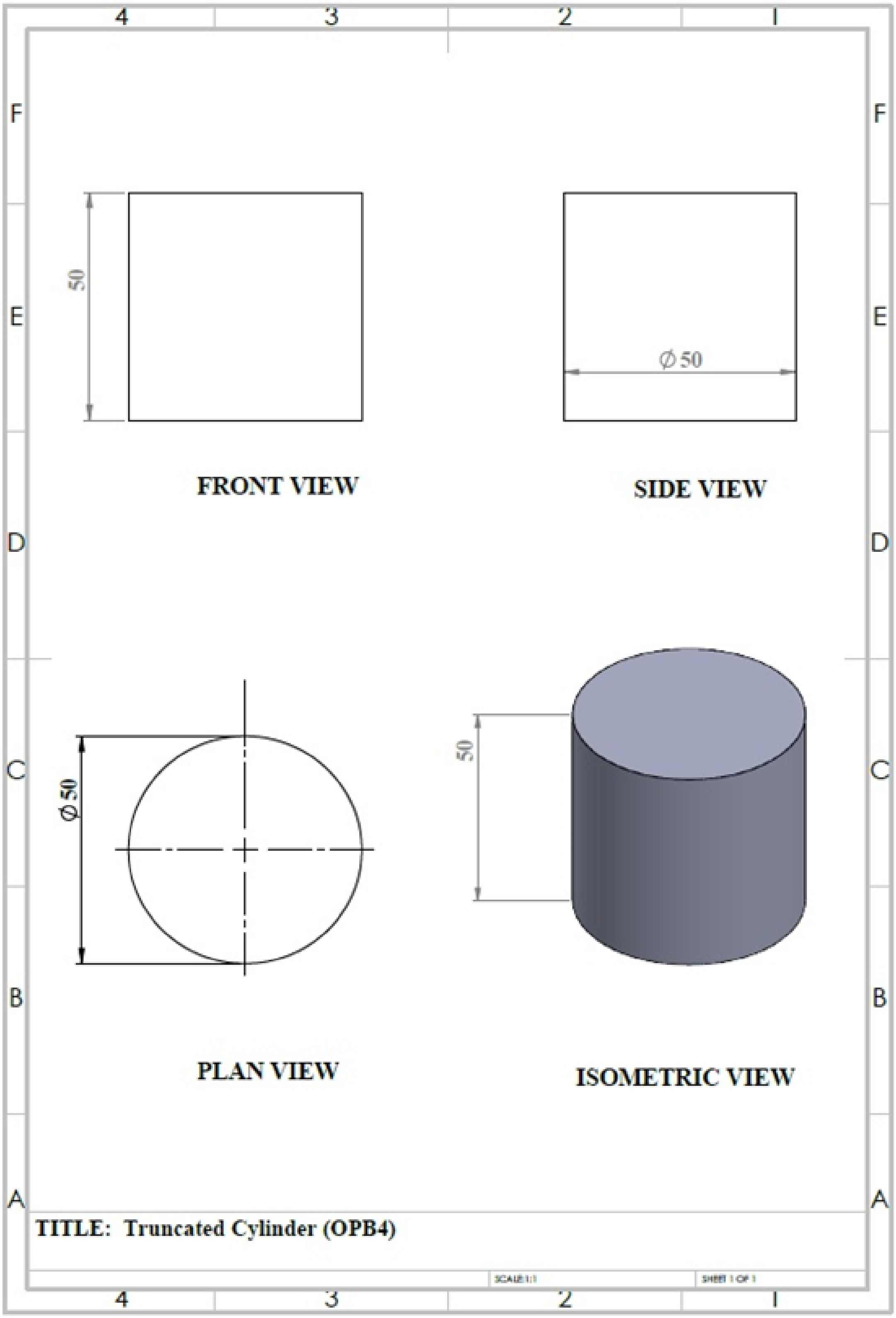


Figure 4.27: Design Parameters of Truncated Cylinder (OPB 4)

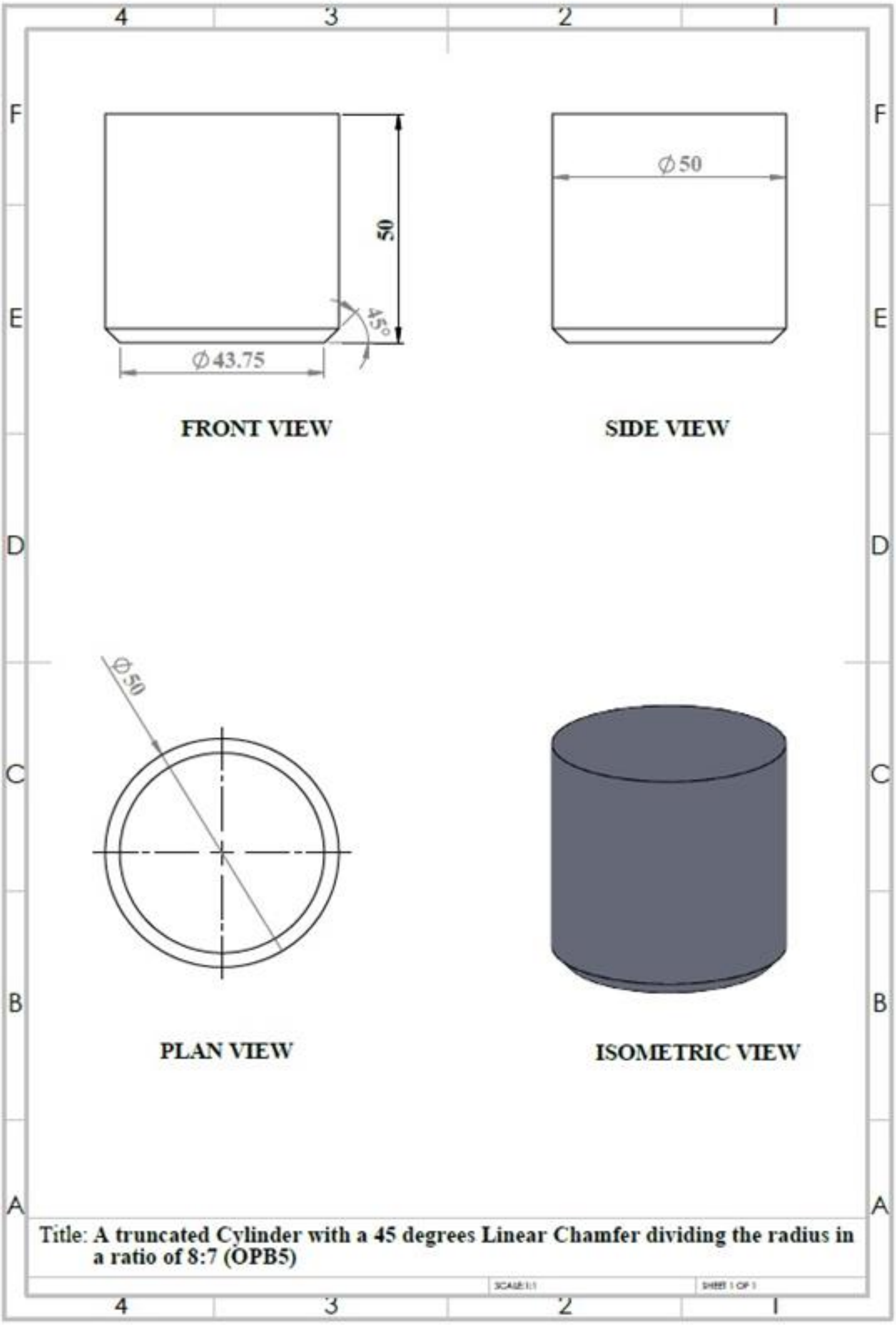


Figure 4.28: Design Parameters of Truncated Cylinder with 45 degree Linear Chamfer dividing the Radius in a Ratio of 8:7 (OPB 5)

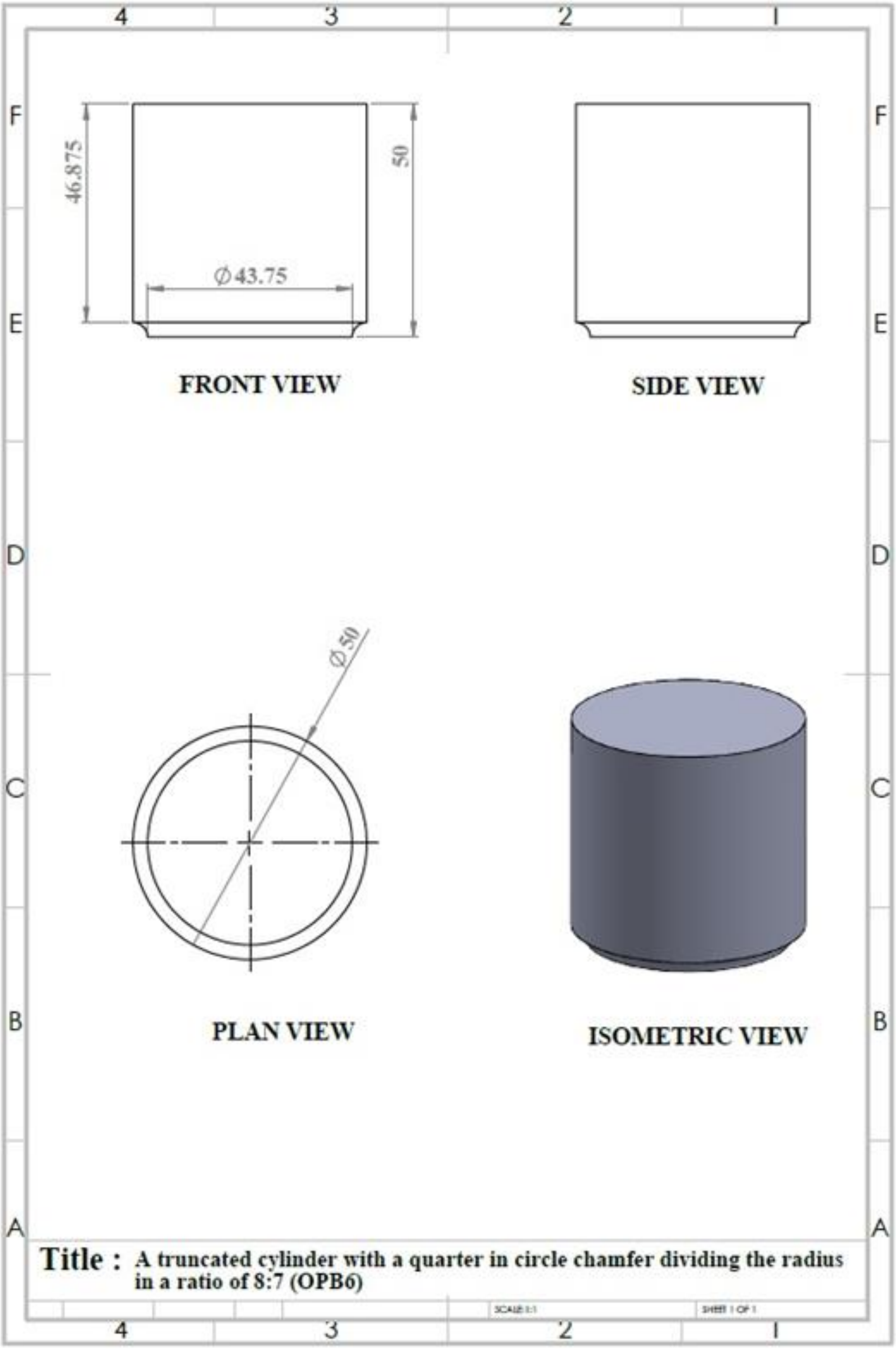


Figure 4.29: Design Parameters of Truncated Cylinder with a Quarter in Circle Chamfer dividing the Radius in a Ratio of 8:7 (OPB 6)

5. ANALYSIS & RESULTS

5.1 Simulation Analysis and Results

Computational Fluid Dynamics (CFD) software, XFlow was used for 2-D simulation of all six buoys. This simulation software is used for simulations in many fields such as Automotive, Aerospace, Manufacturing, Energy, Marine & Civil Engineering.

Initially, the water tank was created with the dimensions of 240m length, 15m width and 10m height and 1m amplitude regular wave was generated for the simulation. The following data sets are generated for simulation of one particular buoy:

a. Static Pressure
b. Vorticity
c. Total Pressure
d. Turbulence Intensity
e. Effective Viscosity
f. Volume of Liquid Phase

In this simulation, the static pressure, volume of liquid phase and the vorticity were considered for the comparison of results. Turbulence intensity was made to zero and effective viscosity is not considered for the comparison of simulation results as the same is not used for finding an important decision for this area of study.

The static pressure of the wave was graphically represented for all six buoys and average value for the static pressure after the particular buoy was interacted with the wave is calculated and tabulated in Table 5.1. The maximum average static pressure was observed in OPB 5 and the next values for the second and third were represented by OPB 3 and OPB 6 respectively. The loss of static pressure of the wave after interacting with the buoy is represented in the following graphs in Figure 5.1 to 5.6.

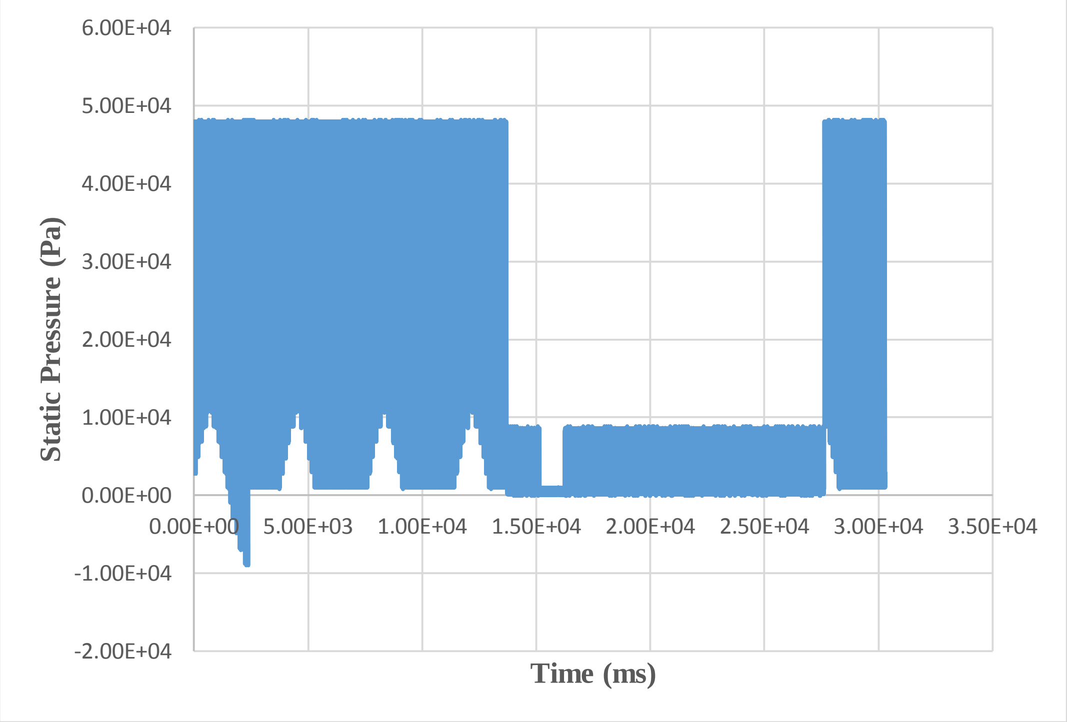


Figure 5.1: Variation of Static Pressure related to OPB 1

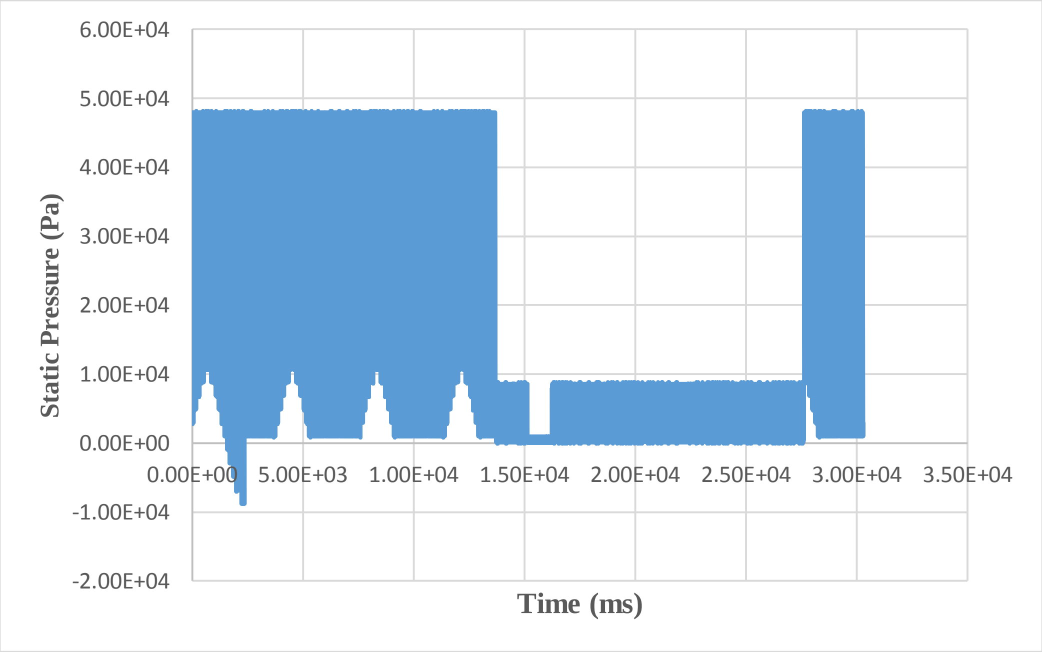


Figure 5.2: Variation of Static Pressure related to OPB 2

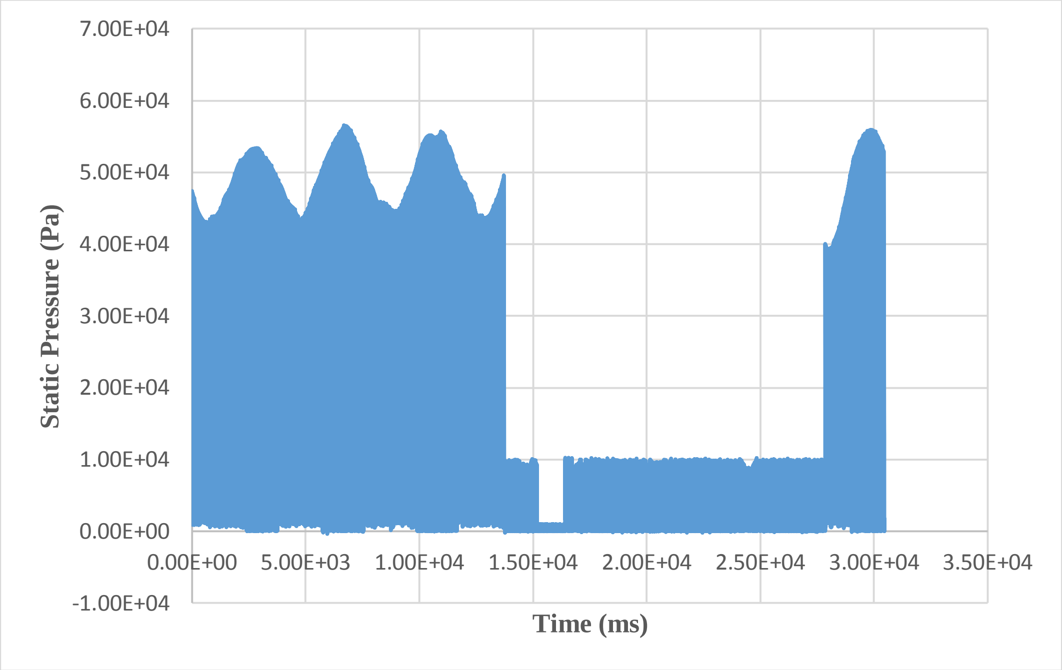


Figure 5.3: Variation of Static Pressure related to OPB 3

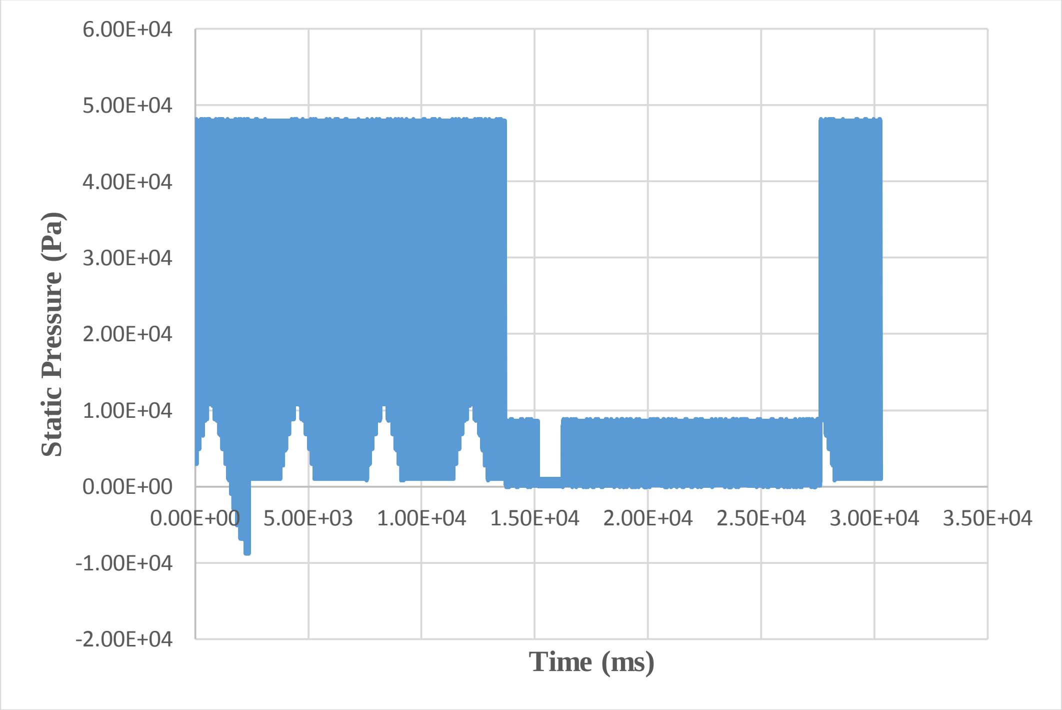


Figure 5.4: Variation of Static Pressure related to OPB 4

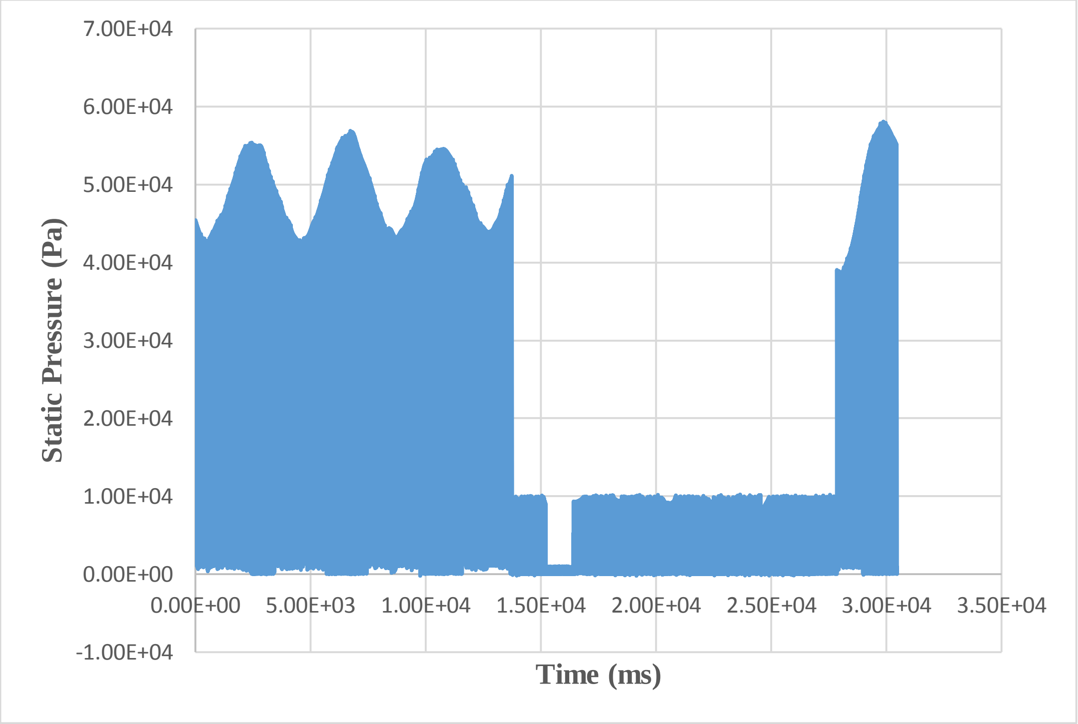


Figure 5.5: Variation of Static Pressure related to OPB 5

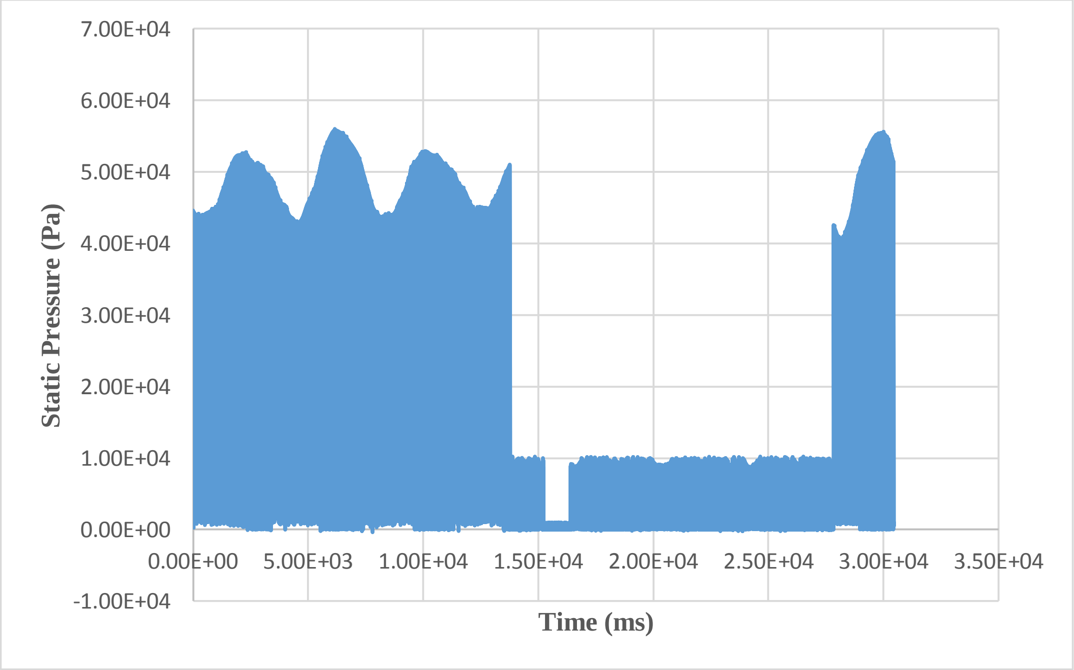


Figure 5.6: Variation of Static Pressure related to OPB 6

Table 5.1: Average Static Pressure of the Wave after Buoy Engagement

Sr. No.	Buoy Description	Average Value of Static Pressure (Pa)
1	OPB 1	3640.99
2	OPB2	3640.13
3	OPB3	3844.20
4	OPB4	3640.03
5	OPB5	3858.44
6	OPB6	3802.47

When analysing the average value of static pressure as per Table 5.1, it is clearly evident that higher the pressure value means, the loss of static pressure of the wave due to buoy interaction with the wave being less when compared to the other buoy arrangements.

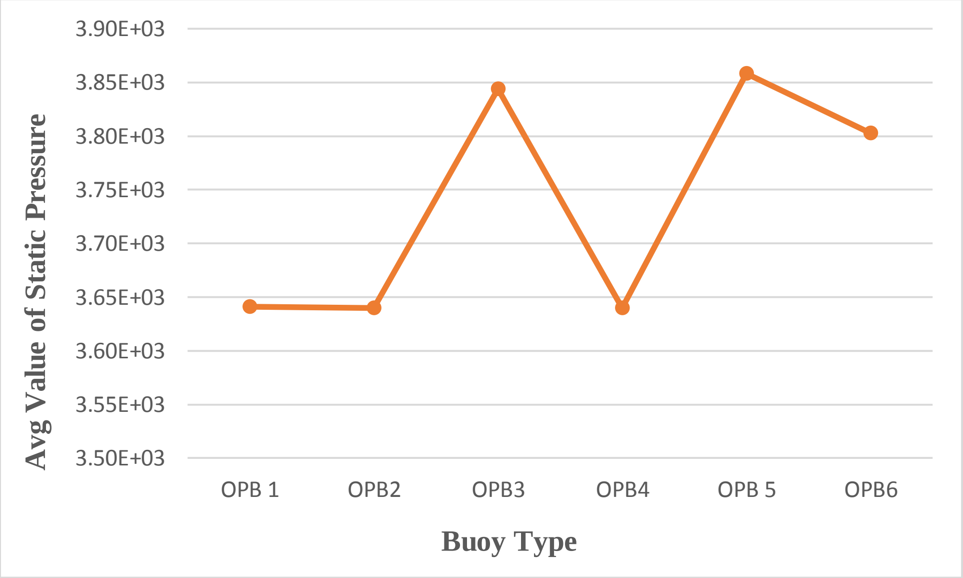


Figure 5.7: The Average Values of Static Pressure after Buoy Engagement

The graph in Figure 5.7 shows that the buoy arrangements belonging to the geometric shapes of OPB 3, OPB 5 and OPB 6 are performing well for the tested rack and pinion power take-off wave energy converter.

The next set of data obtained from the 2-D simulation of buoys is vorticity and is graphically represented in the following figures from Figure 5.8 to 5.13. The average values of vorticity for respective buoy arrangements are tabulated in Table 5.2. A clearly visible gap/difference is observed regarding the vorticity of OPB 2 and OPB 4 and this may be due to the flat underwater surface of both buoy arrangements. Both graphs in Figure 5.9 and 5.11 shows zero vorticity.

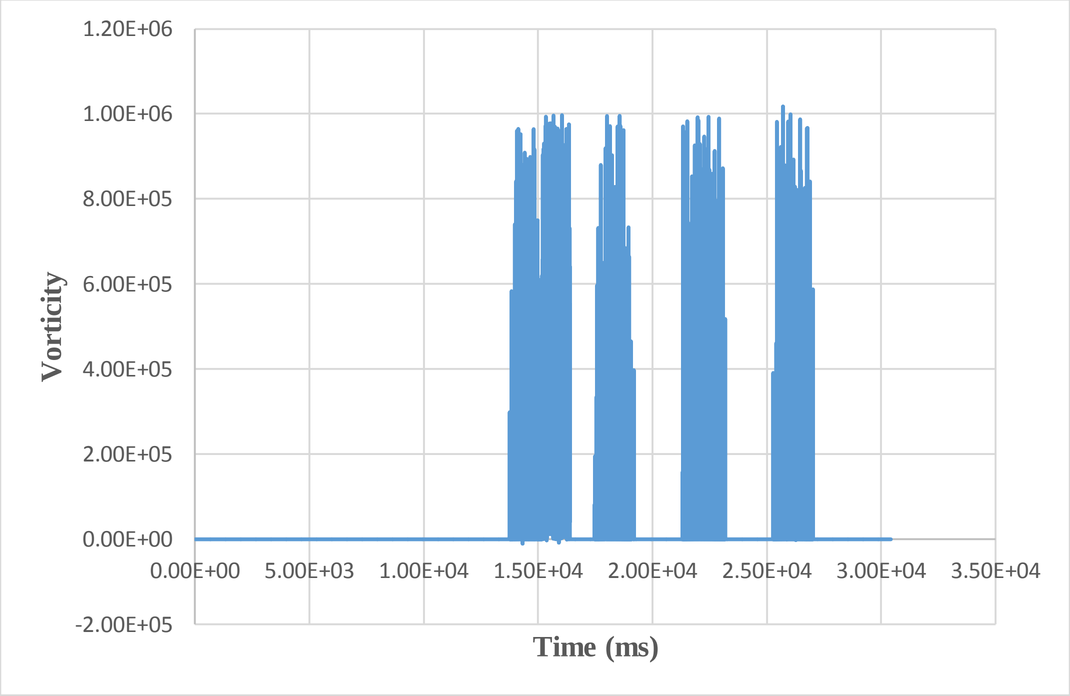


Figure 5.8: Vorticity related to OPB 1

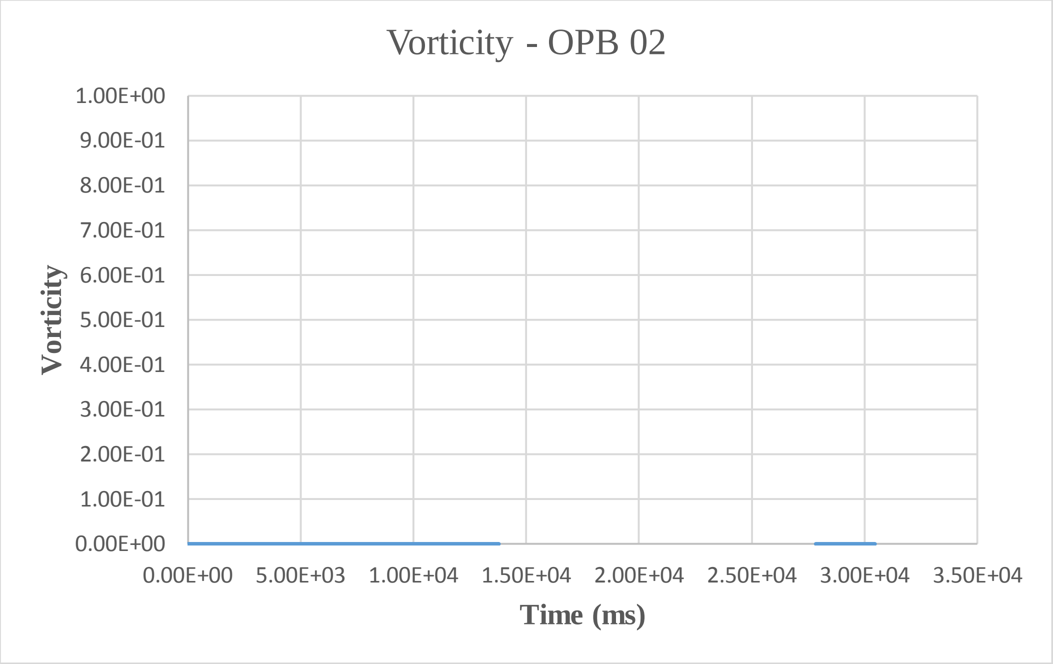


Figure 5.9: Vorticity related to OPB 2

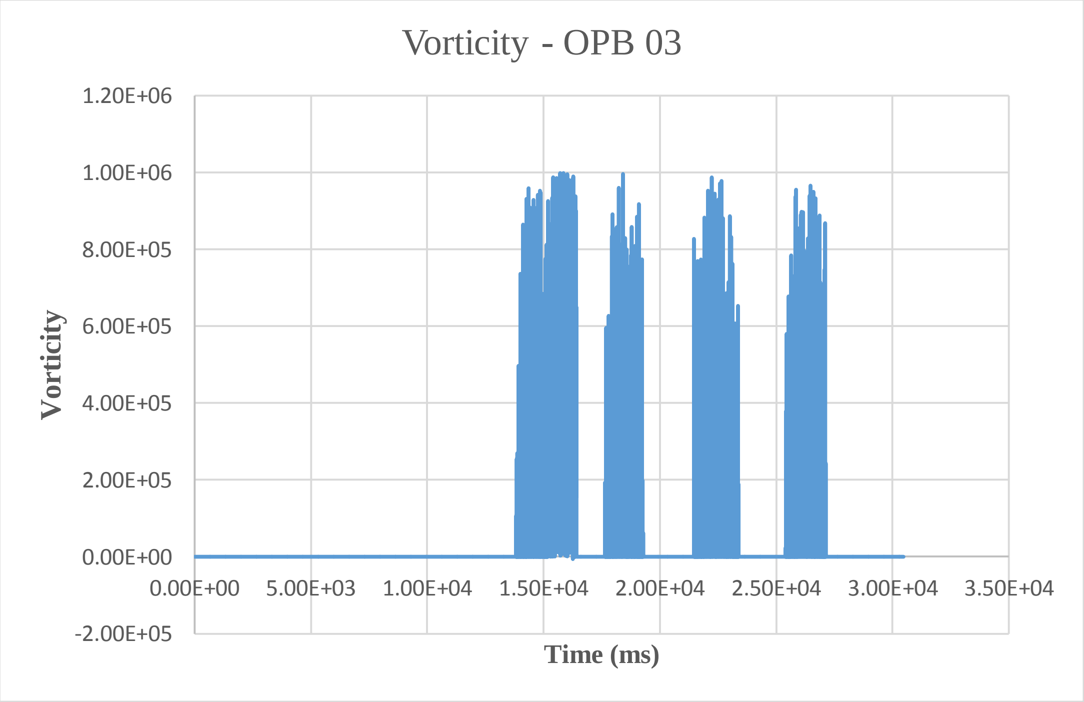


Figure 5.10: Vorticity related to OPB 3

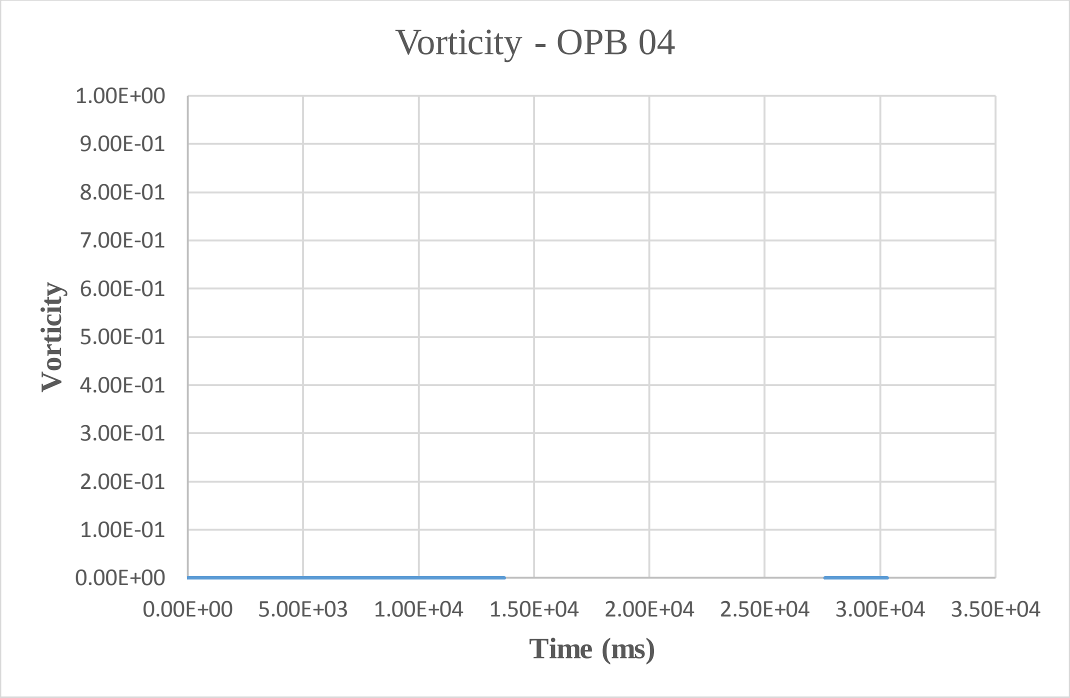


Figure 5.11: Vorticity related to OPB 4

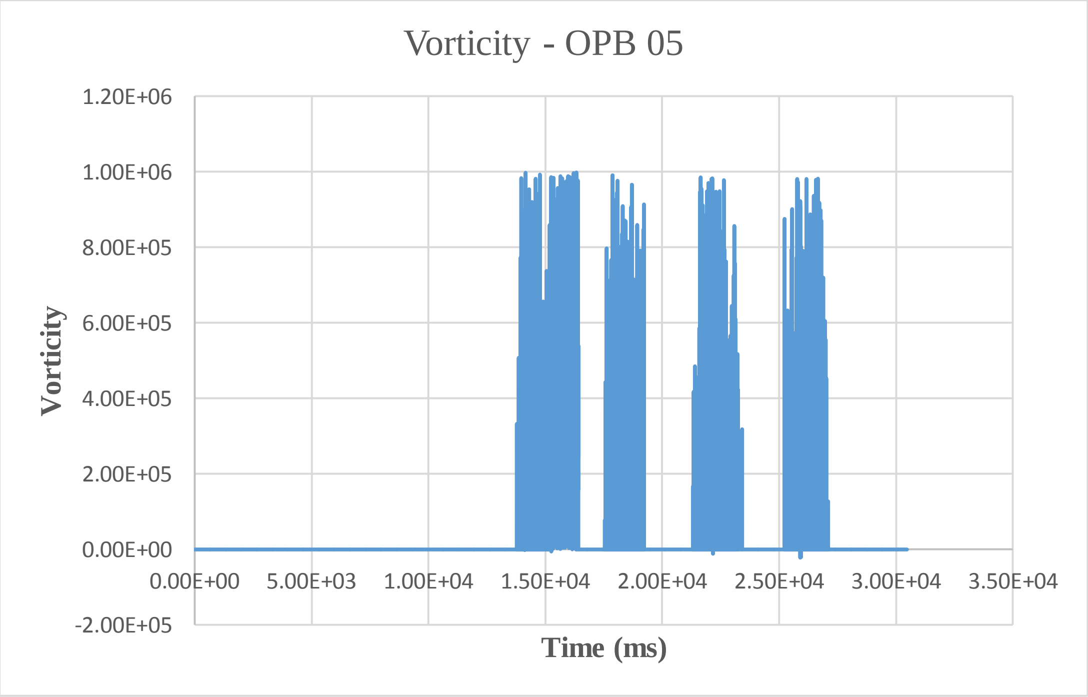


Figure 5.12: Vorticity related to OPB 5

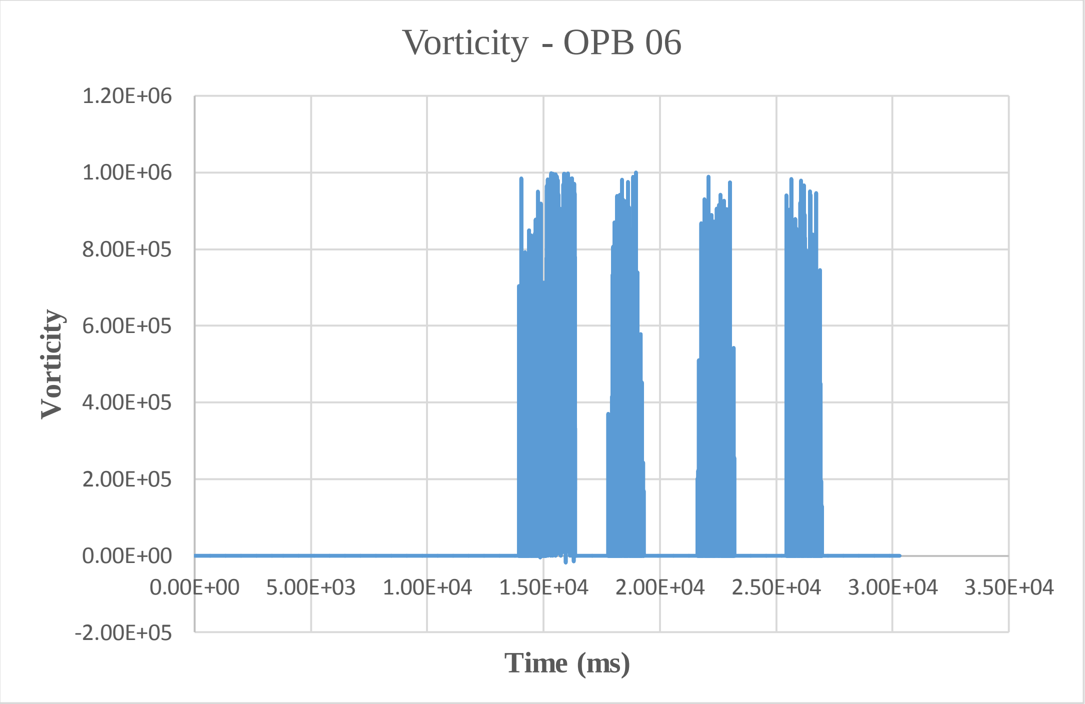


Figure 5.13: Vorticity related to OPB 6

Table 5.2: Average Value of Vorticity of the Wave during Buoy Engagement

Sr. No.	Buoy Description	Average Value of Vorticity
1	OPB 1	58063.29
2	OPB2	0.00
3	OPB3	61080.99
4	OPB4	0.00
5	OPB5	59995.11
6	OPB6	59780.80

When analysing the average value of vorticity as per Table 5.2, it is clearly evident that the higher the vorticity value means the absorption capability of power due to buoy interaction with the wave is high when compared to other buoy arrangements. That means, the geometric shape of the particular buoy is better capable of breaking waves and absorbing more power than the other buoy arrangements.

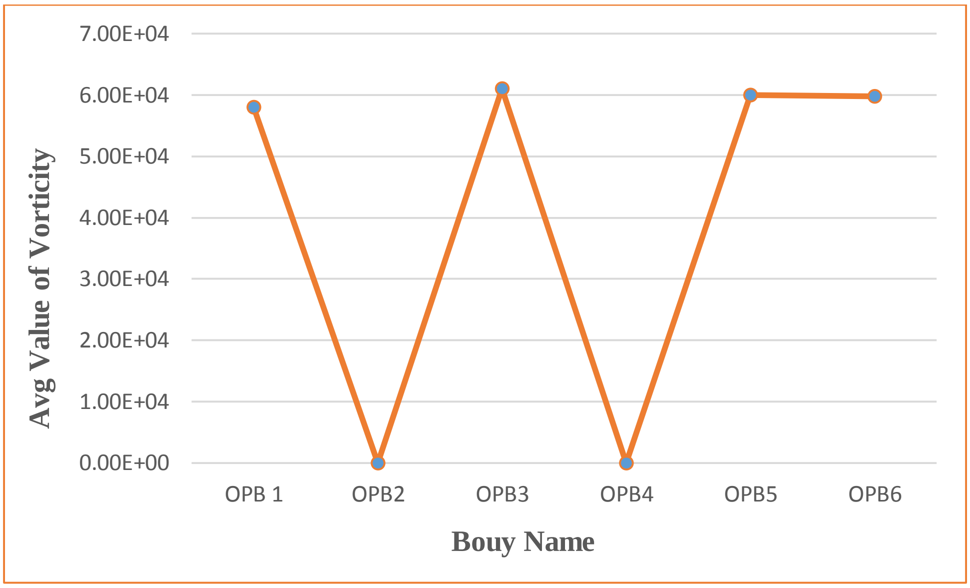


Figure 5.14: The Average Values of Vorticity after Buoy Engagement

The graph in Figure 5.14 shows that the buoy arrangements belonging to the geometric shapes of OPB 1, OPB 3, OPB 5 and OPB 6 are performing well for the tested rack and pinion power take-off wave energy convertor.

The volume of liquid phase is the next set of data which were obtained from the 2-D simulation of buoys and graphically represented in the following figures from Figure 5.15 to 5.20. The average values of volume of liquid phase for respective buoy arrangements are tabulated in Table 5.3. Further, it is observed that the volume of the liquid phase of OPB 1 is totally different from the other buoy arrangements and this may be due to the geometric shape of the sphere arrangement. The value becomes zero after the interaction of the buoy with the wave and this is indicated in Figure 5.15.

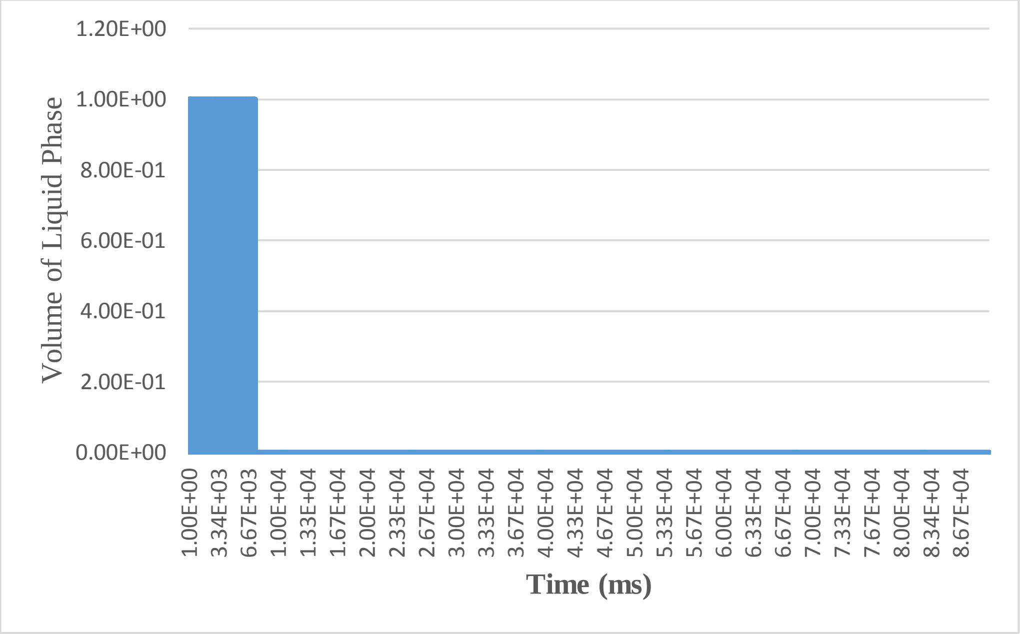


Figure 5.15: Volume of Liquid Phase related to OPB 1

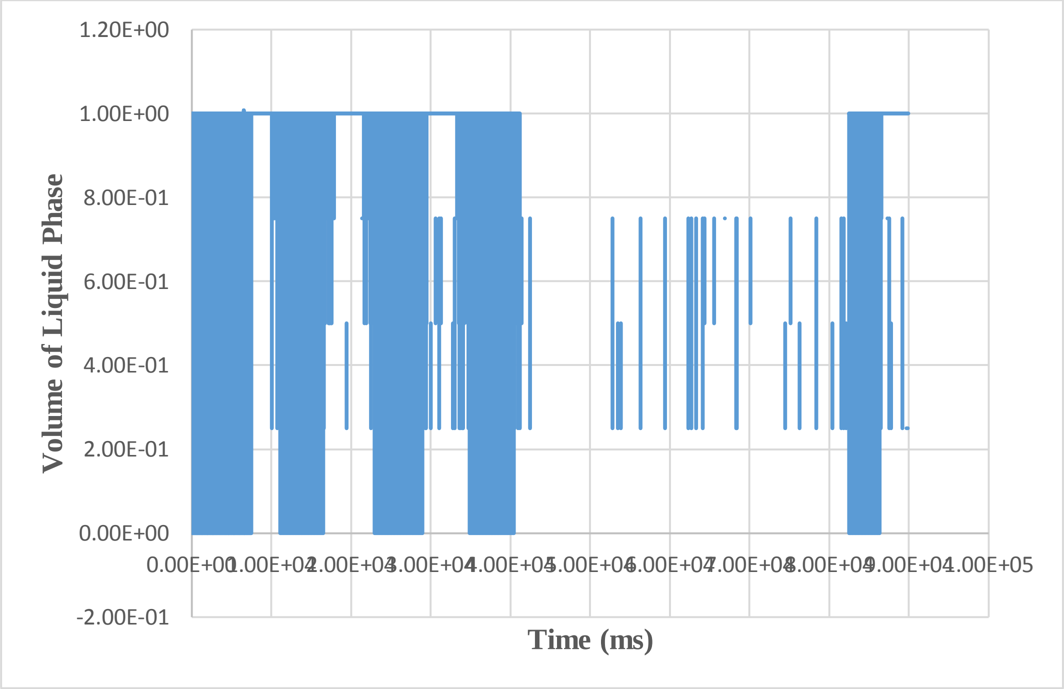


Figure 5.16: Volume of Liquid Phase related to OPB 2

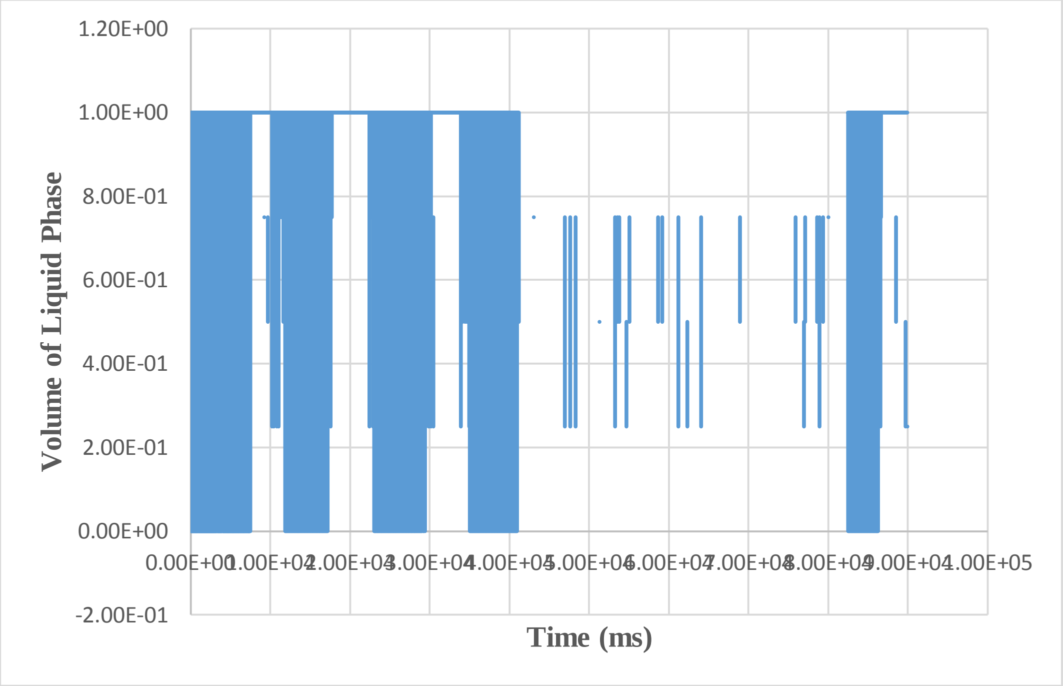


Figure 5.17: Volume of Liquid Phase related to OPB 3

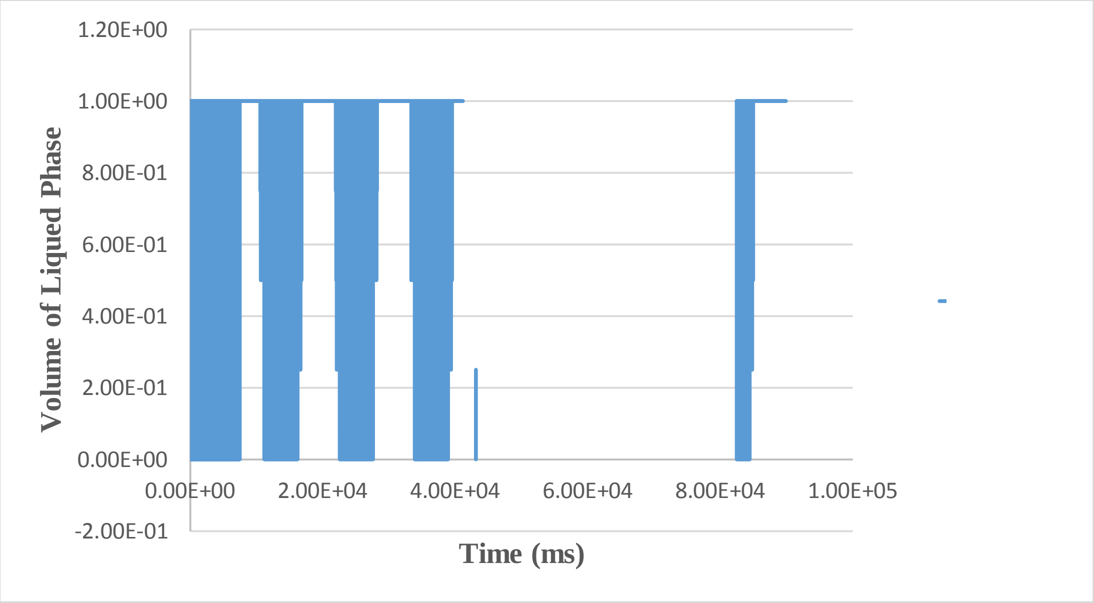


Figure 5.18: Volume of Liquid Phase related to OPB 4

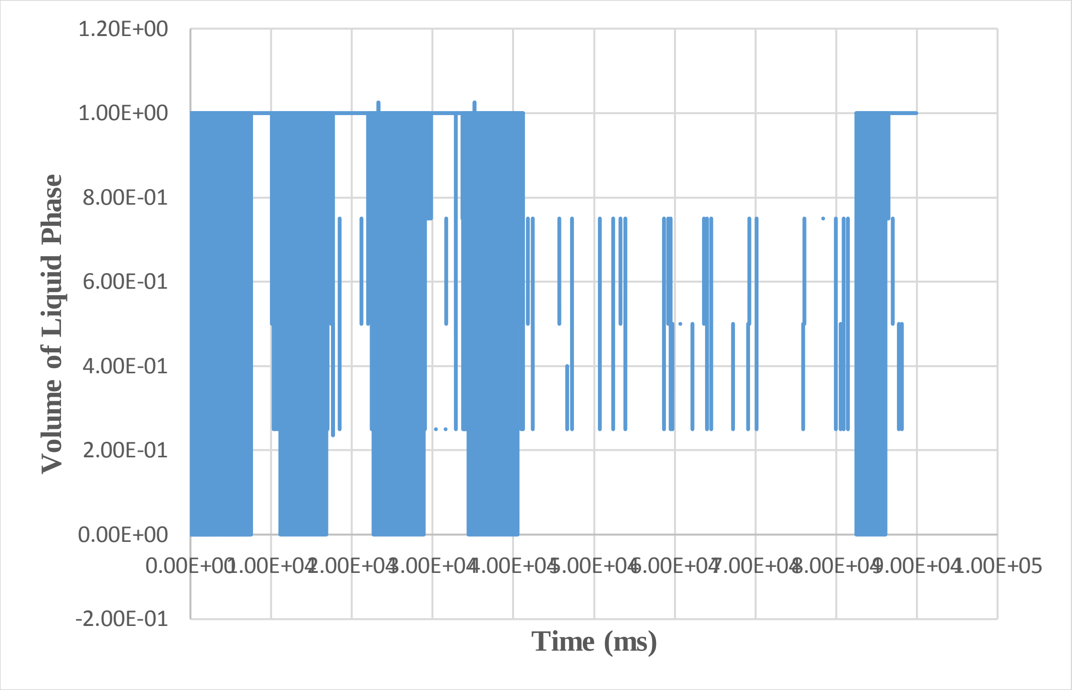


Figure 5.19: Volume of Liquid Phase related to OPB 5

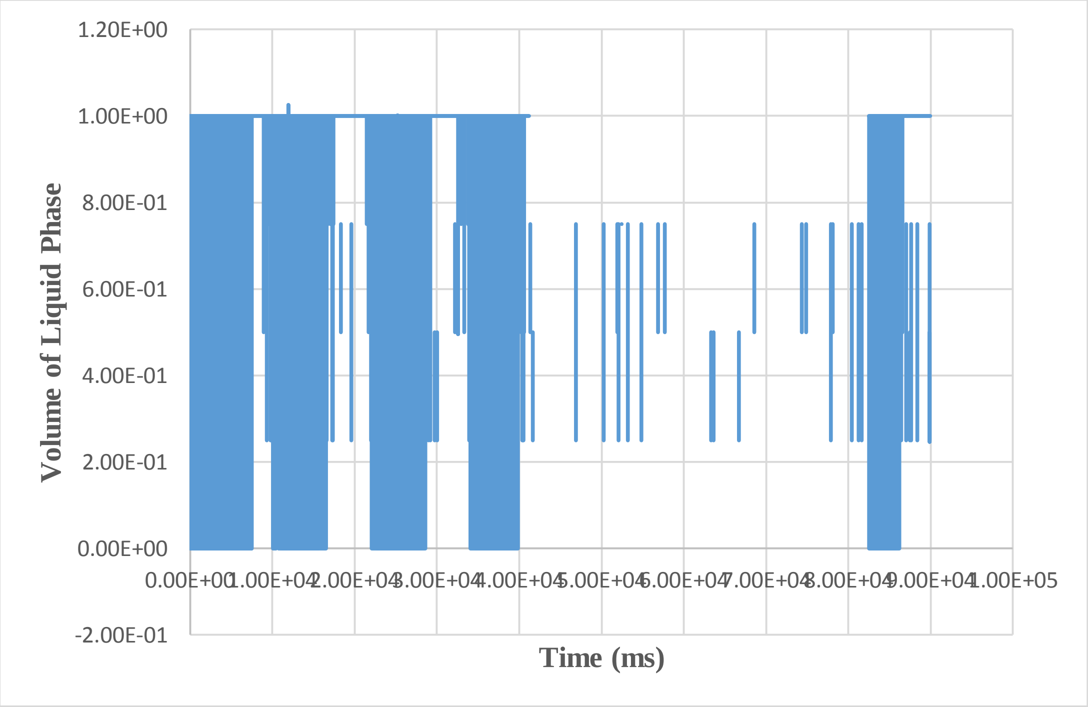


Figure 5.20: Volume of Liquid Phase related to OPB 6

Table 5.3: Average Values of Volume of Liquid Phase of the Wave during Buoy Engagement

Sr. No.	Buoy Description	Average Value of Volume of Liquid Phase
1	OPB 1	0.3691
2	OPB2	2.7518
3	OPB3	0.5064
4	OPB4	3.5205
5	OPB5	0.4918
6	OPB6	0.5349

When analysing the average value of volume of liquid phase as per Table 5.3, it is clearly evident that the lower the volume of liquid phase value means, the absorption capability of power of the selected buoy due to buoy interaction with the wave is high when compared to the other buoy arrangements. That means, the geometric shape of the particular buoy is more capable of withstanding without submerging in the water when the waves get interacted with the buoy arrangement and absorb more power than the other buoy arrangements for the tested wave energy converter.

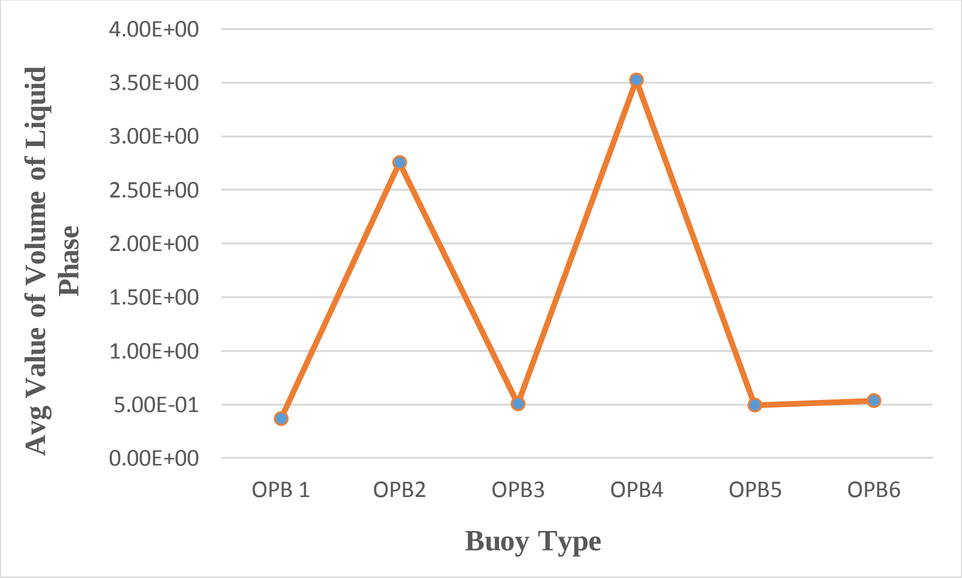


Figure 5.21: The Average Values of Volume of Liquid Phase after Buoy Engagement

The graph in Figure 5.21 shows that the buoy arrangements belonging to the geometric shapes of OPB 1, OPB 3, OPB 5 and OPB6 are performing well for the tested rack and pinion power take-off wave energy converter.

5.2 Experimental Analysis & Results

Practical experiments have been conducted based on the oscillating buoy operated rack and pinion power take-off proto type wave energy convertor assembled in the testing tank with wave making facility. There are three sets of readings taken from the practical experiments and graphically represented as follows:

a. Movement of the Rack vs Wave Height
b. Main Shaft RPM vs Wave Height
c. Motor RPM Median vs Wave Height

Table 5.4: Data Sheet for Movement of Rack vs. Wave Height

Buoy Name	Wave Height (cm)			
	15.0	20.0	25.0	30.0
OPB 01	12.0	15.5	17.0	18.5
OPB 02	14.0	18.0	22.0	23.0
OPB 03	16.0	20.5	23.5	26.0
OPB 04	14.0	17.5	19.0	21.0
OPB 05	17.0	22.0	25.0	28.0
OPB 06	15.5	20.0	23.0	24.0

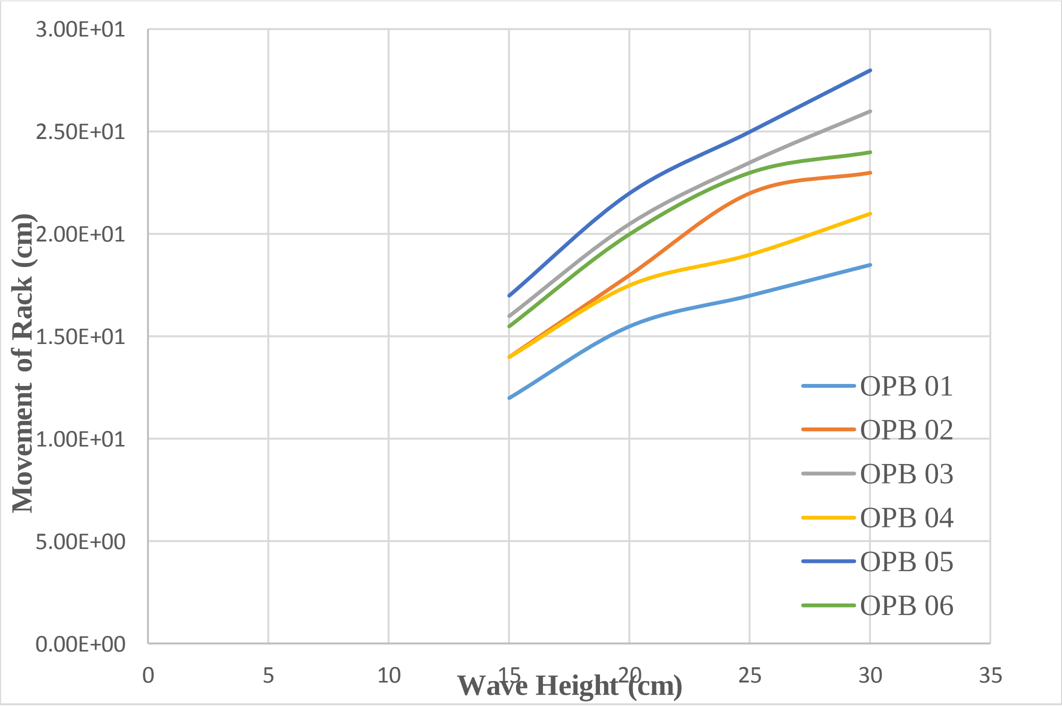


Figure 5.22: Movement of Rack vs Wave Height

Table 5.5: Data Sheet for Main Shaft RPM vs Wave Height

Buoy Name	Wave Height (cm)			
	15.0	20.0	25.0	30.0
OB 01	36.0	40.0	55.5	59.0
OB 02	38.0	41.0	68.0	70.5
OB 03	52.0	62.0	77.5	79.5
OB 04	37.0	41.0	64.0	65.0
OB 05	58.0	65.5	79.5	80.5
OB 06	46.5	55.0	72.0	74.0

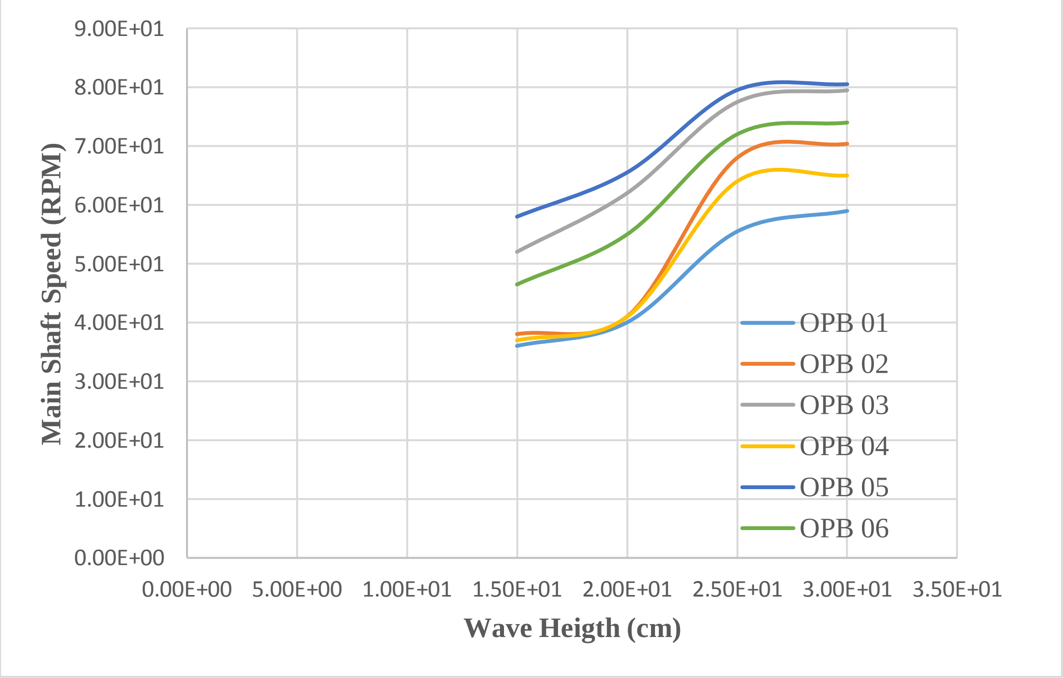


Figure 5.23: Main Shaft RPM vs Wave Height

Table 5.6: Data Sheet for Motor Shaft RPM vs Wave Height

Buoy Name	Wave Height			
	15.0.0	20.0	25.0	30.0
OB 01	106.0	118.0	163.0	174.0
OB 02	110.0	121.5	200.5	206.0
OB 03	153.0	182.5	229.0	233.0
OB 04	109.0	121.0	187.0	191.5
OB 05	171.0	193.0	234.5	238.0
OB 06	137.0	164.0	210.5	216.0

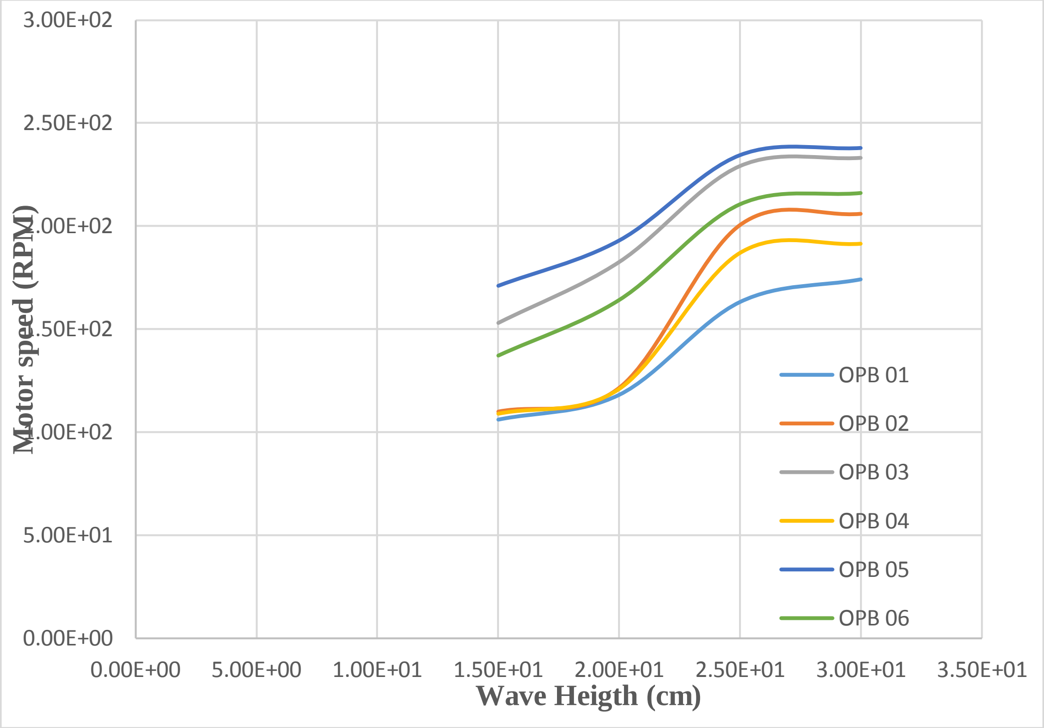


Figure 5.24: Motor Shaft RPM vs Wave Height

A linear positive relationship is observed between the movement of the rack and the wave height. When the movement of the rack is high then this relationship is quite deviated as there are some deficiencies when machining the rack. A non-linear relationship is observed between the wave height and the rpm of the main shaft. However when the wave height increases more than 25cm the rpm decreases. This is also due to the two materials which are being used to machine the rack, and there is a restriction to the movement of the rack at the joint of these two materials. Maximum rpm is obtained when the wave height is 25cm. When collecting data for the analysis the waves were created while using a manual method, the frequency of the waves created were maintained at 0.3 Hz. The graphical results of practical analysis show that the OPB 5 (A truncated cylinder with a 45° linear chamfer dividing the radius in a ratio of 8:7) is the most compatible oscillating buoy arrangement for the rack and pinion power take-off wave energy converter and OPB 3 (A cuboid with a 45° linear chamfer dividing length in a ratio of 8:7) and OPB 6 (A truncated cylinder with a quarter in-circle chamfer dividing the radius in a ratio of 8:7) are in second and third positions respectively.

6. DISCUSSION

After investigating the results of both methods; 2-D simulation results and experimental results, it is clearly noted that the selection of the most suitable wave power converting technique/arrangement, in this area of study, is the oscillating buoy arrangement and it is the most important part of the particular wave energy converter to facilitate the absorption of maximum power from the coming incident waves. The best results are shown in the oscillating buoys of the OPB 5 (A truncated cylinder with a 45° linear chamfer dividing the radius in a ratio of 8:7) and it is the mostly compatible oscillating buoy arrangement for the rack and pinion power take-off wave energy converter while OPB 3 (A cuboid with a 45° linear chamfer dividing length in a ratio of 8:7) and OPB 6 (A truncated cylinder with a quarter in-circle chamfer dividing the radius in a ratio of 8:7) respectively have shown the second and third positions with respect to the performance analysis. Predicting of the results based on the simulation is an economical concept rather than going for producing of prototypes by spending huge amounts of money. Doing a simulation is also not an easy task to get an accurate set of data and well trained personnel on simulation software are essential to undertake analysis based on simulation and to obtain more accurate sets of data.

This study was focussed only on regular waves with known frequency and amplitude and different results can be expected with the interaction of irregular waves with many frequencies and different amplitudes. There are two important parameters discussed in Chapter 3, which are Absorption width and Absorption efficiency. By enabling to float a accelerometer on a low inertia floating object on the coming incident waves, it is possible to calculate the energy of the incident waves which are interacting with the oscillating buoy arrangements and the absorbed energy by the power buoy is also feasible to calculate by using the same mechanism while keeping the accelerometer on top of the buoy when oscillating. On the other hand, once the absorbed power by the oscillating buoy is calculated, it is very easy to calculate the actual power transmitted by the power take-off mechanism up to the power generation section.

Many researches have been carried out around the world to find out the best, suitable wave energy converters and a lot of improvements were implemented to improve the performance of existing wave energy converters such as improvements on wave power converting techniques, power take-off mechanisms, power generating sections, etc.

Many concepts are advancing into the first commercial plant or large demonstration pilot plant and many concepts of wave energy conversion have been proposed and investigated into in recent years, which transform energy produced by ocean waves into electrical energy. These converters can be grouped into five categories: point absorbers, attenuators, terminators, oscillating water columns and overtopping devices. Further, there are three main versions of Power Take-Off configurations which are connected with the WECs: Hydraulic method, Mechanical method and Directly Electrical.

Wave energy converter design ideally involves experimental and numerical modelling in order to get a suitable prediction of the converter performance. Different numerical model techniques have been utilized in order to predict the power performance and the wave structure interaction such as linear wave diffraction theory in time and frequency domains for regular and irregular waves and Computational Fluid Dynamics (CFD) models. Further, some researchers have used numerical simulation techniques by using MATLAB to analyse the performance without going for fabrication of actual prototype models.

Apart from the above, the fabrication of buoys with fibre material will reduce the weight and will facilitate the easy up and down movement of the buoy ensuring the increased rack movement of the WEC for the same experimental analysis.

7. CONCLUSION

In this research work, a prototype model of an oscillating buoy operated Rack and Pinion Power Take-Off WEC is developed as a tank testing model with wave making facility. Six types of buoys were designed in equal weight and fabricated with the height to width ratio as 1. In this study, the thesis work based on two separate analyses; a numerical simulation by using Computational Fluid Dynamic (CFD) software and experimental tests using WEC model was established in the testing tank with wave making facility for all six buoys. The simulation of buoys were modelled with CFD software XFlow and the analysis were done using 2-D simulation to obtain sets of data to analyse the behaviour of the buoys. Regular waves with 1m amplitude was utilised for the simulation analysis for a period of 20 minutes. Experimental tests were implemented by using a tank model of WEC and results were represented such as Wave height vs Rack height, Main shaft speed vs Rack height and Motor Speed vs Rack height. Only regular waves with four different amplitudes were used in experimental analysis of all buoys.

Finally, the best performing buoys were selected based on the numerical simulation analysis and the proving of same was done based on the prototype model of oscillating power buoy operated Rack and pinion PTO WEC. The graphical results of simulation and experimental analysis show that the OPB 5 (A truncated cylinder with a 45^o linear chamfer dividing the radius in a ratio of 8:7) was the best performing oscillating buoy for the rack and pinion power take-off wave energy converter and OPB 3 (A cuboid with a 45^o linear chamfer dividing length in a ratio of 8:7) and OPB 6 (A truncated cylinder with a quarter in-circle chamfer dividing the radius in a ratio of 8:7) showed the second and third positions in performance respectively.

8. FUTURE WORK

The scope of this thesis was limited to regular waves with known frequency and amplitude and 2-D simulation. The path is open for someone who wishes to perform more analysis based on irregular waves with many frequencies and different amplitudes and 3-D simulation. Another option is available to optimise the performance of the rack and pinion power take-off wave energy convertor as a whole. On the other hand, the concept of hybrid WECs while combining this method with a wind power generating mechanism is also another feasible way of researching to harvest the renewable energy sources. The development of a wave energy converter is a challenging issue for a country like Sri Lanka and involves many stages such as understanding of the concepts of different categories of wave energy converters around the world, wave energy absorption methods, optimization of the absorption and conversion systems, analysis based on numerical simulations and finally, experimental analysis based on the prototype tank testing WEC models. Analyses based on computational simulation and experimental analyses based on prototypes are not adequate to implement the real scale WEC in a country. The most important thing is the survivability under extreme conditions, which may be due to storms or any other harmful situation and this is essential to be proved on any WEC. Structural integrity and hydrodynamic stability are the two essential phenomenon that are required to be proved to ensure the survivability of WECs. Someone interested in continuing with a research on this area can continue with extreme analysis with respect to structural integrity and hydrodynamic stability of WECs. Further to the above, the experimental testing can be extended to utilize regular waves, random waves and focused waves for better analysis and results together with 3D numerical simulation. For a WEC, it is a must to select a site based on the appropriate wave data. The next step is to perform a proper economic analysis to define the converter dimensions with the best ratio of average power output to converter system mass. Apart from that, the investigation of the political and environmental regulations of suitable sites for positioning a full scale prototype is also another important aspect. The investigation of all legal documentation together with environmental impact studies should be performed in order to minimise the negative impacts as far as possible. This is also another feasible area to continue with new research works related to wave energy convertors.

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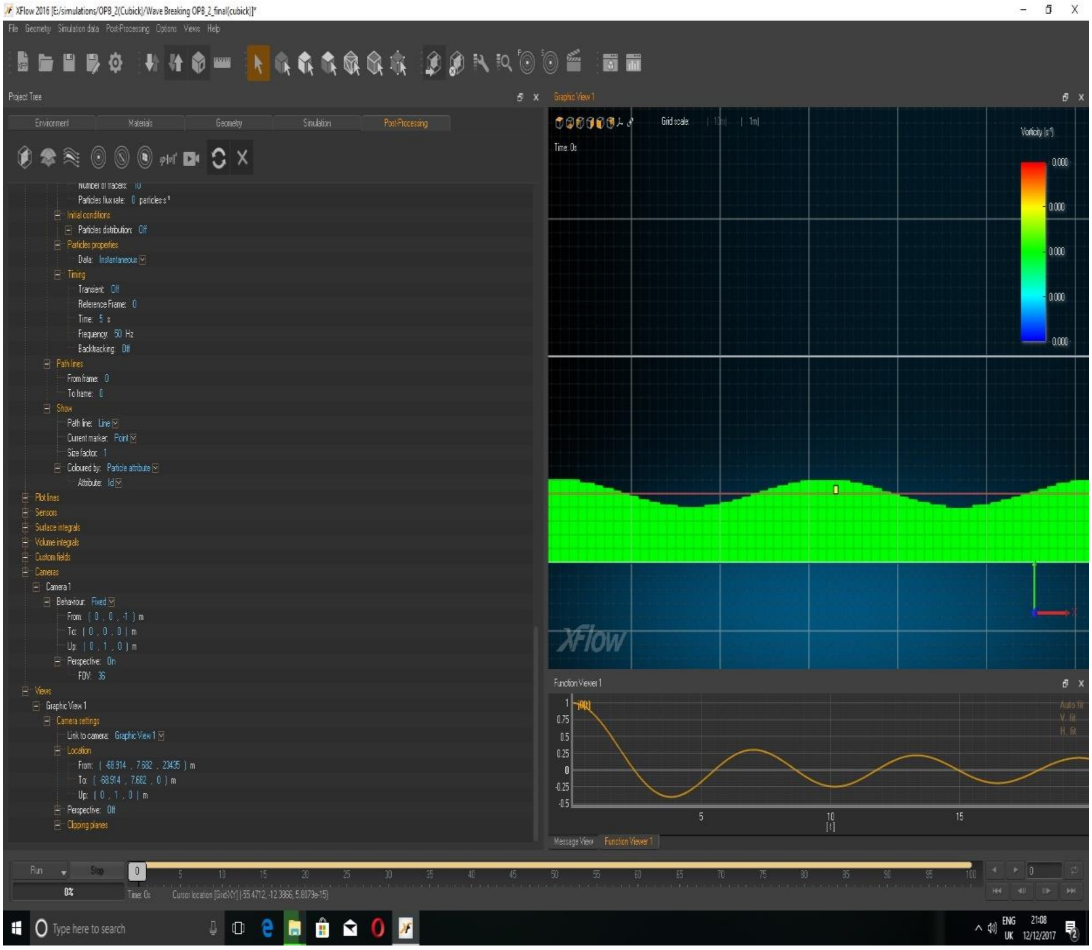
APPENDIX A : Programme Interface



XFlow 2016 [E:/simulations/OPB_2(Cubick)/Wave Breaking OPB_2_final(cubick)]*

Number of tracers: 10
Particles flux rate: 0 particles·s⁻¹
Initial conditions
Particles distribution: Off
Particles properties
Data: Instantaneous
Timing
Transient: Off
Reference Frame: 0
Time: 5 s
Frequency: 50 Hz
Backtracking: Off
Path lines
From frame: 0
To frame: 0
Show
Path line: Line
Current marker: Point
Size factor: 1
Coloured by: Particle attribute
Attribute: Id
Plot lines
Sensors
Surface integrals
Volume integrals
Custom fields
Cameras
Camera 1
Behaviour: Fixed
From: (0 , 0 , -1) m
To: (0 , 0 , 0) m
Up: (0 , 1 , 0) m
Perspective: On
FOV: 36
Views
Graphic View 1
Camera settings
Link to camera: Graphic View 1
Location
From: (-68.914 , 7.682 , 23.435) m
To: (-68.914 , 7.682 , 0) m
Up: (0 , 1 , 0) m
Perspective: Off
Clipping planes

Time: 0s
Cursor location [Grid-XY] (-55.4712, -12.3866, 5.8079e-15)

APPENDIX B: Simulation Picture