DESIGN AND STUDY OF SPINNING SEA WAVE POINT ABSORBER

By:

JOSHUA WONG JIA YI

(Matrix No.: 123302)

Supervisor

Ir. Dr. Chan Keng Wai

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Universiti Sains Malaysia

Declaration

I hereby declare that the project is based on my original work except for quotation and citations which have been duly acknowledged. I authorized Universiti Sains Malaysia to lend this thesis to other institutions or individuals for purpose of scholarly research.

JOSHUA WONG JIA YI

Matrix No.: 123302

Date: 16 MAY 2018

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List of Symbols

Symbol	Description	Unit
ρ	Density	kg/m^3
H	Significant Wave Height	m
T	Wave Period	s
g	Gravitational Acceleration	m/s^2
λ	Wave Length	m
f	Wave Frequency	s^{-1}
L	Capture Width	m
L_{max}	Maximum Capture Width	m
f_n	Natural Frequency	s^{-1}
k	Restoring Spring Coefficient	kgs^{-2}
m	Mass of Buoy	kg
m_w	Added Mass	kg
A_{wp}	Wetted Plane Area	m^2
z	Displacement of Buoy	m
t	Time	s
F_{ex}	Wave Excitation Force	N
F_{rad}	Radiation Force	N
F_{res}	Hydrostatic Restoring Force	N
F_{damp}	External Damping Force	N
F_{tun}	Tuning Force	N
P	Power	W

V	Voltage	V
R	Resistance	Ω

List of Abbreviations

Abbreviation	Description
WEC	Wave Energy Converter
CWR	Capture Width Ratio
$Width_{active}$	Active Width of Device
DC	Direct Current
PTO	Power Take Off
SD	Standard Deviation

Abstract (BM)

Sumber tenaga yang boleh diperbaharui menjadi lebih penting apabila kita ingin memastikan kelestarian dalam penjanaan tenaga untuk masa depan. Dengan potensi untuk mendapatkan lebih daripada 20,000TWh tenaga elektrik dari laut, pelbagai jenis penukar tenaga sedang dibangunkan. Salah satu penukar tenaga sedemikian adalah penyerap titik yang menukarkan tenaga potensi dan tenaga kinetik dalam gerakan gelombang laut kepada elektrik. Walaupun teknologi penyerap titik telah dibangunkan selama lama lagi, tiada penyelidikan telah dijalankan untuk mengkaji keberkesanan penggunaan gerakan berputar untuk penjanaan elektrik di penyerap titik sebagai ganti mekanisme translasi konvensional. Kajian Spinning Sea Wave Point Absorber menumpukan kepada pemahaman, reka bentuk, fabrikasi dan pengujian mekanisme gear spiral yang dilaksanakan dalam penyerap titik yang dijalankan dalam tangki gelombang terkawal. Ia bertujuan untuk membandingkan nisbah lebar tangkapan dengan penyerap titik konvensional serta untuk mengenal pasti sudut lead yang paling berkesan dalam mekanisme gear spiral. Sebuah tangki gelombang dibina dan gelombang yang dihasilkan telah dicirikan. Dengan ciri-ciri gelombang, penyerap titik direka dan difabrikasi. Melalui eksperimen, CWR telah dibandingkan dengan rujukan luaran dan keputusan teori. CWR yang direkodkan menggunakan sudut lead yang berlainan untuk gear spiral telah dibanding untuk mengenalpasti sudut lead yang paling berkesan. Hasil kajian menunjukkan bahawa penyerap titik yang diuji mencapai CWR yang agak rendah berbanding dengan hasil konvensional, dengan maksimum 0.11% di mana konvensionalnya berkisar antara 7% hingga 31%. Keputusan kajian menunjukkan bahawa Spinning Sea Wave Point Absorber yang diuji mencapai CWR yang agak rendah berbanding dengan keputusan konvensional. Keputusan sedemikian boleh dikaitkan pemilihan penjana DC yang tidak berkesa, hasil daripada daya geseran yang ketara dalam mekanisme gear spiral, isu gerakan pelampung, kelembutan bahan yang digunakan untuk mengarang penyerap titik dan kekurangan keberkesanan dalam reka bentuk. Sudut lead yang paling berkesan telah dikenal pasti dengan sudut 55 °, yang berada di tengah-tengah semua sudut lead yang telah diuji. Ia dapat menjana tenaga elektrik yang ketara dengan naik turun yang agak rendah dalam prestasi.

Abstract (BI)

Renewable energy sources are becoming more important when the world tries to ensure sustainability in energy generation for the future. With a potential to harness over 20,000TWh of electrical energy from the ocean, various types of energy converters were being developed. One of such energy converter is the point absorber which converts the potential and kinetic energy in the ocean wave motion into electricity. Though point absorber technology has been developed over the years, no research were conducted to study the effectiveness of utilizing a spinning motion for electricity generation in the point absorber instead of the conventional translational mechanism. The study of Spinning Sea Wave Point Absorber focuses on the understanding, design, fabrication and testing of a spiral gear mechanism implemented in a point absorber, conducted in a controlled wave tank. It aims to compare the Capture Width Ratio with conventional point absorbers as well as to identify the most effective lead angle within the spiral gear mechanism. A wave tank is constructed and the wave generated is characterized. With the wave characteristics, a point absorber is designed and fabricated. Through the experiments, the CWR recorded is compared to external reference and theoretical results. The CWR recorded using different lead angle for the spiral gear were compared to identify the most effective lead angle. The results showed that the tested spinning sea wave point absorber achieved a relatively low CWR compared with conventional results, with a maximum of 0.11% where conventionally it ranges from 7% to 31%. Such result can be attributed to the ineffective DC generator selected, presence of significant frictional force in the spiral gear mechanism, unconstricted motion of the buoy, softness of material used to fabricate the point absorber and lack of robustness in the design. The most effective lead angle identified is 55°, which falls in the middle of all the lead angles tested. It was able to generate a significant amount of electricity with a relatively low fluctuation in performance.

Chapter 1: Introduction

As human progressed from cave dwelling creatures to civilized beings, human have learnt to harness the energy of our surroundings to be put to good use. Our ancestors started to harvest the chemical energy in wood to create fire which brought warmth and security. In modern day, human mostly harvest the energy content within fossil fuels, namely coal, petroleum and natural gas to fuel our civilization. In 2016, a collective total of 1.57×10^8kWh of energy was consumed, as compared to 1.07×10^8kWh in 1996 [1]. This shows the tremendous dependant of human beings towards energy especially when technological advances happen so quickly. The energy consumption of various region of the world across a 26 years period is shown in Figure 1.1.

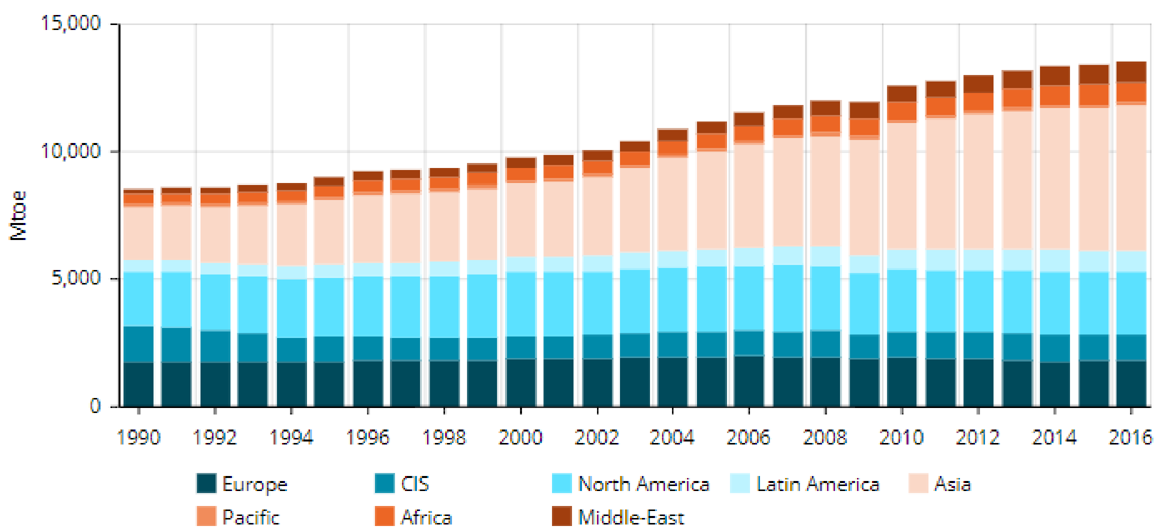

Figure 1.1: Energy Consumption of Various Region of the World across 26 years [1]

For the past 50 years, people also began to notice that the fossil fuels will not last forever. The availability of fossil fuels has caused its prices to fluctuate and affects the global economy significantly. As it is the main source of all human beings' activities, countries who own these production sources are generally rich countries and are often sought after either through business or war. Fossil fuel usage also brings about a bigger problem, the infamous climate change.

After the Second World War, people began to recognize the impact of environmental negligence and the worrying air and water pollution through the environmental disasters that stroke us. Unregulated production and consumption of fossil fuels have led to the exponential increase of the carbon footprint of human activities. The carbon emission normally comes in the form of greenhouse gasses which contributes to climate change. Subsequently, it will bring about serious consequences for human beings and the environment.

As a result of these arising problems, attention began to turn towards creating energy from renewable sources which does little to no harm to the environment. These energy sources are able to provide continuous, sustainable and clean energy to accommodate for the increasing energy consumption. Humans started to venture into solar, wind, rain, tides, geothermal, biomass and wave to seek for alternative sources of energy. As of now, the world collectively generates around 20% of total energy production from renewable sources, with countries such as Sweden, Costa Rica and Nicaragua leading the race to fossil fuel-free energy production [1].

One of the reliable source of alternative energy is from the sea, or marine energy source. These sources and consistent, reliable, clean and never ending. Thus, a lot of resources were put into the development of energy harvesting of the sea. All things considered, there is a potential to develop 20,000 – 80,000TWh of electrical energy from the earth's ocean [2]. One of the more recognized approach to harvest these energy is using the Wave Energy Converters (WECs). Point absorbers are one effective example of WECs which translate the point relative movement of the wave to mechanical energy which is used to generate electrical energy with an electromagnetic generator.

This project aims to study and design a Spinning Sea Wave Point Absorber.

As most of the current point absorber systems uses a PTO system that extract the wave energy through the vertical movement of the buoy, none has ventured into the possibility of produce energy through a spinning PTO system. Such system translate the vertical movement of the buoy into a spinning motion which will drive the electromagnetic generator by using a spiral drive mechanism [3]. The current efficiency of point absorbers ranges from 7% to 31% [4]. By using the same principle as a DC Dynamo Generator, a Spinning Sea Wave Point Absorber might prove to be a more efficient conversion system from wave energy to electrical energy.

By designing a more efficient point absorber system, it is possible to up-scale it to real life applications and generate significant amount of clean electrical energy for human consumption. Other than that, it will also able to operate non-stop to produce continuous electrical energy without the problem of running out of raw ingredients, since it relies on the movement of the wave which is everlasting. It also create little to none carbon footprint as the production of electrical energy from a point absorber do not emit any harmful waste or greenhouse gases. The success of this project will be able to contribute to the future development of the production of clean and sustainable electrical energy.

1.1 Problem Statement

The consumption of electrical energy has increased steadily over the past decades along with technological advancement. This shows the correlation between the growth of a civilization and the energy consumed by the said civilization. As our current sources of electrical energy are based off of non-renewables, it creates two complications for human beings. First of all, as the supply of raw materials to generate electrical energy depletes, humankind face a situation where electrical energy production can no longer support the needs of civilization. Such situation creates an imbalance in the supply and demand of energy and will eventually create an economical and existential crisis for all human beings. Next, the current sources of electrical energy create by-products that are harmful to the environment, wild life and humans. It contributes to the rapid climate change and harsh weather conditions which threatens the very fabric of life on Earth. In short, the current supply of electrical energy is not sustainable and not environmental friendly.

With the developments in WECs which harvest the wave energy and generate electricity, point absorbers are one of the WECs that show a promising future. Unfortunately, the current Capture Width Ratio (CWR) of point absorbers lie between 7% and 31%. Thus, there is still plenty of improvements that can be done to develop the point absorbers into a reliable and effective WECs.

To improve the overall efficiency of a point absorber, it is crucial to analyse the PTO system, which is responsible for generating electricity. One of the aspect of PTO that has yet to receive any sufficient research on is the possibility of having rotary PTO system for point absorbers. As of now, most PTO systems uses a linear generator. Since rotary generators have been the primary way to generate electricity from several sources, such as dams, wind farms and driven turbines, it shows that rotary generators have already evolved to be a matured technology in terms of generating electricity.

Thus, this project aims to tackle the low efficiency of current generation sea wave point absorber due to their PTO system.

1.2 Objectives

1. To design and fabricate a Spinning Sea Wave Point Absorber with a scale of 1:50.
2. To determine the Capture Width Ratio of Spinning Sea Wave Point Absorber.
3. To identify the most effective lead angle in the spiral gear mechanism.

1.3 Scope of work

This project will strive to design a working down-scaled model of Spinning Sea Wave Point Absorber. Throughout the process, in depth study is needed to identify the parameters and variables that affect the power generation. With a theoretical result, it will be compared with the actual power generation of the model where experiments will be carried out with different wave condition simulations. If both theoretical and experimental results show a promising correlation, the power generation will be estimated for a full scale Spinning Sea Wave Absorber.

Among the 3 primary motions of a floating body, which are the pitch motion, surge motion and the heave motion, which are shown in Figure 1.2. The design of the Spinning Sea Wave Point Absorber will focus on harvesting energy through the heaving motion of the buoy only. The PTO system will utilize an electromagnet generator together with a spinning mechanism which is activated when the buoy moves in the vertical direction. The scale of the model will be 1:50 due to practicality limitations in the laboratory.

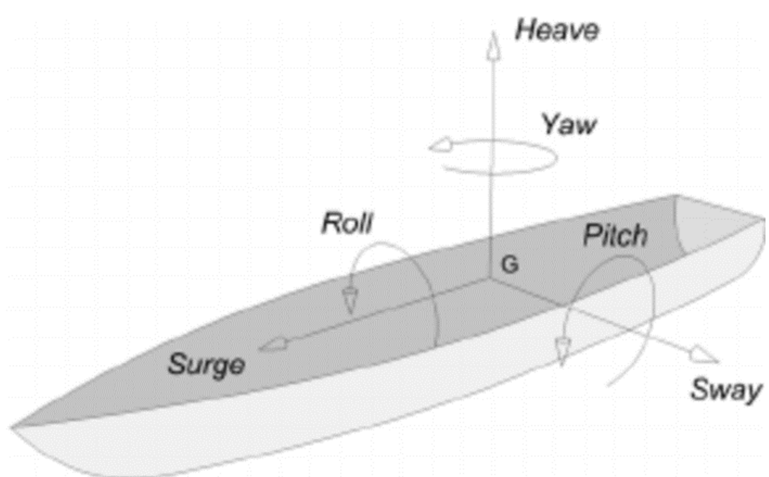

Figure 1.2: Motions of a floating body [5]

1.4 Type of Project

This project will focus on the analytical study and design with fabrication of a Spinning Sea Wave Point Absorber and conduct experiments to validate the findings.

1.5 Project Requirements

To successfully implement this project, a few facilities and equipment are needed.

1. Software
    a. SolidWorks
       To conduct CAD drawing and analysis of the model

2. Hardware
    a. Wave Tank
    b. Wave Generation Assembly
    c. Spinning Sea Wave Point Absorber

1.6 Thesis Outline

This thesis is separated into five different chapters to report on the project findings. The first chapter that has been discussed focuses on the introduction of the project background and providing context on the issue being investigated which is the spiral gear mechanism implementation in a point absorber.

In the next chapter, different sources of literatures regarding wave energy and wave energy converters are reviewed to further understand the reality in the industry. In depth review regarding the operational theory of a point absorber and the referenced spiral gear mechanism are done to justify the methodology of the project.

In the third chapter, the methodology used to conduct this project is thoroughly discussed. From idea conceptualizing to experimental set up, all aspects on how to conduct the investigation on the performance of a spinning sea wave point absorber are reported.

The fourth chapter comprises of the results gathered from the experiment as well as the discussion of results. All primary results and secondary results are recorded, tabulated and calculated. The results are also presented in graphical method to facilitate the reader's understanding. The results gathered are discussed and explained on the reasons behind it.

Last but not least, the final chapter will conclude the whole project and suggest future work that can be conducted. It concludes on the findings through this project and also summarizes the reasoning behind. Future work are suggested based on the experience in conducting the project as well as aspects that could not be covered in the project timeframe.

Chapter 2: Literature Review

In this literature review, the energy source responsible for the operation of a point absorber is discussed, which is the wave energy. Next, the different locations of deployment of WECs are discussed, namely onshore, nearshore and offshore as shown in Figure 2.1. The most promising location for a point absorber is identified and further study is conducted with regards of the types of WECs which can also be deployed at offshore locations.

The literature review continues with more in depth study particularly on point absorber. The necessary formulas and equations governing the operations and evaluation of point absorber is identified. Other than that, the various kinds of PTO method for a point absorber is discussed to understand better the advantages and flaws of current gen PTO. The method of fine tuning a point absorber to achieve maximum power absorption is discussed as well. Lastly, the spiral gear mechanism which is the core study of this project is discussed with main reference from the spinning mop.

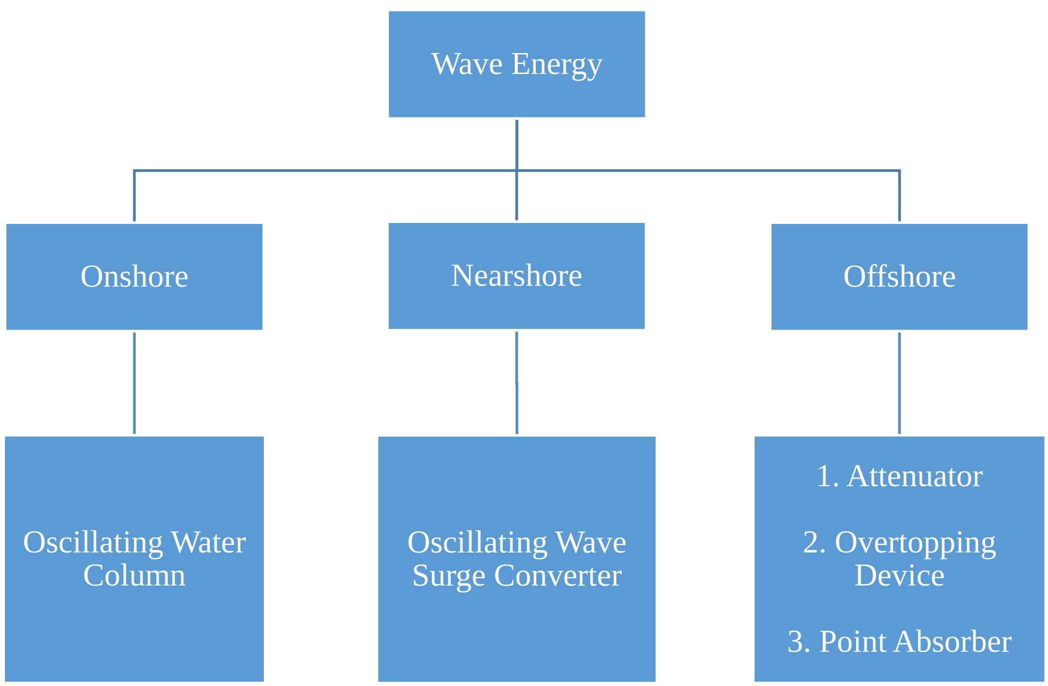

Figure 2.1: Types of Wave Energy Converters

2.1 Wave Energy

In the previous few decades, a lot of effort and resources were invested into the development of solar and wind energy generation. But as the understanding towards renewable energy increases, wave energy slowly but steadily established itself as one of the most potential renewable energy source. As civilization began to acknowledge the energy crisis and being aware of the environmental impacts, wave energy received significant amount of attention to reach where it is today.

Wave energy power is enormous and relatively more reliable than other renewable resources such as solar and wind energy as wave energy contains a higher density of power of 2 – 3kW/m^2 while wind energy has a power density of 0.4 – 0.6kW/m^2 and solar energy with 0.1 – 0.2kW/m^2 [6]. It is also useful to note that the wave energy occurs in the movement of water near the surface of the sea, of which 95% of the energy contained in a wave is stored in between the water surface and ¼ of a wavelength below the water surface. Thus, it allows easy harvesting of energy at the near surface of the water [7]. These trait has positioned wave energy at its importance today in the scientific community. Below are the benefits of harnessing wave energy:

1. Waves travel large distances with low energy loss [6],
2. WECs can generate power up to 90% of the time (20 – 30% fir wind and solar energy converters) [7],
3. Wave energy has a greater predictive capacity than wind energy [7],
4. Wave energy is widely available because it has multiple harvesting locations (shore to deep waters) [6],
5. Wave energy causes little environmental interference [7].

Though it is one of the most promising source of renewable energy, there still exist a lot of challenges which need to be overcome. These challenges are the barrier between a conceptually excellent source of energy and a commercially competitive energy source in the global energy market.

Below are the current challenges of harnessing wave energy:

1. Conversion of the random and slow oscillatory motion of waves into useful motion to connect to a generator to provide a sustainable output to the grid [8],
2. Conversion of varying wave heights and periods and subsequently varying power levels to smooth electrical signal [8],
3. Self-alignment of WECs to the direction of wave in the offshore zones to capture as much energy as possible [7],
4. Difficult structural engineering design for offshore WECs to withstand the extreme sea conditions as well as the difficult maintenance procedures [8],
5. High investment cost in a volatile economy age causes minimal opportunity of investors' funding [6].

It is obvious that wave energy harvesting currently stands at a situation where it promises a sound future of energy generation and has acquire the attention and interest it needs to develop further. But, the high amount investment and research needed to bring Wave Energy Conversion systems to become commercially implementable are becoming the bottleneck of generating clean energy from wave. With such scenario at hand, it is crucial to find alternatives that could provide more development of WECs by showing the significant advantage it brings if the sufficient monetary support and resources are provided.

2.2 Types of Wave Energy Converters

WECs are normally categorised by the location of its deployment in relation to the shoreline. In general, WECs are separated into 3 main types, namely Onshore, Nearshore and Offshore. All 3 main types of WECs will be discussed below.

2.2.1 Onshore

Onshore WECs are devices that are deployed on the shoreline. They have the advantages of being close to the electricity grid network, relatively easy to maintain with minimal amount of travelling distance and working environments comparative to dry land and less likely to be damaged by the waves as the waves at shallow water are attenuated.

On the other hand, such devices struggle to generate significant power as the incident waves contain low wave power. Due to the location of their construction, there are normally site-specific requirements that need to be complied. Such requirements are shoreline geometry and geology conditions and preservation of coastal scenery, causing onshore WECs unable to be designed for mass manufacturing.

Oscillating Water Column

An oscillating water column consists of a chamber with an opening to the sea below the waterline. As waves approach the WEC, water is forced into the chamber, thus applying pressure on the air in the chamber. The pressurised air escapes to the atmosphere through a turbine. Conversely, as the water retreats from the chamber, air is then drawn in through the turbine. A low-pressure Wells turbine is often used in an oscillating water column as it rotates in the same direction irrespective of the air flow direction, removing the need to rectify the airflow. An illustration of the operation of the oscillating water column is shown in Figure 2.2. One of the advantages of the oscillating water column is its simplicity in design and robustness in operation [7].

On the other hand, oscillating water column poses some problems to the society. The biggest concern for the operation of an oscillating water column is the amount of noise it produces. This causes a significant degree of noise pollution to the surrounding population. Other than that, the construction of an oscillating water column will damage the natural beauty of a seascape as well [9].

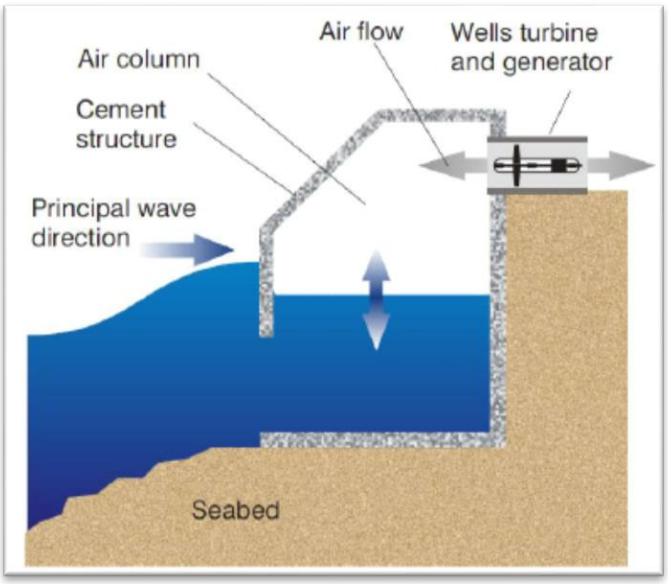

Figure 2.2: Illustration of an Oscillating Water Column [10]

2.2.2 Nearshore

Near shore WECs are devices that are deployed at relatively shallow water, though there is a lacking of exact definition of ‘relatively shallow water’, it has been suggested to be a depth of less than ¼ of the wavelength [7]. Devices at this location are normally attached to the seabed, which provides a stationary base for an oscillating body to work on.

As near shore devices are located between onshore and offshore, they have a relatively intermediate comparison of advantages and disadvantages. But still, since it is located at relatively shallow water, the incident waves can only provide a significantly reduced power as compared to the waves travelling in the open water. Such attribute causes it to have a limiting factor in its harvesting potential.

Oscillating Wave Surge Converter

An oscillating wave surge converter is normally comprised of a hinged deflector, positioned perpendicular to the wave direction. When waves propagates through the oscillating wave surge converter, the hinged deflector moves back and forth. It exploits the horizontal particle velocity of the wave, using it to drive a pump. The pump then delivers high pressure water to drive a typical hydroelectric generator, normally located onshore. One example of the oscillating wave surge converter is the Oyster Wave Energy Converter shown in Figure 2.3.

Oscillating wave surge converter has few moving parts underwater, allowing for simplicity in design and survivability in harsh sea environment. It also has the electrical components located onshore, making the maintenance easier for the hydroelectric generator as well as the device itself since it is located nearshore [11].

Though the oscillating wave surge converter provides significant benefits, it requires a lot of resources for the installation and production processes, not to mention the difficulty in those processes [12]. The turbine and generator in the oscillating wave surge converter also produces noise pollution, thus disturbing the wildlife in the nearby region. The installation and operation of oscillating wave surge converters will interfere with marine mammal life and fish life as well. If an array of oscillating wave surge converters are to be built, it could also result in loss of habitat for marine species [12].

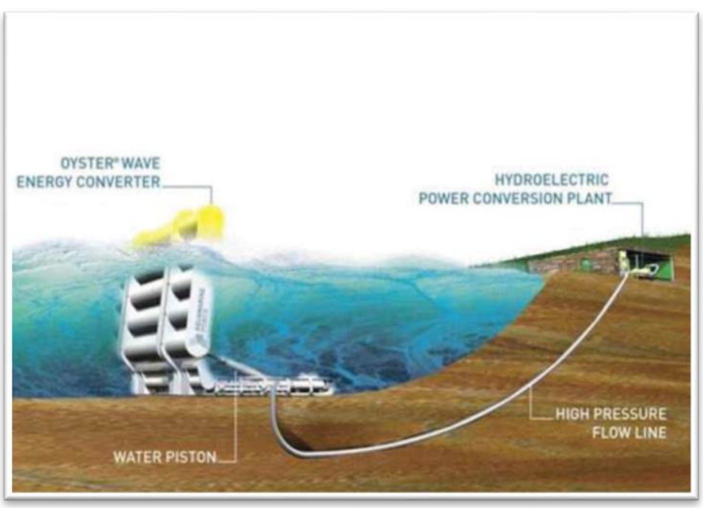

Figure 2.3: Oyster Wave Energy Converter [10]

2.2.3 Offshore

Offshore WECs are devices that are deployed at deep water. Though there are numerous suggestions on what is considered as ‘deep water’, some generally accepted options are ‘depth of tens of meters’, ‘depth greater than 40m’ and ‘depth exceeding ⅓ of the wavelength’ [7]. By deploying these devices in deep water, they can harvest the maximum amount of energy because of the high energy content in deep water waves.

Though offshore devices promises high amount of energy generation, they do come at a cost. Offshore devices are significant more difficult to construct and maintain due to the harsh environment they need to operate in. Due to the bigger wave height and incident wave energy content, they need a robust design which is able to withstand the extreme conditions at deep water, further increasing the construction cost of WECs which is already high. Despite this, it was argued that with the more powerful incident waves, the normally floating offshore devices are able to generate more power, which has an economical value that outweighs the structural and maintenance cost [13].

From the 3 locations where it is possible to deploy a WEC, offshore seems to be the most promising region to develop a WEC system which can provide sustainable and significant amount of energy to the electrical grid. At deep water region, there exists the maximum potential of energy harvesting from wave. The output from it might generate enough economic value such that it can offset the expensive development, construction and maintenance cost to operate an offshore WEC. Given that the significant advantage of such system can be observed from the investors’ point of view, it will directly contribute to better development of the system by generating more investments.

Attenuator

An attenuator is an elongated, floating WEC with dimensions larger than the wavelength of the waves. One of the commercialized attenuator is the Pelamis WEC as shown in Figure 2.4. It is aligned in parallel with wave propagation direction, which effectively rides the waves. It has a lower area perpendicular to the waves compared to a terminator so that the device experiences lower forces. Each attenuator consists of a chain series of cylindrical components that are interconnected by hydraulic pump joints. Movements along its length are selectively constrained to produce energy when it conform to the local shape of the oscillatory wave. As the waves pass along the length of the attenuator, the long cylindrical body sags downwards into the troughs of the waves and arch upwards when the wave crest is passing through. Connecting joints flex in the waves, exerting a significant amount of force which is utilized to power the hydraulic pumps at each joint. The hydraulic pumps then drive oil through a hydraulic motor which in turn drives a generator, producing electricity [6, 7, 14-16].

The downside of an Attenuator is its dependence on its orientation to harvest the maximum amount of wave energy when the waves propagate parallel to it. As mentioned in the current challenges in WEC industry, the ability of WECs to self-align itself to a certain direction relative to the wave propagation direction is an existing challenge. Thus, considering the current technology being utilized in this industry, the Attenuator might not be able to extract the maximum amount of energy from the waves due to the heavy dependence on the alignment [7].

Figure 2.4: Pelamis WEC [17]

Overtopping Device

An overtopping device is designed to accumulate sea water of incident waves that enters a tapered channel into a reservoir which is raised above the sea level. The accumulated sea water in the reservoir is then controllably released back to the ocean through a hydraulic turbine to generate electricity, converting potential energy to electrical energy. An example of a working system is the Wave Dragon developed by a Danish company, Wave Dragon Aps as shown in Figure 2.5. It is a joint European Union research project, involving partners from Austria, Denmark, Germany, Ireland, Portugal, Sweden and the UK. It utilized a pair of large curved reflectors to direct waves into the central receiving part, where the wave will flow up a ramp and over the top to deposit sea water into a raised reservoir. The water is then allowed to return to the sea via a number of low-head turbines. [6, 7, 14-16]

Overtopping devices normally suffer from low overtopping rate, meaning only a small portion of water carried by the incident wave actually reaches the reservoir [18]. This is because the wave losses energy as it climbs the ramp of the central receiving part. Only part of the wave which still holds sufficient energy will be able to flow over the top to deposit sea water into the reservoir. Based on a simulation of the wake effects in a farm of Wave Dragon WECs conducted using the application of the time-dependent mild-slope equations, it is found that the overtopping rate is only a mere 28%, with 2% of the incident wave get transmitted under structure while the remaining 70% get reflected back in front of the floating ramp. This proves that overtopping devices are not effectively enough to capture the maximum amount of the incident wave energy as most of it is reflected back to the sea [19].

Figure 2.5: Wave Dragon Overtopping Device [20]

Point Absorber

A point absorber is a device that possesses small dimensions relative to the incident wavelength, normally composed of a buoy which is connected to some sort of PTO system. They are normally found to be a floating structure that heave up and down on the surface of the water or submerged below the surface to rely on the pressure differential. The pitching and heaving of the waves causes a relative motion between a floating absorber and a fixed reaction point, usually a suspended heavy ballast plate or a fixed dead-weight on the ocean floor. As the buoy goes up and down according to the motion of the waves, an oscillatory mutual reaction force is generated between the freely moving buoy and the fixed reaction point. The force is transferred to a PTO system which eventually moves a generator to produce electricity. An illustration of a point absorber is shown in Figure 2.6. The small dimensions of a point absorber allows it to absorb wave energy from all directions, thus the wave direction is not important for these devices. There are a number of examples of point absorbers, one of which is produced by Ocean Power Technologies, the PowerBuoy.

The ability of point absorber to absorb wave energy irrespective of the wave propagation directions make it one of the most researched WEC. Point absorbers are relatively easy to construct and install at deep water, with PowerBuoy being able to deploy after transported to the intended location with just a push of a button on the controller as shown in Figure 2.7. The flexibility of point absorber system allows it to harvest the maximal amount of wave energy throughout the day without worrying about the change in direction of the waves. It is also relatively easy to upscale and downscale for actual deployment and research purposes respectively [6, 7, 14].

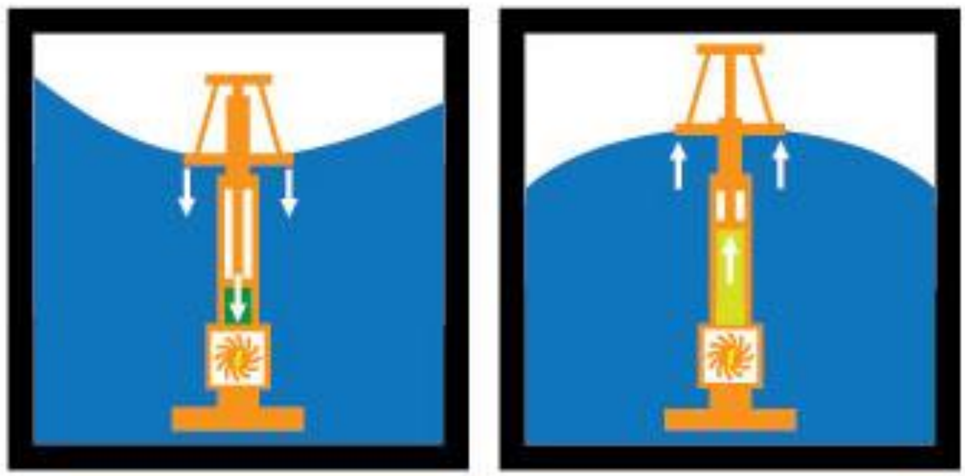

Figure 2.6: Illustration of a Point Absorber [21]

Figure 2.7: PowerBuoy Point Absorber [22]

2.3 Operational Assessment of Wave Energy Converter

The operation of a WEC can be comprised of a variety of forms and nature, but the essential part of any mechanical devise is the operational efficiency. The section below will discuss on the efficiency identification process of a WEC.

2.3.1 Maximum Wave Power Transmitted per Unit Width

Surface water waves contain enormous amount of energy and it is stored in 2 forms. The moving water particles contain kinetic energy due to their mass and motion; the displaced water particles that are above the mean water level contain gravitational potential energy due to their vertical position [23]. Deep water waves generally contains higher amount of energy when compared with waves from shallow water where the waves are able to feel the bottom surface. The approximate equation for wave power transmitted per wavelength in deep water is as below [24].

$$P_{wave} = \frac{\rho g^2 H^2 T}{32\pi} \qquad (2.1)$$

2.3.2 Maximum Absorbed Power by an Axisymmetric Body

When a body oscillates in the water due to the passing waves, it captures a certain amount of wave energy. The energy content in the waves is transferred to the body and causes the oscillatory motion. The oscillatory motion of the body itself will radiate waves as well in order to counteract the incident waves. The radiated waves give the impression as if after passing through the body, the incident waves lose part of its energy content and propagate with a lower wave height.

The maximum amount of power that can be extracted from incident waves is characterized by the ability of the body to radiate waves. The equation that governs the maximum absorbed power by an axisymmetric body, oscillating in heaving motion, in monochromatic waves is as below [25, 26].

$$P_{abs} = \frac{\rho g^2 H^2 \lambda}{64\pi^2 f} \tag{2.2}$$

2.3.3 Capture Width Ratio

The efficiency of a WEC does not merely consider the input power and the output power, thus the term "Capture Width Ratio" is widely used in the industry to indicate the efficiency of a WEC. The CWR describes the effectiveness of the WEC to absorb the energy contained in the incident waves. This value is based on two major underlying specifications, namely the wave conditions and the size of the wave activated body. The formula for the CWR is given as below [27].

$$CWR = \frac{P_{abs}}{P_{wave} \times width_{active}} \tag{2.3}$$

In terms of a point absorber, the active width of it is the diameter of the floating buoy. A point absorber generally has a CWR between 7% to 31%, with reference to the experimentally tested, full scale point absorbers [4].

2.4 Make Up of a Point Absorber

The theory behind the operation of a point absorber is discussed below, including the modelling of a point absorber, the equation of motion, the PTO systems currently used in the industry as well as how to fine tune a point absorber to increase the power absorbed. The last part of this section includes the review of the proposed spiral gear mechanism which is extracted from the patent of a spinning mop.

2.4.1 Mass-Spring-Damper System

A point absorber in operation can essentially be visualized as a mechanical oscillator, composed of a mass-spring-damper system with one degree of freedom. The incident waves which produces wave excitation force acts as an external force in the direction of the degree of freedom. Other than that, different forces also contributes to the point absorber's response. The schematic representation is shown in Figure 2.8 [28].

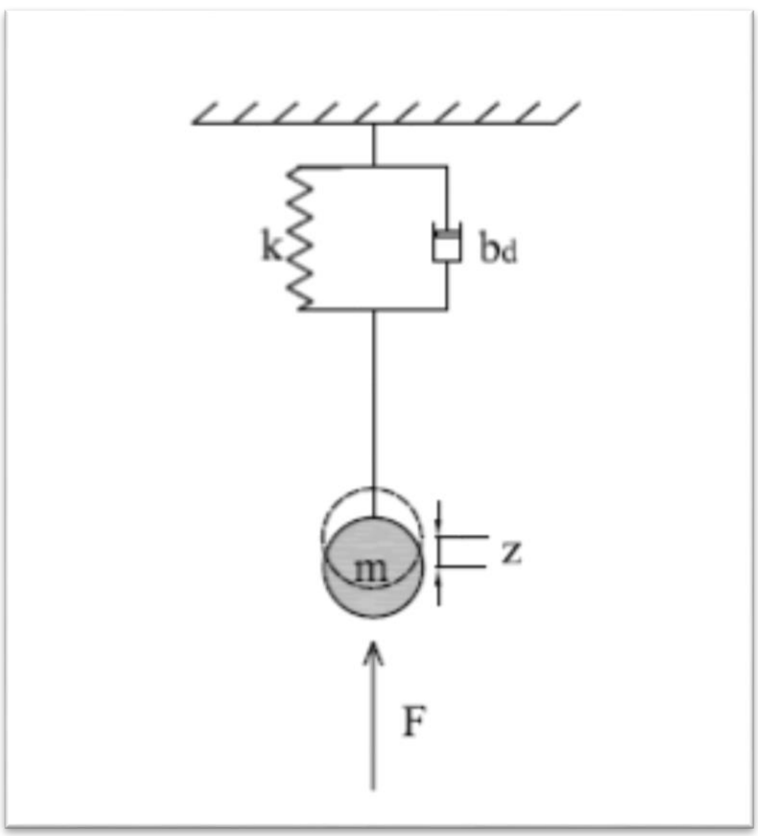

Figure 2.8: Schematic of a mass-spring-damper system [28]

2.4.2 Equation of Motion

Below is the equation of motion governing the mechanics of the point absorber.

$$m\frac{d^2z}{dt^2} = F_{ex} + F_{rad} + F_{res} + F_{damp} + F_{tun} \qquad (2.4)$$

The net force acting on the buoy can be determined by analysing the various forces that acts on it. The left side of the equation of motion is the net force while the right side of the equation of motion is the sum of the various forces.

The wave excitation force is caused by the incident wave where the wave exerts a certain force to displace the buoy from the equilibrium position. The radiation force is caused by the radiated waves from the buoy when it heaves at the water surface and creating its own waves. The hydrostatic restoring force is the net upward force acting on the buoy due to buoyant force and gravitational force.

The external damping force is caused by the PTO system. The PTO system which is made up of the spiral gear mechanism will have a certain amount of resistance in spinning. This resistance is equivalent to resisting the heaving movement of the buoy, thus causing the external damping force.

The tuning force is a supplied force to phase-control the buoy. A mass and/or a spring will be added to the point absorber to achieve a natural frequency which is similar to the generated waves to ensure the buoy oscillate at resonance during operation. At resonance, the buoy will oscillate with maximum amplitude, allowing the maximum absorption of power from the incident waves. The added mass and/or spring creates the one degree of freedom tuning force for the system [28].

As discussed, the 2 parameters that need to be optimized to allow the maximum power to be absorbed is the external damping force, determined by the PTO system's damping coefficient, and the linear tuning force, determined by the added mass and/or spring.

2.4.3 Power Take Off System

The PTO system of a point absorber is the mechanism with which the absorbed energy by the motion of the buoy is transformed into usable electricity. The PTO system is very important as it directly affects the efficiency of the conversion of energy from the absorbed wave power into electricity. It also contributes to the mass, size and structural dynamics of the point absorber as it acts as an external damping to the point absorber system [27].

From previous studies and commercialized point absorbers, most of the PTO used are Hydraulic Converters, Direct Electrical Drive System and Direct Mechanical Drive System. Each of these PTO systems will be discussed below.

Hydraulic Converters

Point absorbers capture energy through the movement of buoy in response to the interaction with the waves, rendering conventional rotary electrical machines incompatible directly. Hydraulic converter is often the direct solution chosen to interface the point absorber with the electrical generator since they are well suited to absorb energy when experiencing large wave forces at relatively low frequencies. The hydraulic converter system is shown in Figure 2.9.

A point absorber moves up and down while connected to a hydraulic cylinder causes hydraulic fluid to flow through controlled hydraulic manifolds before reaching the hydraulic motor which drivers the electric generator. Accumulators can also be added to the system to smoothen the supply of pressurised fluid in the system by either providing or accumulating hydraulic energy when necessary.

Though straightforward, hydraulic converters pose a few issues to be selected as an effective PTO system. Fluid containment of the hydraulic system has to be addressed with regards to performance and environmental impacts. Multiple secondary equipment are needed to support a hydraulic converter. These equipment includes hydraulic gas accumulators which store the absorbed peak loads and smoothen the wave energy conversion from the motor, digital displacement motors which increase the part-load efficiency of hydraulic motor and facilitate their controllability. Hydraulic systems also compose of many moving parts, and the seals of the piston will wear over time which can increase significantly the maintenance cost. During extreme weather conditions, the hydraulic actuator also risks exceeding its design travel length and damage the hydraulic system [27].