DESIGN AND STUDY OF SPINNING SEA WAVE POINT ABSORBER

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Declaration

I hereby declare that this thesis represents my original work, except where explicitly stated otherwise in the text, and that this thesis has not been submitted to any other degree qualification.

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LIST OF SYMBOLS

Symbol	Description	Unit
ρ	Density	kg/m^3
g	Gravitational acceleration	m/s^2
H	Wave height	m
T	Wave period	s
λ	Wavelength	m
B	Characteristic diameter of WEC	m
A_w	Maximum horizontal cross sectional area of WEC	m^2
f_z	Natural frequency of point absorber	Hz
r	Radius of buoy	m
m	Mass of buoy of point absorber	kg
m_w	Added mass of point absorber	kg
I	Moment of Inertia	kg.m^2
ω	Angular velocity	rad/s
ω_{max}	Maximum angular velocity	rad/s
ω_{min}	Minimum angular velocity	rad/s
ω_{mean}	Average angular velocity	rad/s
m_f	Mass of flywheel	kg
r_o	Outer radius of flywheel	m
t	Time taken for flywheel to complete one revolution	s
η	Efficiency	-

LIST OF ABBREVIATIONS

Abbreviations	Description
OES	Ocean Energy System
IEA	International Energy Agency
WEC	Wave Energy Converter
OWSC	Oscillating Wave Surge Converter
OWC	Oscillating Water Column
PTO	Power Take-off
CW	Capture Width
CWR	Capture Width Ratio
CNC	Computer Numerical Control

ABSTRAK (BM)

Point absorber merupakan salah satu jenis penukar tenaga yang mempunyai fungsi untuk menukar tenega ombak ke tenaga elektrik. Setiap point absorber mengandungi sebuah pelampung yang memain peranan sebagai elemen utama dalam proses penukaran tenaga. Pelampung itu bergerak bersama dengan ombak dan proses penukaran tenaga berlaku melalui sejenis sistem Power Take-Off (PTO). Sejak beberapa dekad yang lalu, beberapa jenis sistem PTO telah digunakan dalam point absorber seperti penukar hidraulik dan penukar pemacu elektrik. Malah tiada sebarang penyelidikan yang berkaitan dengan spinning point absorber yang menggunakan sistem spiral drive sebagai sistem PTO. Projek ini berminat untuk menyelidik kebolehan sistem spiral drive sebagai sistem PTO dalam spinning point absorber. Sistem spiral drive menukar gerakan linear pelampung ke gerakan putaran. Satu prototaip telah direka, dihasil and diuji dalam tangki. Prototaip yang direka mempunyai sudut lead serta ketebalan roda tenaga yang berbeza. Antara sudut lead yang digunakan ialah 45°, 50°, 55°, 60° dan 65° malah ketebalan roda tenaga yang digunakan ialah 3mm, 6mm dan 9mm. Melalui eksperimen, sudut lead yang paling cekap ialah 55° malah ketebalan roda tenaga yang paling cekap ialah 9mm. Kombinasi paramter ini membolehkan spinning point absorber projek ini untuk menyimpan tenaga kinetik sebanyak 4.6mJ atau mempunyai kecekapan sebanyak 33.2%.

ABSTRACT (BI)

The point absorber is a type of Wave Energy Converter (WEC) that is used to harness wave energy and convert it into useful electrical energy. It consists of a buoy, which acts as the primary converter the process of energy conversion. The waves drive the buoy and the wave energy absorbed by the buoy is converted into other form of energy through a Power Take-Off (PTO) system. Over the past few decades, there are various type of PTO mechanisms being implemented in the point absorbers such as hydraulic converter or the direct electrical drive system. None of these studies is related to the utilization of spiral drive mechanism. The main interest of this project is to study the feasibility of spinning point absorber that uses spiral drive mechanism as its PTO system. In spiral drive mechanism, the linear heaving motion of buoy is converted into rotational motion through a spiral gear and twisting shaft. A prototype with scale 1:50 has been designed, fabricated and tested in a wave tank in the laboratory. The prototype comes with five sets of twisting shaft, each with different lead angles and 3 sets of flywheel, each with different thicknesses. The twisting shafts are designed and fabricated in lead angle of 45°, 50°, 55°, 60° and 65°. The flywheels are designed and fabricated in thickness of 3mm, 6mm and 9mm. Through experiment, the most effective lead angle and thickness of flywheel are determined. Based on the results, it is found that the spinning point absorber shows optimum result when the twisting shaft with lead angle 55° and flywheel with thickness of 9mm are used. It is able to store of 4.6mJ kinetic energy, which is equivalent to 33.2% of efficiency.

CHAPTER 1

INTRODUCTION

1.1 Background Study

Wave energy is a renewable energy that is inexhaustible. Compared to the non-renewable resources such as fossil fuel, coal, petroleum and natural gas, wave energy is clean and sustainable. The area of ocean is approximately 360 million square kilometres, which covers about 71 percent of the Earth's surface. The ocean is capable to supply 2TW of energy worldwide (Kolios et al., 2018). This indicates that ocean wave contains tremendous amount of energy potential to be used as the alternative energy sources to replace the non-renewable sources.

Over the past few decades, focus on renewable energy is mainly given to the harvest of wind energy and solar energy. Meanwhile, the growth of wave energy sector is immature and slow in progress. There are a few reasons that cause this, such as high investment costs, high technical risks and most importantly the harsh environmental conditions of the ocean which is unpredictable. Despite the challenges faced by the energy wave sector, it is worth to be explored and investigated because wave energy is unlimited and clean to the environment.

Indeed, the development of wave energy technology takes tremendous effort and time to obtain satisfying outcome. In year 2001, the Technology Collaboration Programme on Ocean Energy System (OES) is initiated and joined by three countries from the world. It is a programme under the International Energy Agency (IEA) to carry out activities related to the feasibility, sustainability and recognition of ocean energy technology. Under this programme, researchers, government organizations and scientists from the countries over the globe gather, share and exchange research information regarding ocean energy system. As of December 2018, the number of countries involved in the effort of developing wave energy technology has increased to 25. This positive number of growth shows that there are potentials in wave energy technologies awaiting to be explored.

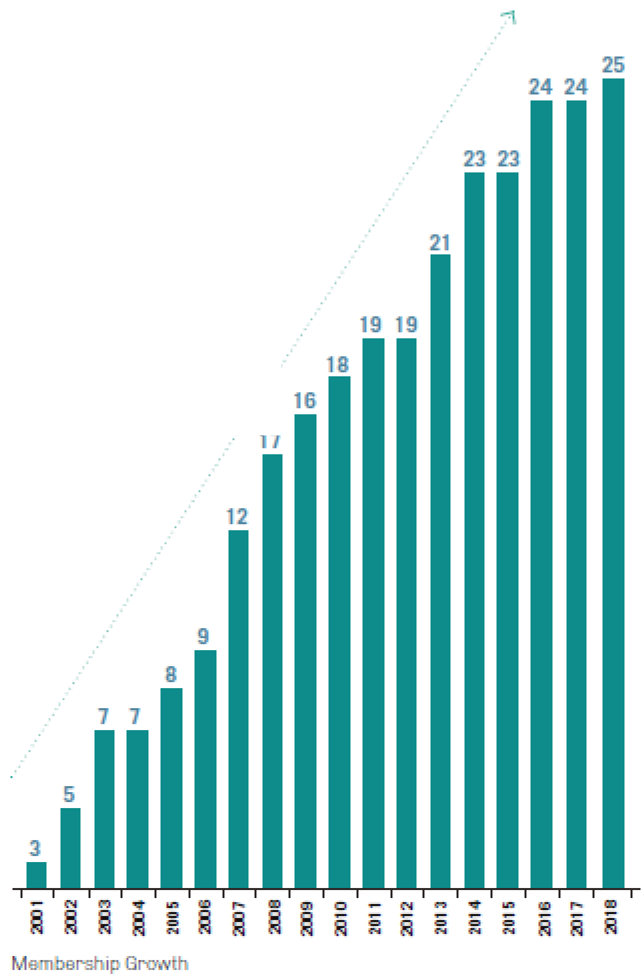

Figure 1.1: Membership growth of OES from year 2001 to 2018 (Hemer et al., 2019)

To convert the wave energy into electrical energy, various types of Wave Energy Converters (WECs) have been invented by scientists for the past few decades. The WECs are categorized by the locations they are installed – shoreline, near shore, or offshore. Among these three locations, the WECs that operates in offshore is able to harvest most amount of energy. This is due to the fact that offshore with deepest waves contain highest amount of wave energy. WECs can also be classified according to their operating technology. The developed technology is generalized by five different types of device, which are the attenuator, point absorber, oscillating wave surge converter (OWSC), oscillating water column (OWC), and overtopping.

In this project, a point absorber will be studied. A point absorber captures wave energy from all wave directions in offshore and converts it into electrical energy. It consists of a float or buoy which is connected to power take-off (PTO) system. Through PTO system, the buoy converts the wave energy into such as kinetic, hydraulic or pneumatic energy to drive the generator, depending on the PTO system of the design. To prevent the point absorber from drifting away from desired operating location, the device is moored using mooring system. The mooring can be either fixed or non-fixed. Compared to other type of WECs, the size of point absorber is relatively small, and easy to be fabricated and installed (Thomson Reuters, 2009).

The point absorber being studied in this thesis is called the spinning point absorber. It uses spiral drive mechanism to convert the wave energy into kinetic energy, before converting into useful electrical energy. In this mechanism, vertical motion of float is transformed into rotational motion and the energy is stored in the flywheel of the system. The efficiency of this PTO system is studied through experiments.

1.2 Problem Statement

Though many point absorbers have been developed by industrial companies in the past few decades, there has not yet been any literature papers on the study of spinning point absorber. Spinning point absorber is a point absorber that uses spiral drive mechanism as PTO system. This mechanism might have the potential to perform better than any other direct mechanical drive PTO system in harnessing the wave energy.

1.3 Objectives

1. To design and fabricate a point absorber by using spiral drive mechanism as PTO system.

2. To determine the most effective lead angle of spiral drive mechanism.

3. To determine the most efficient thickness of flywheel of spinning point absorber.

1.4 Scope of Research

This project includes the set-up of equipment, where a tank of size 2440mm (L) × 300mm (W) × 910mm (H) is used to mimic the ocean conditions. A wave generation mechanism will be designed to produce artificial waves in the tank and wave characteristics will be studied. A prototype with scale 1:50 is designed and fabricated to study the feasibility of spiral drive mechanism. It is designed in five lead angles and three thicknesses of flywheel. Finally, experiment will be carried out to study how efficient is this PTO system in converting wave energy into kinetic energy, by identifying the most efficient lead angle and flywheel thickness.

1.5 Thesis Outline

This thesis is divided into 5 chapters to present the research findings. In the first chapter, the project background, problem statement, objectives and scope of works are presented.

In the second chapter, literature review on the studies and researches that have been previously done by the others are reported. The understanding on the wave energy, current technologies, working principle of different WECs, equation for analysis and experimental works that are related to the spinning point absorber have been summarized.

In the third chapter, the details on the designs, fabrication and experimental process are discussed. First, the constraints and the factors that must be taken into consideration before starting the work of design are described. Next, the details of design and fabrication of the sloped beaches, wave generator and spinning point absorber are reported. Lastly, this chapter is ended by summarizing the experimental procedure.

In the fourth chapter, the experimental results recorded and the data is analysed into useful information. The theoretical results are calculated based on the wave characteristics obtained from experiment. The average angular speed of the spinning point absorber, average kinetic energy stored by the device and its efficiency are presented in tables and graphs. The relationships between the lead angle and thickness of flywheel with the performance of the spinning point absorber are discussed.

Finally, the findings of the project are concluded to determine where if the objectives of this project have been achieved. The flaws found in the results and process of research have been identified accordingly. Based on the obtained results, any related works that are useful for future improvement are discussed and suggested.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, the primary source of energy for the spinning point absorber to operate, which is the wave energy is discussed. Next, the types of WEC available currently are studied based on installation location and operating technology. Then, the types of PTO system used in the device are reported. The useful equations for the evaluating the performance of the WEC are also reported.

The understanding on the point absorber is discussed into deeper extent by reviewing the current technologies being implemented to the point absorber. The concept of spinning point absorber is studied by understanding the operational theory of the spiral drive mechanism in the spin mop. In addition, the theory and energy equations of the flywheel are presented as well.

Finally, the wave tank experiment is discussed. The suitability of testing based on the prototype scale and the methods to produce wave in a closed tank are introduced in this part.

2.2 Wave Energy

Sea waves are mainly formed in the presence of wind. When there is pressure difference from the Sun's heating, winds are form and they blow across the surface of ocean. The disturbance caused by the blowing wind on the ocean's surface results in the formation of wave crest. In addition, tidal waves are formed due to gravitational pull from sun and moon, while hazardous waves such as tsunami are form when earthquake happens or there is volcanic eruption. Figure 2.1 shows the distribution of wave energy on the Earth. It can be said that it is not evenly distributed over the globe. The north and the south region of the Earth have higher wave power available compared to the other regions. Meanwhile, the energy content of the ocean also depends on the ocean depth and the intensity of wave. The size of waves on offshore is bigger than that on near shore. It also means that the energy power on offshore is enormous compared to the near shore. This is because as the waves propagate, energy is dissipated. Hence, it can be concluded that the availability of wave energy depends on the location and distance from the shoreline.

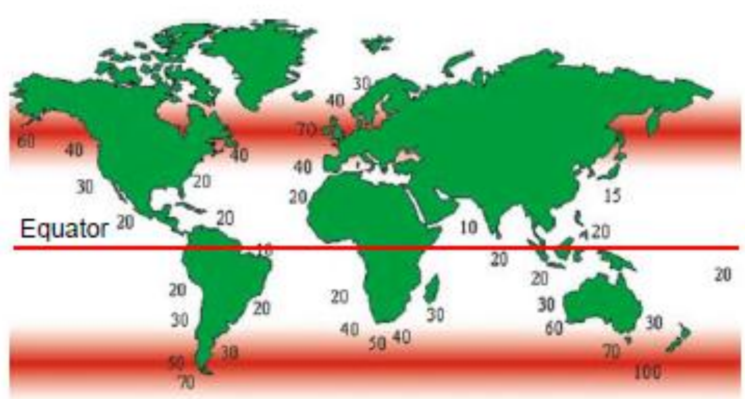

Figure 2.1: The distribution of wave power in kW/m over the globe (Rodrigues, 2008)

For regular wave, the mean wave energy density per unit horizontal area on the water surface, E_T in the wave is the sum of potential and kinetic energy per unit horizontal area. It is given by the formula (Vicinanza, Contestabile, & Ferrante, 2013):

$$E_T = \frac{1}{8}\rho g H^2 \tag{2.1}$$

The power or wave energy flux, P_{wave} per unit crest width of a monochromatic wave is given by (Vicinanza et al., 2013):

$$P_{wave} = \frac{\rho g^2}{32\pi} T H^2 \tag{2.2}$$

The maximum available energy to be absorbed by a axisymmetric body, P_{max} is given by (Jens Engstrom, 2011):

$$P_{max} = \frac{\rho g^2}{64\pi^2} T H^2 \lambda \tag{2.3}$$

2.3 Classification of the WECs

WECs are the devices that operate on the ocean to convert the wave energy into useful electrical energy. WECs can be categorized in different ways, depending on which aspects we are interested to look into. In general, they are classified according to the location being installed and their operation technology.

2.3.1 Location of Installation of WECs

By referring to the location of WECs being installed, they are categorized as the shoreline devices, near shore devices and offshore devices.

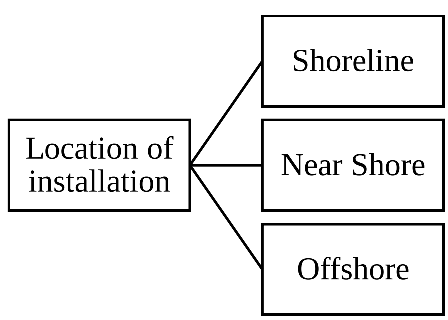

Figure 2.2: Classification of WECs based on the location of installation

Shorelines refer to the part where the ocean wave meets the land or beach. Since the location is close to the land, shoreline devices have high accessibility for maintenance work. They also carry the advantage of close to the utility network. Compared to the near shore WECs and offshore WECs, the less extreme ocean condition on shoreline reduces the possibility of damage on the shoreline WECs. This is because the wave energy dissipates as it travel through the shallow water. However, there are a few limitations on the shoreline WECs. The wave energy available in this location is lower due to the shallow water level. In addition, they are not suitable for mass production as their existence will affect the preservation of coastal scenery while there are some site-specific requirement to be obeyed (Drew, Plummer, & Sahinkaya, 2009).

Near shore refers to the transition zone between shoreline and offshore. Although there is no exact measure that specify the physical depth on near shore location, it has been considered as the location with depth of less than one-quarter wavelength (Drew et al., 2009). Since the near shore is further away from the land compared to shoreline, more energy is expected to be harnessed by the near shore WECs than shoreline WECs. Near shore WECs are being fixed to the seabed by static structure (Bhattacharjee & Karmakar, 2014).

Offshore WECs are located on the deep water zone of the ocean. Among these three locations, offshore has the highest potential to harness the maximum wave energy. This is due to the higher depth of water contains higher amount of energy. The significant depth of water also leads to the extreme condition for operation. The design and material selection of offshore WECs must allow it to withstand such challenging condition. Hence, offshore WECs are more difficult to maintain and construct, which leads to higher construction cost to offshore WECs than shoreline and near shore WECs (Drew et al., 2009).

2.3.2 Operation Technology of WECs

There are different operation technologies being used in the WECs to capture the wave energy. Figure 2.3 classifies the operation technologies of WECs into five groups.

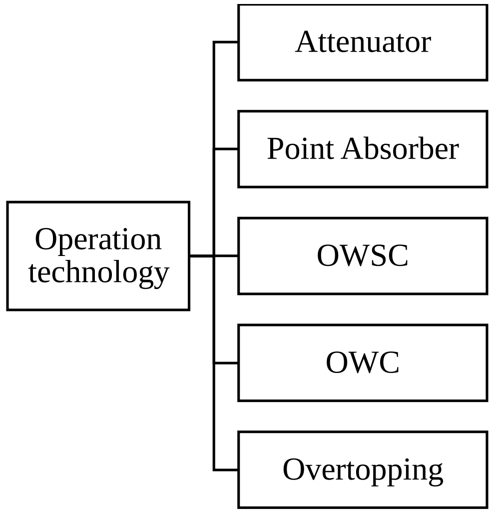

Figure 2.3: Classification of WECs based on their operation technology

<u>Attenuators</u>

Attenuators are situated on the ocean in a direction parallel to the force of predominant waves. They are held in position by mooring on the seabed. The wave energy is captured through the motion of devices from the crest and trough in a hydraulic line and then converted into electric current.

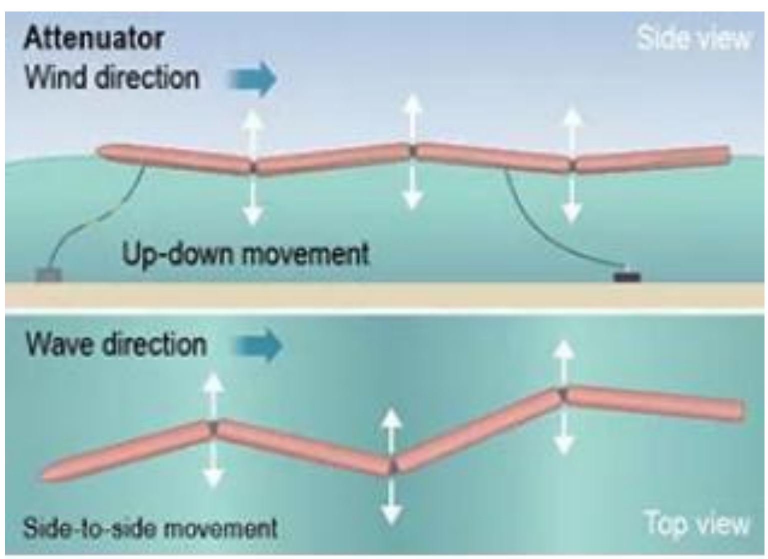

Figure 2.4:The attenuators (Department of Energy, 2018)

An example of attenuators is the Pelamis WEC. It is a product developed by Ocean Power Delivery Ltd (now known as Pelamis Wave Power). It is used to operate in water depth of approximately 50m. The Pelamis consists of at least two cylindrical hollow steel segments with diameter of 3.5m, connected by two degree-of-freedom hinged joints. The central unit of these joints contains a complete power conversion system similar to universal joint. There are four hydraulic cylinders that accommodate both horizontal and vertical motion to resist the wave-induced motion of these joints. The function of these hydraulic cylinders is to act as pumps that drive the fluid through hydraulic motor to activate an electrical generator later. Due to its unique design, attenuators require minimal onsite construction. However, there is possibility of leakage in the hydraulic cylinder through evaporation which will lead to failure of the system. (Drew et al., 2009).

Figure 2.5: The Pelamis WEC (Drew et al., 2009)

<u>Point Absorber</u>

Point absorbers are floating WECs that possess small dimension relative to the incident wavelength. Since they are compact in size, they are insensitive to wave direction so capable to absorb the wave energy from all direction by heaving together with the waves to produce electricity. However, their small dimension carry disadvantage of capturing lesser amount of energy compared to other type of WECs. This problem is compensated by deploying multiple point absorbers with several floats on the sea. In the point absorbers, there is a float or buoy that heave with the wave. The motion of float will be transformed to move a PTO system that activates a generator to produce electricity (Thomson Reuters, 2009). As point absorber is the type of WEC being studied in this project, more literature reviews related to it will be discussed in this thesis later.

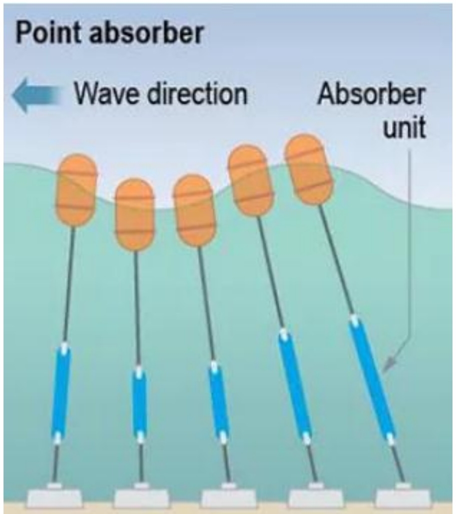

Figure 2.6: The point absorbers (Department of Energy, 2018)

OWSC

In OWSC, a hinge deflector or oscillator is positioned perpendicularly to the wave direction. As the wave travels, the deflector moves backward and forward to exploit the enhanced horizontal fluid particle movement of wave. The movement of oscillator will then drive the generator located at the land, thus it is operating at shoreline. The figure below illustrates the example of OWSC, called the Aquamarine Power Oyster which is situated on near shore (Drew et al., 2009).

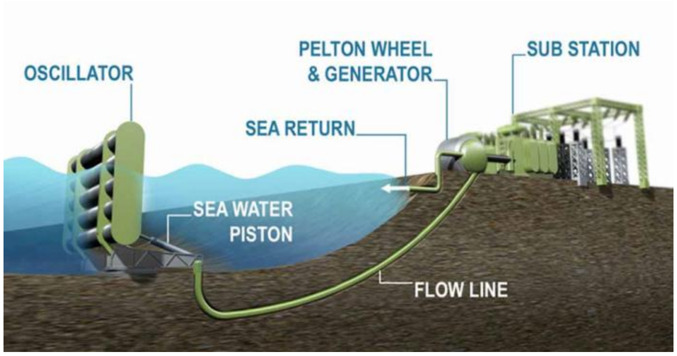

Figure 2.7: The Aquamarine Power Oyster (Drew et al., 2009)

OWC

An OWC device has a converter with a collector which is a semi-submerged chamber. The collector has an inlet that allow sea water to enter as shown in Figure 2.8. As waves enter and exit the collector, the water column behaves like a piston to move in upward and downward direction. This movement causes the compressed air to be channelled towards a turbine and then activate the generator. This device is easy for installation and maintenance because it does not contain any moving parts or electrical equipment in contact with the sea water. Proper conditioning of the device and the favourable may compensate the lost energy through diffraction and reflection. OWC devices can be either floating or fixed, depending on the location being installed. Floating OWC devices are meant for offshore while fixed OWC devices are designed for shoreline or near shore (Bhattacharjee & Karmakar, 2014).

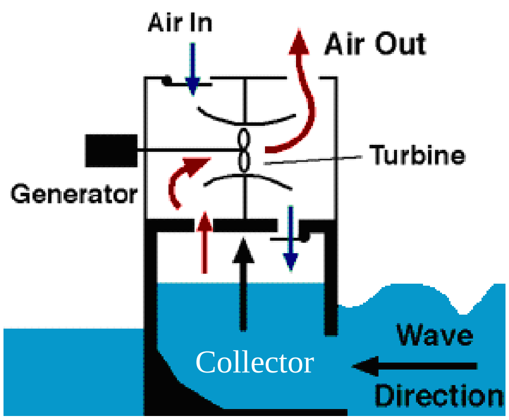

Figure 2.8: Schematic diagram for OWC device (Bhattacharjee & Karmakar, 2014)

Overtopping

An overtopping device works like a hydropower system, in which water is drained to turn a turbine. The device channels the sea water into big reservoirs that are placed above the sea level. When the level of water collected in the reservoirs is higher than the sea level, the excess water is returned to the sea through turbine outlet. The turbine is coupled to generator, thus electricity is produced during the returning of sea water. The risk of failure of device is less as the only moving part of the device is the turbine, and there is no components moving with the unpredictable waves (Bhattacharjee & Karmakar, 2014). Figure 2.9 shows an example of overtopping device called the Wave Dragon. In this device, two reflectors are used to focus the incident wave towards the ramp before entering the reservoir, and there are a few hydro turbines that convert the pressure head into useful power (Kofoed et al., 2006).

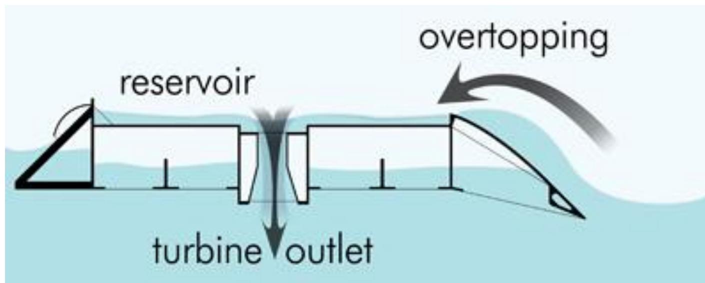

Figure 2.9: Schematic diagram for floating overtopping device (Kofoed et al., 2006)

It is found that the effectiveness of a WEC is not solely measured by its efficiency in extracting energy, but also is evaluated based on other factors such as the cost of construction, environmental impact, mode of failures and ease of maintenance work. The table below summarised the discussed operation technologies in terms of their operation location, advantage and disadvantage.

Table 2.1: Summary of the operation technology of WECs.

Operation technology	**Location**	**Advantage**	**Disadvantage**
Attenuator	Offshore	Require minimal onsite construction	Leakage issue
Point absorber	Offshore	Able to capture energy from all directions due to its compact size. High design flexibility because many type of PTO systems can be used.	Multiple units is required to achieve high electricity output.
OWSC	Shoreline	High accessibility for maintenance	Negative environmental impact due to its location

OWC	Shoreline/ Near shore/ Offshore	Easy installation because no undersea cable is required. Ease maintenance because there is no moving part or electrical equipment in contact with the sea water.	Performance is dependent on the installation location.
Overtopping	Offshore	Reliable technology is implemented, which is the turbine.	High maintenance cost

2.4 PTO system of WEC

The PTO system of a WEC describes the mechanism for primary converter of WEC to convert the wave energy into electrical energy. The examples of primary converter are the hydraulic cylinders of attenuators, the collector of OWC and the buoy of point absorbers. There are 5 types of PTO systems, which are the air turbine, hydraulic converter, hydro turbine, direct mechanical drive system and direct electrical drive system. The type of PTO system being used in a WEC can vary. It is correlated with the technology of WECs. For instance, air turbine is found in OWC. For point absorber, different PTO systems can be used, depending on their configuration and may require cascade mechanisms. Until 2014, statistic shows that the percentage of WECs that use hydraulic converter is the most (42%), followed by direct drive system (30%), hydro turbine (11%) and air turbine (11%) (Ruud & Frank, 2014). There is no any specific industrial standard for the selection of PTO standard, which show that the PTO systems are in development stage with very limited experience gained in the industry. The PTO system used in a WEC has significant effect on its efficiency, as well as the size and mass of WECs. Figure 2.10 summarizes the different paths for the conversion of wave energy (Têtu, 2017).

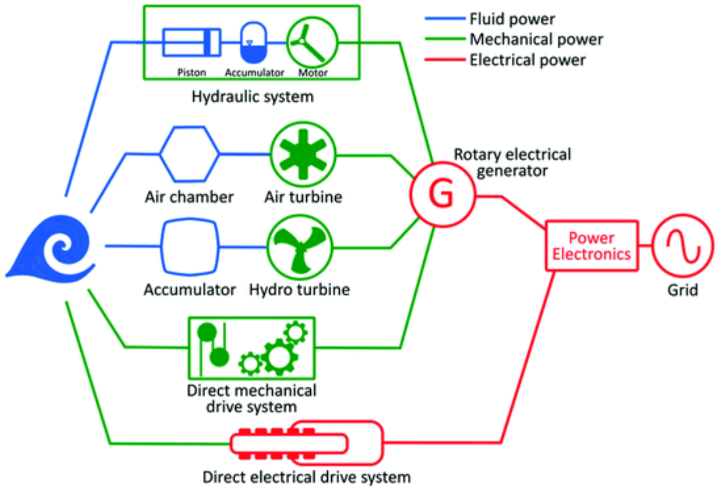

Figure 2.10: Overview for PTO system (Têtu, 2017)

2.4.1 Air turbine

Air turbine is used in OWC. As explained before, in the semi-submerged chamber, the oscillating air pressure induced by the movement of water in chamber drives the turbine. One of the significant problems of this PTO system is that the nature of bidirectional air flow causes the rotational direction of turbine varies. To overcome this problem, non-returning valve is used to rectify the flow, or self-rectifying air turbine is used to convert air flow into unidirectional rotation (Têtu, 2017).

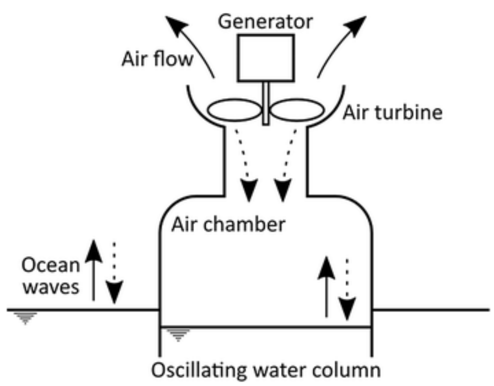

Figure 2.11: Air turbine in OWC (Têtu, 2017)

2.4.2 Hydraulic Converter

Hydraulic converter is found in point absorbers and attenuators, in which the conversion of wave energy relies on the movement of buoy or float of WECs. Hydraulic converter is a good option when it is dealing with large force with low frequency (Têtu, 2017). Figure 2.12 illustrates hydraulic converter PTO in point absorbers. A hydraulic cylinder is connected to a buoy and it will respond to the movement of buoy that is induced by ocean waves. As the buoy moves upward and downward, the fluid is forced through controlled hydraulic manifold to hydraulic motor to drive electric generator. The generator is a constant speed device, and hydraulic motor has variable capacity to allow different fluid flow rates to drive the generator at constant capacity. When necessary, accumulator will provide or accumulate hydraulic energy to smoothen the supply of high pressure fluid in the system (Drew et al., 2009; Têtu, 2017).

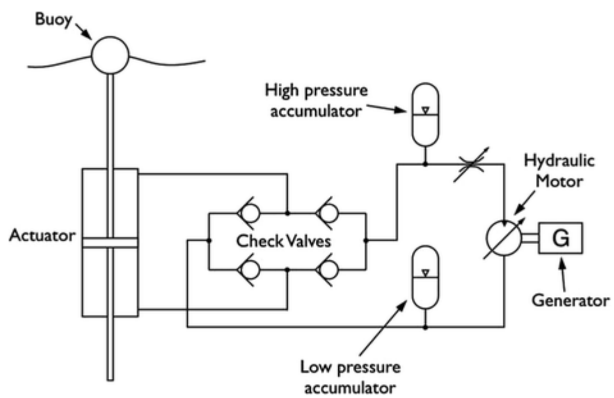

Figure 2.12: Hydraulic converter PTO system in point absorber (Drew et al., 2009)

2.4.3 Hydro Turbine

Hydro turbine is used in overtopping device or OWC. Compared to other PTO systems, hydro turbine is a more stable and mature technology since it has been used in power generation for decades. It has efficiency up to 90% and requires less maintenance. Even if leakage occur, it does not bring any negative impact to the environment since the sea water will leak to the ocean. However, if it is used in near shore devices, abrasive particles could destroy or damage the seals or valves or hydro turbine (Drew et al., 2009;

Têtu, 2017). Figure 2.13 shows the Kaplan turbine. It can be found in the Wave Dragon. This reaction turbine consists of a rotating element named runner immersed in the water and a guide vane to regulate the water flow through the runner.

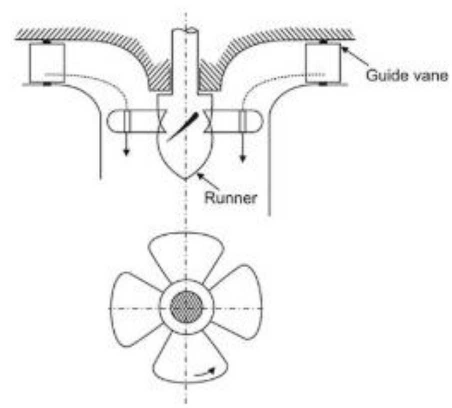

Figure 2.13: Kaplan turbine in Wave Dragon (IIT, 2016)

2.4.4 Direct mechanical drive system

Direct mechanical drive system is a PTO system that transforms the mechanical movement of buoy or float of WECs through an extra mechanical conversion system to drive a rotary electrical generator. The mechanical conversion system can be any mechanisms such as gearbox, rotating shaft, pulley or cable. As the operation of this system involves uncountable load cycles, the life cycle and study on failure of components has to be taken into consideration in the design (Têtu, 2017).

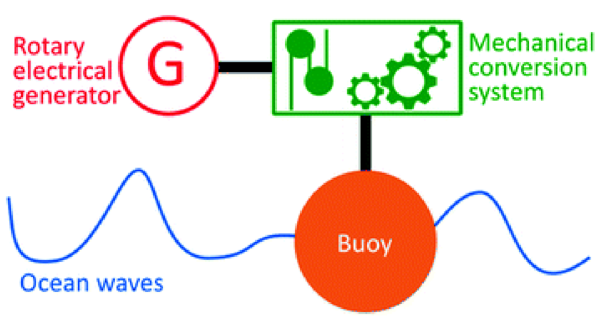

Figure 2.14: Direct mechanical drive system (Têtu, 2017)

2.4.5 Direct electrical drive system

Figure 2.15 illustrates the direct electrical drive system. Unlike direct mechanical drive system which buoy is connected to an extra mechanical conversion system to interface with the rotary generator, the buoy is directly coupled to the moving part of linear electrical generator to generate electricity. Alternating polarity permanent magnets are mounted on a translator and this translator is connected to heaving buoy. In addition, there is stationary stator equipped with coils in this system. As the ocean waves induce heaving motion, the magnets move upward and downward to induce electrical current in the stator (Drew et al., 2009; Têtu, 2017).

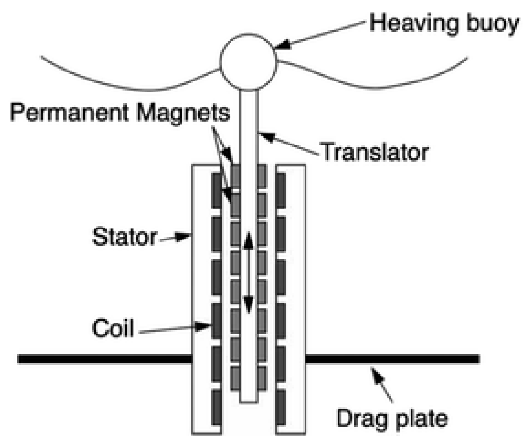

Figure 2.15: Direct electrical drive system (Drew et al., 2009)

2.5 Performance Evaluation of WEC

In this section, formulations needed to calculate the efficiency of the WEC will be discussed (Jens Engstrom, 2011) (Pecher, 2012).

2.5.1 Capture Width (CW)

The CW is defined as the ratio of $P_{absorbed}$ to the P_{wave}. As as P_{wave} in kW/m and $P_{absorbed}$ in kW, CW is in meter. It represents the width of wave front from which the energy is extracted from the waves (Babarit, 2015).

$$CW = \frac{P_{absorbed}}{P_{wave}} \tag{2.4}$$

2.5.2 Capture Width Ratio (CWR)

The best indicator to evaluate the efficiency of a point absorber is CWR. It indicates how efficient a point absorber to capture the energy from the incident waves. It is obtained by dividing the capture width with the characteristic dimension B of the point absorber (Babarit, 2015). It can be also be explained as the ratio of $P_{absorbed}$to the power of wave flowing through the device.

$$CWR = \frac{CW}{B} = \frac{P_{absorbed}}{P_{wave} \times B} \tag{2.5}$$

where B is the characteristic diameter of WEC. It can be calculated by

$$B = \sqrt{\frac{4A_w}{\pi}} \tag{2.6}$$

For vertical cylinder or floating hemispheres, A_w is equal to the diameter of main driver. In other words, the characteristic diameter of a point absorber is the diameter of its buoy. For other cases, A_w refers to the maximum horizontal cross sectional area of the WEC.

2.6 Point Absorber

Though there are many type of WECs being developed by the industry, the interest of this project is on the point absorbers. Research and studies on various conceptual designs and prototypes of point absorber have been done by several private companies or research administrations in the last few decades. The outcomes have proven that point absorber represents one of the most promising technologies among the WECs, in which point absorber is currently considered as a reference WEC (Piscopo et al., 2008).

2.6.1 Current Technology Review of Point Absorbers

Point absorbers can be divided into 2 types according to its bottom structure, either it is fixed or is non-fixed. The examples of non-fixed point absorber are PowerBuoy, developed by Ocean Power Technologies and AquoBuOY, developed by Finavera Renewable. Meanwhile, the example of point absorber with a fixed bottom is the Archimedes Wave Swing, developed by Teamwork technology BV of Netherlands.

PowerBuoy

The PowerBuoy is developed by Ocean Power Technologies. The float of PowerBuoy is connected to a push rod and they move along a spar, a cylindrical structure beneath the float and encloses the push rod. Due to the presence of a heavy plate at base of the spar, the likelihood for the spar to heave is less. The PTO system used in the PowerBuoy is direct mechanical drive system, where rack and pinion with a fixed input rod are used as the core components of energy conversion process. This system allows the relative motion between the linear motion of float and spar to be converted into rotational motion which will then drive an electric generator (Mekhiche & Edwards, 2014; Poullikkas, 2014). In 2016, the PB3 PowerBuoy is deployed off the New Jersey.

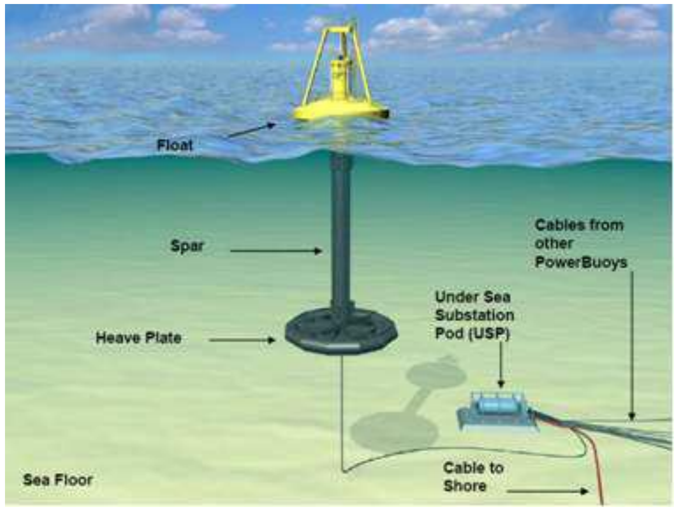

Figure 2.16: The PowerBuoy (Mekhiche & Edwards, 2014)

AquaBuOY

The AquaBuOY is developed by Finavera Renewables to operate at offshore with water depth of approximately 46m. In AquaBuOY, the PTO system is hydraulic converter. A broad buoyant disk which is situated in a long tube beneath the buoy is coupled with its buoy. The movement of buoy induced by ocean waves causes the disk to move together and act like a water piston. As the water piston heaves, the hose which contains sea water elongates and relaxes alternatively. Due to the change in the hose volume, it has the ability to act as a pump to pressurize the fluid to drive the turbine generator. However, the prototype of AquaBuOY experienced failure before the completion of power tests, where the device sunk off after 7 weeks of deployment on the Oregon coast. The leakage in structure causes pump to malfunction (Poullikkas, 2014).

Figure 2.17: The AquaBuOY (Poullikkas, 2014)

<u>Archimedes Wave Swing</u>

The Archimedes Wave Swing was the first WEC that utilizes linear electrical generator to produce electricity. It is suitable to be deployed in water depth of more than 25m (AWS Ocean Energy Ltd, n.d.). It consists of a float and a fixed base. The type of PTO used is the direct electrical drive system where the buoy is connected to permanent magnet through a shaft. As the float heaves up and down with crest and trough wave, the interior pressure acts as the spring and causes the motion is resisted by the linear generator thus produce electricity (Poullikkas, 2014).

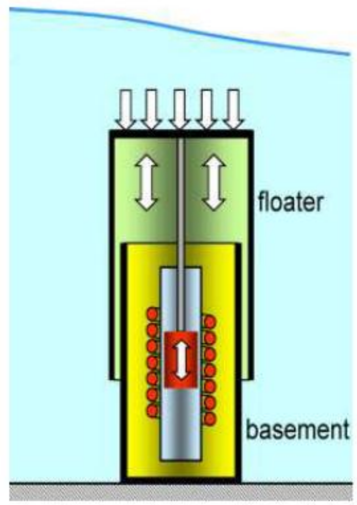

Figure 2.18: Archimedes Wave Swing (Poullikkas, 2014)

The table below summarises the discussed point absorbers in terms of the PTO system used, development status and capacity.

Table 2.2: The point absorbers.

Point Absorber	**PTO system**	**Status**	**Capacity**
Power Buoy	Direct mechanical	Commercialised in 2016	3 kW
AquaBuOY	Hydraulic converter	Full scale testing	250 kW
Archimedes Wave Swing	Direct electrical	Full scale test	25kW – 250 kW

2.6.2 Natural Frequency of Point Absorber

For a point absorber to vibrate at maximum amplitude, it has to oscillate at its natural frequency. The natural frequency of the point absorber has to be adjusted until it is equal or close to the frequency of the waves. The natural frequency of the point absorber is given by the formula: