한국마린엔지니어링학회지 제36권 제5호, pp. 707～715, 2012. 7(ISSN 2234-8352 Online) / (ISSN 2234-7925 Print)
Journal of the Korean Society of Marine Engineering http://dx.doi.org/10.5916/jkosme.2012.36.5.707

Ocean Wave Energy Converters - A Perspective

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(Received June 26, 2012; Revised July 10, 2012; Accepted July 18, 2012)

Abstract: Ocean waves are mighty and powerful. Humans have explored the possibility of harnessing this mighty power for decades now. Estimated as suffice, if only, a fraction of this energy is captured and harnessed, the worry for decrease in fossil fuels diminishes and the current energy consumption of the world can be met. Though different types of methods and devices for extracting energy from this nonstop, free source has been proposed, a handful of them have reached commercialization and others are on the verge. This paper discusses the journey so far in terms of devices that have been developed or prototypes proposed or commercialized. Only a list full of them have been discussed though they exist in numbers.
Key words: Ocean Wave Energy, Ocean Wave Energy Conversion, Wave Energy Converters.

1. Introduction

Ocean wave energy is the most abundant resource of renewable energy. Though the oil crisis in the early 70's stimulated the need for renewable energy resources, looking from a different standpoint, over 30% of the world's population lives within 60 miles of the coast line [1] and if only 0.2% of the ocean's energy could be tapped it could provide power to the entire world. A single meter of wave has the raw power for 23 coastal homes [2]. The energy available is about 8,000 to 80,000 Terra Watt (TW) [1] and about 10 TW in open sea is considered to be available wave energy resource worldwide [3]. It has high power density of typically 30 kW/m and usually a wave crest transmits 10-50 kW/m [1]. In most tropical waters, the average wave power level is below 20 kW/m. The global power potential that hits all coasts worldwide has been estimated to be in the order of 1 TW [4]. The wave power, defined as the transport of energy per unit of the progressing wave front, will vary from time to time on different time scales which is twice higher than that of wind power [1]. Energy from the ocean exists in different forms, as shown in **Figure 1** [5]. Classical text books related to and on the subject includes [3], [6-10]. Reviews on the subject includes [4], [11-14]. This paper focuses solely on ocean wave energy and its power extraction modules and is not an exhaustive list which includes all prototypes, but, rather only covered are a list of handful of prototypes which have either been deployed, tested or commercialized. However, a table is listed on the number of prototypes available.

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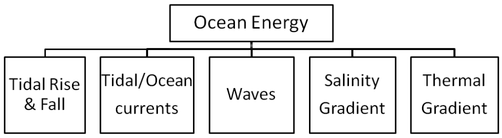

Figure 1: Principal forms of Ocean Energy [5]

1.1 Wave Formation

The uneven heating of the earth's surface forms winds. These winds blows over the ocean's surface which transforms waves into a mighty power, often known as wind seas. The stretch of these long waves are known as swells, as shown in **Figure 2** [15], which spreads out over the ocean. Once transformed they can travel for miles with little energy loss, decreasing in intensity near the shore [1]. These waves travel at phase velocity and a group of waves travels at group velocity, where the energy is transmitted [16]. Wave sources are strongest towards poles from the west with winter bringing six times more energy than summer [1]. About 95% of the energy in the waves lies in the region between mean water depth and one quarter of a wave length below it. This energy can be captured, converted and stored by means of a floating or fixed wave energy conversion device with a power take-off system included in it. Generally, a floating body has six modes of oscillations, namely surge, sway, heave, roll, pitch and yaw, where the first three are translational motions and the next three are rotational ones [6] as shown in **Figure 3.**

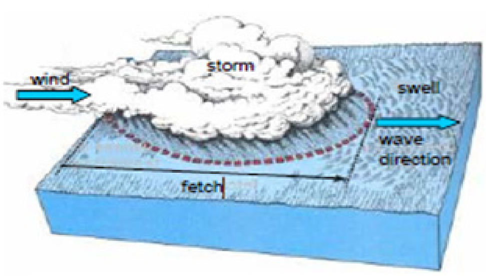

Figure 2: Formation of wind sea and swell [15]

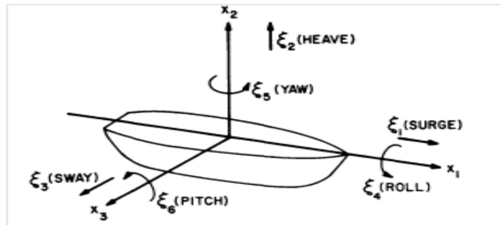

Figure 3: Motions of a body in six DOF [6].

2. Ocean Wave Energy Conversion

Extracting energy from the oceans is not new as it dates back to a lot many years ago. In fact, the first patent filed dates back to as early as 1799 [7]. In his famous paper, Evans starts with the following quote made by Stodder on a discussion made to a long paper by Stahl as "I have great many reasons why I think wave power can be put to practical and profitable use, but I don't wish to occupy too much of your valuable time, or, perhaps, there are not many of you particularly interested in the subject", goes to show well how long the idea of extracting energy from ocean waves has been of interest [17]. Since the 1940s, Yoshio Masuda, a Naval Officer in Japan, worked extensively with wave energy devices and went on to commercialize them in 1965 [18]. In the United states, J. N. Newman [19], W. E. Cummins [20], J. V. Wehausen [21] made key contributions to the filed of (Marine) hydrodynamics which forms the basis of ocean wave energy conversion. M. E. McCormick was an early academic researcher who contributed his classic book on this field initially [7]. During this time researchers in Europe, in particular in the UK and Norway showed interest in this field. In 1974, Prof. S. Salter (UK) started exploring the possibilities of extracting wave energy by means of Wave Energy Converter (WEC), what is now famously called "The Salter Duck" [22]. Two researchers from Norway, namely Kjell Budal and Johanes Falnes [23], David V. Evans (UK) [24] and a few others have all worked extensively on wave energy conversion thereby contributing immortal articles from where the current generation has carried on. Simultaneously research was carried out in countries like Norway [25] and India [26]. Recently many countries have stepped up research in pursuit of renewable energy. **Figures 4 and 5** shows the trend in this field of research with many countries like Portugal, Denmark, Korea, China, Turkey, Iran, Canada, Israel and Spain and many others have given importance.

3. Design

3.1 Wave Energy Converter (WEC)

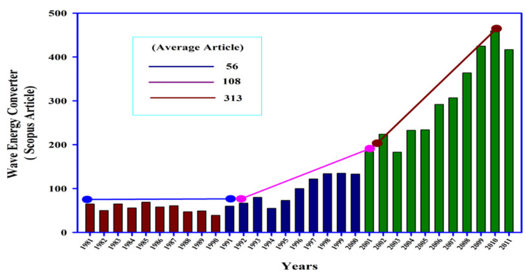

Figure 4: Research using Wave Energy Converters

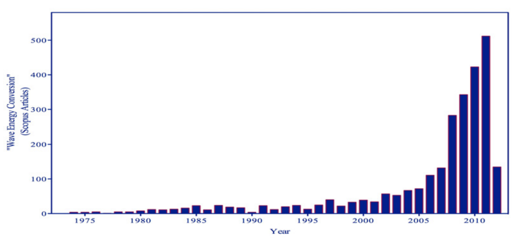

Figure 5: Research using Wave Energy Conversion

It is useful to think of a primary conversion of wave energy by an oscillating system as a wave intereference phenomena [4]. A WEC is a machinery, where in the physical movement of the device is converted into electrical energy. Different types of WECs are proposed, some are even commercialized and some are on the verge. To capture energy, all devices result in a reciprocating motion at low velocities in the region. The main issue of a wave energy device is that they are not directly compatible with local conventional rotary electrical machines. Hence there is a need of a power take off mechanism by means of air, water and hydraulic systems or the use of turbines or the concept of direct drive or contact less force transmission, as a proposed interface with the electrical generator is highly desirable and essential. These interfaces increase the complexity of the system and introduces reliability issues. Also the moorings and safety of the device has to be ensured at sea during rough conditions.

3.2 Wave Energy Converter Classifications

WECs can be classified into four types.

1). Oscillating Water Columns (OWCs)
2). Attenuators
3). Overtopping
4). Point Absorbers

3.2.1 Oscillating Water Column

The Oscillating Water Column WECs are the most widely known and used since the early days of Yoshio Masuda. These devices are placed either on shore line or near shore. The housing is just placed above the water surface. The OWC devices can be classified into two types, namely floating and fixed type. **Figure 6** shows a general description of an OWC working principle.

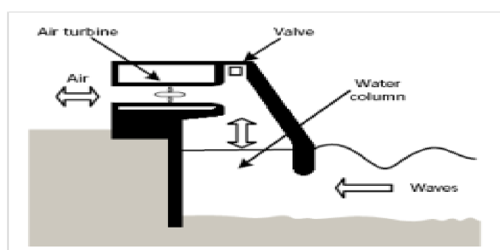

Figure 6: Oscillating Water Column Device [1]

An OWC device works via the principle of wave induced air pressurization [1]. The air chamber is placed above the water. Wave action causes the water level to rise and fall forcing trapped air in the chamber to pass through small opening on the top, where a turbine is placed. Due to the reduction in volume the pulsating air's velocity is increased. This higher velocity air is then directed towards the blades of an air turbine causing it to rotate. This air is bidirectional since it passes into and out of the chamber due to wave troughs and crests. To get rotation in one direction the air is rectified through one way valves or using a self rectifying axial flow Wells turbine, which was designed for this type of application used in most OWC devices. The turbine is coupled to an electric generator to produce electricity [1].

(a) Floating Type OWCs:

The floating type includes the "Mighty Whale", Ocean Energy Buoy, the Oceanlinx OWCs, Sperboy.

The "Mighty Whale"

Since 1998, off the coast of Mie Prefecture, based on the experiences on the study of the Kaimei barge in 1978, and from 1985 to 1986 [27-28], JAMSTEC, started testing this converter the "Mighty Whale", as shown in **Figure 7**, a terminator type, which is a floating OWC device to extract energy from the ocean and convert it into a form of energy, mainly electricity. It has three mouths where the waves that pour into and out of the them compress the air inside the chambers. The incident waves cause rise in the water level in the air chambers. This creates a high speed air flow through the air turbine passage causing the turbines to rotate which in turn causes the generators coupled to them to rotate, thus producing electricity, similar to the OWC principle. More details on the "Mighty Whale" can be found in [29].

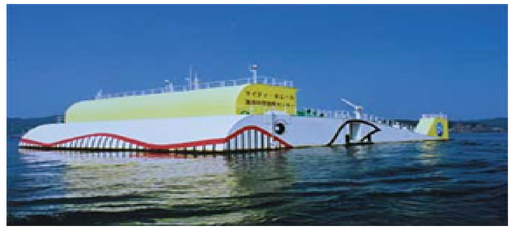

Figure 7: The "Mighty Whale" in the sea [27]

(b) Fixed Type OWCs

The fixed type includes the Pico, Limpet and Mutriku.

The Limpet

LIMPET - Land Installed Marine Powered Energy Transformer, as shown in **Figure 8,** is a fixed type converter working on the principles of an OWC. Owned by the company Voith Hydro Wavegen, it is located at the Island of Islay, Scotland, The current device Limpet-500, installed in 2000, produces power for the national grid. The OWC couples with the surge dominated wave field adjacent to the shore. The turbines generates a total of 500 KW with two 250 KW generators driven by counter rotating turbines. Wave intensities between 15 and 25 KW/m has been optimized for annual average peak performance. The company has developed a 18.5 KW power take-off module which consists of a Wells turbine, valve and noise attenuator for different purposes such as incorporating into break waters, coastal defences, land reclamation schemes and harbor walls. The company's directional wave rider buoy gathers valuable site specific wave data which records wave

Figure 8: The Limpet [30]

height, wave period and wave direction which can be used for tank test model performance and response in real seas [30]. A recent review on the Limpet can be had from [31].

3.2.2. Attenuators

An attenuator device is one which consists of long multisegment floating structures, which are parallel to the wave direction. There are three types of attenuators, namely, the pelamis, the wavestar and the oyster converters.

Pelamis

Developed by Pelamis Wave Power, earlier known as Ocean Power Delivery, the Pelamis WEC is an offshore floating type, attenuator device. It is named after a sea snake. It has four segments joined by hinges. It's motion is converted to power by means of a hydraulic power conversion system in each of the three power conversion modules. It is slack moored with a compliant mooring configuration that both points the device into the waves and enhances survivability. In 2008, off the coast of Agucadoura, in Portugal three first generation converters were tested.

The farm started delivering 2.25 MW produced by three Pelamis generators. However they were to be towed back to the port after four months of operations due to technical problems. Another 28 machines were planned as a part of phase 2 to generate 22.5 MW for state run power company Energias de Portugal. More details about the Pelamis can be found in [32-33]. **Figure 9** shows the Pelamis in sea.

Figure 9: Pelamis in Sea [32]

3.2.3 Overtopping

An overtopping device is a form of a collector of waves to extract energy from the oceans. When waves are collected into a reservoir, they are elevated above the sea level where water is let out, which passes through turbines. The turbines are coupled to a generator. It is placed either offshore or onshore. **Figure 10** shows a working principle of an overtopping device.

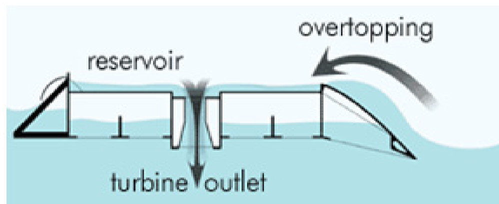

Figure 10: Overtopping WEC [34]

Wave Dragon

Wave Dragon is a company that uses the overtopping technique to extract energy from waves. As of 2003, the company launched a 1:4:5 scale prototype off the coast of Denmark. After a setback due to financial crisis, the company has started the development of a 1.5 MW Wave Dragon with the aim of making 4MW and 7MW devices. Overtopping type devices are less common. More details of the overtopping devices can be had from [34-35].

3.2.4. Point Absorbers

Recently, point absorbers have received much attention and is now the most commonly used principle in extracting energy from the ocean. Point absorbers harvests energy from all directions in the ocean. They are placed on shore or offshore. They are either tube type or float type [1].

AquaBuoy

Formerly owned by Finavera, now under SSE Renewables, the AquaBuoy WEC is a point absorber device. It consists of four elements, namely a buoy, an acceleration tube, a piston and an hose-pump. When an incident wave hits the device, water is rushed to an acceleration tube which causes the piston to move, which in turn forces a rubber hose to stretch. This stretch, acting as a pump activates a turbine which drives a generator. The Buoys can also be placed as arrays to harvest more power, where the desired output would be more. The technology was also tested off the coast of Newport, Oregon. **Figure 11** [36] shows the device deployed in sea. More details on the AquaBuoy including its modeling can be had from [37-38].

4. Control

Despite many devices being deployed in sea, the control strategies are the same. That is, for the device to be an efficient absorber, it should oscillate in tune with the over passing waves. Two types of control exists, namely Latching and Complex Conjugate.

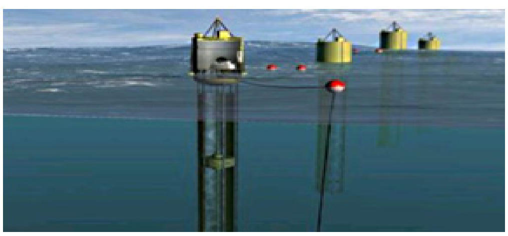

Figure 11: The AquaBuoy in arrays in sea [36]

Latching - Also called phase control, is a process where the body velocity is in phase with the excitation force of the waves. An alternative for latching, namely Unclutching has been proposed recently.

Complex Conjugate - Can be further classified into Optimal and Suboptimal, where in the former, the generator power is negative periodically while in the latter, the generator power is always positive. Prediction of the incoming waves are crucial for this type of control [13, 39, 40].

5. Power Take-Off (PTO)

The forces exerted on the device can exceed 1 MN with velocities of 2.2 m/s. Hence, to run a conventional electric generator, an intermediary is needed to convert the linear motion into a rotary motion [1]. Based on the designer's choice and where the device will be placed, different mediums are used as PTOs for different devices. Classified, they are Hydraulics, Linear generators, Magneto hydrodynamic generators and Contact-less force transmission system. Conventional generators use turbines (air or water) to run them. Reviews of turbines can be had from [41-42].

6. Current Status and Future Perspectives

Table 1: List of WECs [43]

	Name	Company	Country
1	AquaBuOY	AquaEnergy Group Ltd.	U.S.
2	Archimedes Wave Swing	Teamwork Tech. BV	Netherlands
3	Backward Bent Buoy	Indian Inst. of Tech.	India
4	Bristol Cylinder	Univ. of Bristol	U.K.
5	Circular Clam	Sea Energy Associates Ltd.	U.K.
6	Cockerell Raft	N/A	U.K.
7	Combined Energy System	Ocean Motion Int.	U.S.A.
8	Floating Wave Power Vessel	Sea Power International AB	Sweden
9	Hose-Pump	AquaEnergy Group Ltd.	Sweden
10	Hydraulic Platform	S.D.E. Energy Ltd..	Israel
11	Lilypad	Ove Arup	U.K.
12	Mace	Edinburgh Univ.	U.K.
13	McCabe Wave Pump	Hydam Tech. Ltd.	Ireland
14	Multi OWC	ORECon Ltd.	U.K.
15	Ocean Wave Energy Converter	Ocean Wave Energy Co.	U.S.A.
16	OPT Piezo-electric Polymer	Ocean Power Technologies, Inc.	U.S.A.
17	OWC Limpet 500	Wavegen	U.K.
18	OWC Mighty Whale	JAMSTEC	Japan
19	OWC Osprey 2000	Wavegen	U.K.
20	OWC Parabolic	Energetech	Australia
21	Pelamis	Ocean Power Delivery Ltd.	U.K.
22	Pendulor	N/A	Japan
23	Pitch & Surge Frog	Lancaster Univ.	U. K.
24	Pneumatically S. Platform	Float Inc.	U.S.A.
25	Point Absorber	Danish Wave Power Org.	Denmark
26	Power Buoy	Ocean Power Tech., Inc.	U.S.A.
27	Salter's Duck	Edinburgh Univ.	U.K.
28	SEADOG	Ind. Natural Resources Inc.	U.S.A.
29	Seawave Slot-Cone Generator	Wave Energy AS	Norway
30	Sloped IPS Buoy	Edinburgh Univ.	U.K.
31	Tapered Channel	Indonor AS	Norway
32	Wave Dragon	Wave Dragon ApS	Denmark
33	Wave Energy Module	U.S. Wave Energy Inc.	U.S.A.
34	Wave Plane	Wave Plane Solutions Ltd.	Denmark
35	Wave Rider	Tetra Research	U.S.A.
36	Wave Rotor	Ecofys & Eric Rossen	Netherlands & Denmark
37	Waveberg	Waveberg Dev. Ltd.	U.S.A.
38	Wavebob	Wavebob Ltd.	Ireland
39	Wavemill	Wavemill Energy Corp.	Canada
40	WECA Breakwater	Daedalus Informatics Ltd.	Greece

Figures 4 and **5** shows the current trend in ocean wave energy conversion. **Table 1** [43] shows a list of WECs. It clearly shows that ocean wave energy has crossed the infancy stage or is on the growth with many countries now involving in this field with support from Government and other agencies. With many universities nowadays conducting research and organizations monitoring and setting new standards to be implemented, and moreover, the lessons from the past experiences from failure to understanding, the future looks bright and optimistic. But still a long way to go in terms of commercialization, cost, design, safety and cheap production of electricity. In the first author's opinion, the hope lies in this field for our future energy demands.

7. Conclusions

Though interest of many years, and unimaginable power that can be harnessed, one can say ocean wave energy has just crossed infancy. With this status in mind, a brief history of this field and the key contributors who contributed initially were discussed. The WECs were classified into four main types and one among the many converters of each type were discussed. Why control and power take-off methods are necessary was stressed. A table with the number of converters available was also listed, though the list extends.

Acknowledgment

This Research was supported by the National Research Foundation of Korea, financially backed by the Ministry of Education, Science and Technology (MEST) (No.2010-0026578) 2010.

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