Wave Energy Converter

A Review of Wave Energy Conversion Technology

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***Abstract*—The Ocean has a vast amount of energy that could be harnessed and is being pinned as a promising resource. This paper highlights the development of wave energy converter technology since the late 1960s. Main topics discussed are: the characterization of various wave energy converter technologies; conceptual and practical working principle of various devices; and briefly discussed about the power take-off systems for various concepts. This paper will provide the reader with information on varies technology and concepts that have been developed over the years which are available for harvesting energy from the ocean.**

Keywords-Power take-off; Wave energy converter; Renewable energy; Wave Energy; Wave power

I. INTRODUCTION

The ocean holds a tremendous potential, possibly because of apparent propagation and the destructive force that it possesses. Ocean waves are induced by the action of wind, which itself is induced by differences in temperature caused by solar radiation.

Since the recognition of the possibility of harnessing wave energy and converting into usable energy, over one thousand patents had been registered by 1980 [1]. The earliest dated patent was filed in France 1799 [2]. The number has been to be increasing since.

Over the years, several reviews have been published in book forms, journal, conference papers, and reports. One of the first pioneering books was by McCormick [3] in 1981. Much information on the state-of-the-art technology for those periods can be found in the report prepared by the UK department of energy [4] in 1999. Other shorter reviews can be found in [5-9]

Wave energy extracting technology known today as oscillating water column (OWC), was first developed by Y.Masuda [10] using a navigation buoy equiped with an air turbine. These buoys were first commercialized in Japan and later in the USA [11]. In 1976, Masuda promoted the construction of a larger realization of the concept: a barge (80m x 12m) named Kaimei. Kaimei consisted of a floating testing platform housing several OWC's equiped with different types of air turbines [12]. The project was a failure due the fact that theoretical knowledge on wave energy absorbtion was in its infancy.

A major boost in interest was seen during the oil crisis of 1973 with the rising need for large-scale energy production from ocean waves. Stephen Salter [12], brought wave energy to the attention of the international community, making the University of Edinburgh a landmark. Importnant R&D program into wave energy was initiated by the British Governmert after this publication [13].

In 1985, Norway went on to the construction of a 350kW and 500kW prototypes, off the coast of Bergen. Activity in Europe remained mainly at the academic level till the 1990's with the only notable achievement being a 75kW OWC shoreline prototype deployed at the island of Islay, Scotland in 1991 [14].

Wave energy absorbtion, being a complex hydrodynamic process as it is, had added difficulty of the conception of a power take-off (PTO) mechanism. PTO's are technologies used to convert wave induced oscillations from mechanical to used to convert wave induced mechanical energy to usuable electricity. Common power take-off mechanisms include air turbine, power hydraulics, electrical generator and others. Difficulty lies in the variable influx of energy absorbed from ocean waves due to topological influences such as seasonal variations.

Most projects initiated to target largescale power production. Technology that can harvest wave energy, at a small scale, are oscillating body systems [15]. Research into micro-scale sytems and PTO's is minimal since wave farms may not be a realistic option due to high capital cost of deployment [4].

This paper is concerned with the different technologies available for wave energy conversion and their general working principles. It does not however emphasize on issues like policies but briefly addressed; areas of economics and environmental impacts.

From this paper the reader will be able to distinguish between the different types of technology present and categorize them with respect to their area of application. Also, the reader will be introduced to different mechanisms (power take-off) available for converting ocean energy to useful electrical energy and their advantages or disadvantages. Upcoming technology will also be higlighted.

II. WAVE ENERGY

Wave energy is considered as a secondary form of solar energy. Differential heating of the earth generated winds which in turn induced ocean waves. Issues with wave energy (wind energy) are largely random [4] and variations occur in different time scales such as seasonal variations.

Wave energy resource assessment is a prerequisite for the strategic planning of its utilization and for the design of wave energy devices [16]. For the purposes of coastal engineering,

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navigation, offshore engineering, and harbour, the charaterization of the wave climate has to be done.

The studies for the charaterization of wave energy resources, with regard to its untilization, was first initiated by countries where the wave energy technology was first realized, this was notably the UK [17,18]. In 1991, when European Commision (EC) decided to start a series of two-year (1992-1993) preliminary actions in wave energy R&D. A project was included to review the background on wave theory required for the exploitation of the resource and to produce recommendations for its characterization [19]. As a follow-up to these recommendations, the WERATLAS (wave energy atlas) [20] was developed. The WERATLAS remains the basic tool for energy planning in Europe.

Wave energy is expresed in power per unit length. This length is found along crest of the wave or along the shoreline direction [21]. Typical values for ‘good’ offshore locations (annual average) range between 20 kW/m to 70 kW/m and occur mostly in moderate to high latitudes [22]. Seasonal variations are in general considerably larger in the northern than in the southern hemisphere [23], which makes the southern coasts of South America, Africa, Australia and the South Pacific particularly attractive for wave energy exploitation. Further reviews on characterization of wave energy resources can be found in [24].

III. AVAILABLE TECHNOLOGY

Unlike other sources of renewable energy, there is a variety of wave energy technologies that have developed to adapt to different locale. They vary depending on shoreline, near-shore or offshore deployment.

Classification of wave energy systems can be done using several methods that depend on location, working principle and size. (e.g. “point absorbers” versus “large” absorbers) [25]. To avoid an exhaustive list of technology, Fig. 1 shows classification of wave energy converter based on working principle and emphasizes technology that have reached prototype stage or have been objects of extensive development initiatives.

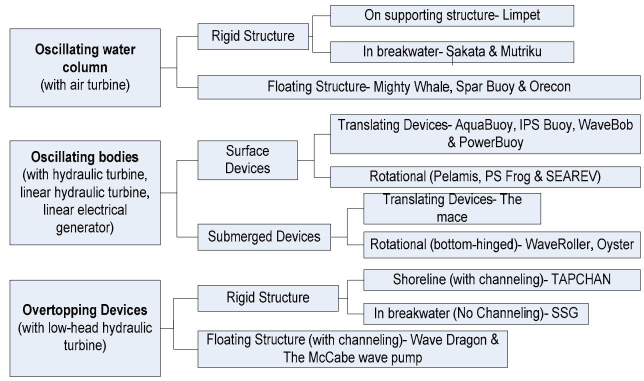

Figure 1. Wave Energy Technology classified according to working principle

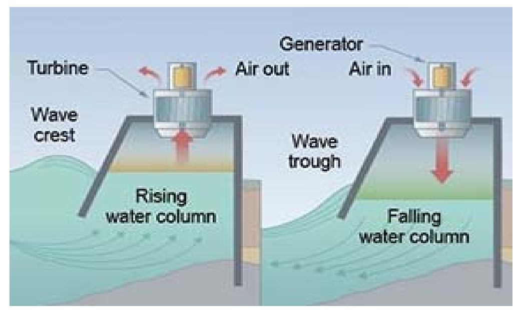

Figure 2. Cross-Sectional view of an OWC device [13]

A. Oscillating water column (OWC)

Also known as first generation devices, OWC’s have been deployed along shorelines or near-shore locations. These devices either stand on sea bottom or are fixed on rocky cliffsides close to shore. Advantage of these devices over other technology is that they have easier installation and maintenance and do not require long underwater cables and deep-water anchorage (moorings), which is relatively challanging and expensive.

The oscillating water column (OWC) device comprises a partly submerged concrete or steel structure, open below the water surface, inside which air is trapped above the water free surface (Fig. 2). The oscillating motion of the internal free surface produced by the incident waves make the air to flow through a turbine that drives an electrical generator [12].

Working plants have been constructed in Norway (Toftestallen, 1985 [26]), Japan (Sakata, 1990 [27]), India (Trivandrum, Kerala state, 1990 [20]), Portugal (Pico, Azores, 1999 [28]), UK (the LIMPET plant in Islay island, Scotland, 2000 [29]). All these plants were constructed as fixed structure (either bottom-standing or on a sloping wall). The main component in these plants are “Wells air turbine” [30] that drives an electrical generator. Their power production capacity ranged between 60-500 kW. Civil construction cost of the OWC plant is the substancial. Integrating the OWC with an existing breakwater has several advantages; access for construction, operation and maintenance of the wave energy plant become much easier [12].

1) Floating OWC structures

First introduced by Yohio Masuda, mentioned in section 1, was the floating OWC Kaimei karge which was developed and deployed in Japan in the 1960’s and 1970’s. After its unsatisfactory performance, Yoshio conceived a different geometry for the floating OWC: the Backard Bent Duct Buoy (BBDB) (Fig. 3). The BBDB device was studied in several countries such as Japan, China, Denmark, Korea, Ireland and used to power approximately one thousand navigation buoys in Japan and China [31]. In this way, the length of the water column could be made sufficiently large for resonance to be achieved, while keeping the draught of the floating structure within acceptable limits [12]. A large BBDB, equipped with a horizontal axis Wells turbine, was

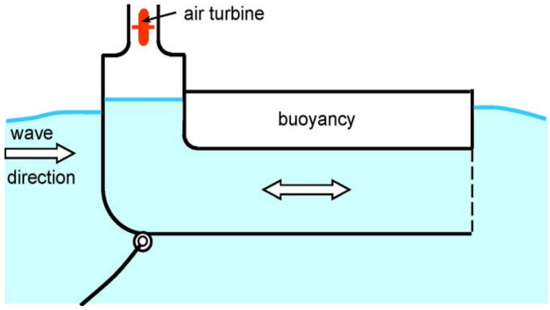

Figure 3. Backward Bent Duct Buoy [13]

deployed and tested in the sheltered sea waters of Galway Bay (Ireland) [32]. Other prominent variations of the technology were the Mighty Whale [33], Spar buoy [34] and the Oregon [35].

B. Oscillating devices

Oscillating devices (heaving devices), consists of buoys that float on the surface of ocean waves. PTOs are activated by the movement (induced by ocean waves) of the buoy perpendicular to the sea bed. This principle is used in various devices mentioned in the sections that follow.

1) Single –body heaving buoys

Classified as third generation devices, heaving buoy devices are the simplest oscillating-body devices having a fixed frame of reference at sea bottom or a bottom fixed structure. These systems are considered as point absorbers as their horizontal dimensions are smaller than the wavelength.

Early designs had wedge shaped buoys with rectangular platform whose vertical motion was guided by steel structure mounted to a breakwater. The PTO used in these devices was hydraulic rams in a circuit including gas accumulators [36].

Another example is the Norwegian buoy; it performed heaving oscillations relative to a strut using a spherical floater. The strut was anchored to the sea bed through a universal joint. This device was equipped with an air turbine, inside the floater, which was stimulated by an orifice on the buoy. The model was tested, along with its latching control, in Fjord, 1983 (Fig. 4).

Relative motion between the buoy and the sea bed structure activates the PTO. In the device that was tested in Denmark in the 1990s, the PTO (housed in a bottom-fixed structure) consisted in a piston pump supplying high-pressure water to a hydraulic turbine [12].

Developments of this technology lead to the taut-moored buoy concept which is being developed at Uppsala University, Sweden. A linear generator is placed on the ocean floor instead of a piston pump. Connected to the top of the generator is a line, attached to the buoy on the other end, which acts as a PTO. Springs attached to the translator of the generator store energy during half a wave cycle and simultaneously act as a restoring force in the wave troughs [12] (Fig. 5). Sea tests conducted on a 3 m diameter cylindrical buoy off the western coast of Sweden is reported in [37].

Figure 4. Norwegian heaving buoy [14]

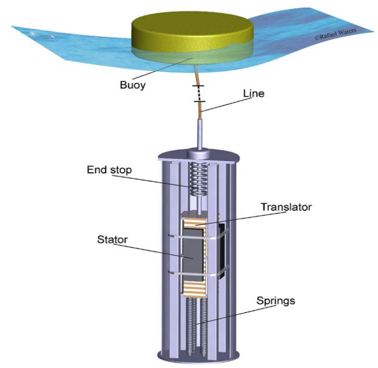

Figure 5. Swedish heaving buoy with linear generator [4]

Another similar device where a linear electrical generator is driven by a heaving system was developed at Oregon State University, USA [38]. In this device, the freedom of movement of the annular saucer-shaped buoy is constrained. It can only move relative to the deep-draught spar and all other degrees of freedom is constrained by a linear bearing system (Fig. 6). The spar is taut-moored to the sea bed. The relative velocity between it and the buoy is converted into electrical energy by a permanent magnet linear generator. A 10kW prototype was deployed and tested in Newport, Oregon, in September 2008.

2) Two-body heaving buoys

Single body system raised difficulties due to the distance between the floating body and the sea bed and/or tidal oscillations in the sea level. Multi-body systems may be used instead, in which the energy is converted from the relative motion between two bodies oscillating differently.

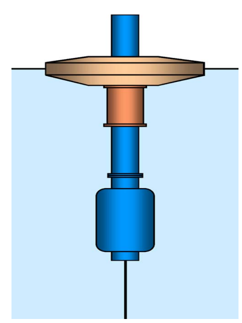

Figure 6. Deep draught-spar device [13]

This concept was theoretically analyzed [39] but control problems arise from multi-body wave energy converters [40].

Amongst the first concepts for multi-body wave energy converters was the Bipartite Point Absorber [41]. Most interesting two-body absorber is the IPS buoy, invented by Sven A. Noren and developed by Interproject Service (IPS). IPS buoy [42] was prototyped, deployed and tested in Sweden. Other notable variants of the IPS buoy are AquaBuoy [43] and the Wavebob [44].

Ocean Power Technologies, an American company, developed another axisymmetric two-body heaving WEC named PowerBuoy [44]. A disc-shaped floater reacts against a submerged cylindrical body, terminated at its bottom end by a large horizontal damper plate whose function is to increase the inertia through the added mass of the surrounding water [44]. Relative heaving motion between two plates in converted into electrical energy using a hydraulic power take-off (PTO). A prototype was deployed in Northern Spain, in September 2008 (Fig. 7) without grid connection.

Figure 7. PowerBuoy, Spain, in 2008 [4]

C. *Pitching devices*

Pitching devices, unlike heaving systems, use relative rotation rather than translation for energy conversion. The nodding Duck is the best concept form the 1970's and 1980's, created by Sephen Salter [45], which is basically a cam-like floater oscillating in pitch. The Duck was designed with a hydraulic-electric PTO. Multiple Ducks, attached to a long spine, aligned with the wave crest direction was the first version. This concept did not reach full- scale prototype stage.

The most successful of the pitching devices is the Pelamis; it has been well researched and is part of detailed development program over several years. This device is the successor to the Raft that was invented by Sir Christopher Cockerell [11]. Pelamis consists of four cylindrical sections linked by hinged joints which are aligned to the direction of the waves. This, along with being slack moored, gives Pelamis a snake-like appearance. Wave induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors driving three electrical generators. Set of three Pelamis was deployed off the northern Portuguese coast in 2008 making it the first grid-connected wave farm internationally (Fig. 8).

Figure 8. Pelamis wave farm off the coast of northern Portugal [4]

Another concept originated from the Cockerell Raft is the McCabe Wave Pump. McCabe shares the similar hydraulic power take-off (PTO) as the Pelamis, but unlike the Pelamis, it comprises of a central pontoon to which two rectangular steel pontoons are hinged. The central pontoon is damped by an attached underwater horizontal plate, therefore, heaving motion of the two outer pontoons to drive two sets of hydraulic rams [46]. The PTO converts the rotational energy from the pontoons into useful energy (Fig. 9). Other notable Pitching devices are PS FrogMk5 [47] [48] and the Searev [49].

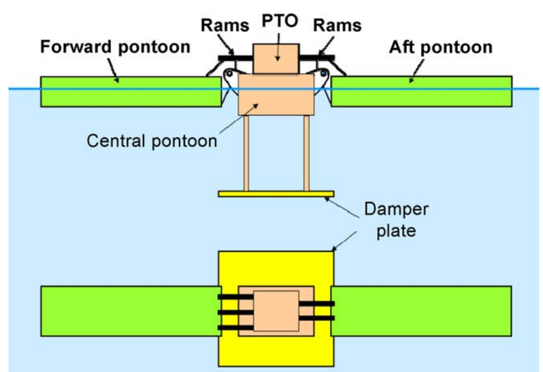

Figure 9. McCabe Wave Pump [4]

1) *Bottom-hinged systems*

The Mace, invented by Stephen Salter [50], has a structure like an inverted pendulum hinged at the sea bottom with a universal joint. A buoyant spar at the top extreme can swing about the universal joint acting like a single oscillating-body device in pitching mode. The PTO is via cables connected to sea bottom and wound several times around a winch drum in the spar (Fig. 10). Prevailing waves induce reciprocating rotation of the drum that is converted into useful energy by use of hydraulic systems. Other examples of bottom hinged wave energy converters are the Oyster [51] and the WaveRoller [52].

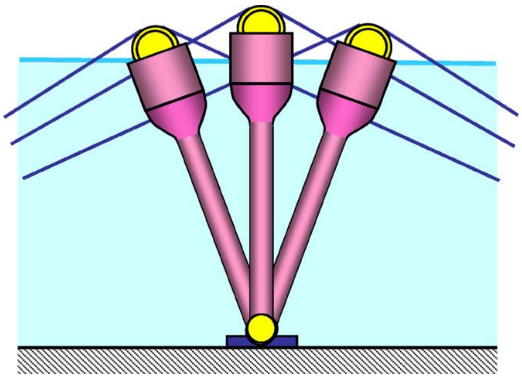

Figure 10. The Mace in three angular positions [13]

2) *Overtopping WECs*

The concept of overtopping converters is basically capturing water that is close to the wave crests and storing it in a reservoir by over spilling. Water in the reservoir is at an elevated height in comparison to the average free-surface level of the sea and is therefore has potential energy. This can be converted into useful energy by low-head hydraulic turbines.

Tapchan (Tapered Channel Waver Power Device), was a prototype built in 1985 (rated at 350kW) in Norway that operated for several years [53]. The horn shaped collector concentrated incoming waves into the converter which is a narrowing that guides raises the waters over into the reservoir (Fig. 11). Low-head Kaplan –type axial flow turbines is fed by flow of water from the reservoir, at higher potential, back into the sea.

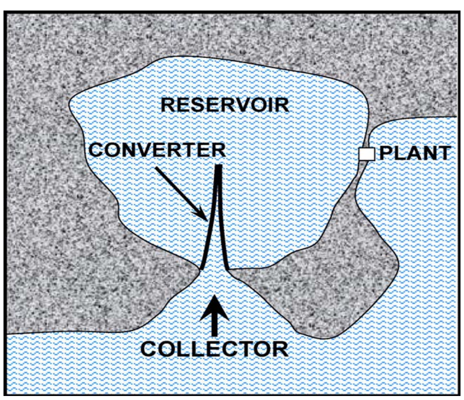

Figure 11. Plan view of the Tapchan [4]

Other variants of the concept are the Wave Dragon [54] that was deployed Nissum Bredning, Denmark in May 2003 and the Seawave Slot-Cone Generator (SSG) [55].

IV. CONCLUSION

The current situation is that there is a wide variety of wave energy systems, at several stages of development without a clear indication of which technology will be deployed on a global scale. Table I shows a summary of various WAC.

Table I: SUMMARY OF VARIOUS WAC

Type	**PTO**	**Application**	**Structure**	**Device**	**Description**
Oscillating Water Column	Air turbines	Shoreline	Fixed	Limpet [29]	These devices generally produce electricity using air turbines. Electrical generators are stimulated by the air flow induced by a column of oscillating water above which is trapped air. Advantage of these devices is that they low installation and maintenance costs.
				Sakata & Mutriki [27]	
		Near-Shore	Floating	Mighty whale [33]	
				Spar buoy [34]	
				Orecon [35]	
Oscillating bodies	Linear electrical generator and Air turbines	Off -shore	Surface	Aquabuoy [43]	With this technology, either the generator of the buoy is moored to the sea bed. The heaving motion of the buoy is the source of motion for PTOs.
				IPS Buoy [42]	
				WaveBob [41]	
Pitching Devices	Hydraulic	Off -shore	Surface	Pelamis [11]	These devices use the motion on the surface of the ocean to activate the PTOs. Hydraulic turbines are driven by hydraulic rams.
				McCabe wave pump [46]	
				PS Frog [47]	
				SEAREV [49]	
			Submerged	The Mace [50]	The pressure variations caused by adjacent crest and trough of passing waves is used as source to activate the PTO.
				Waveroller [51]	
				Oyster [52]	
Overtopping Devices	Hydro-electric turbines	Shoreline	Fixed	TAPCHAN [53]	This concept uses potential energy to drive hydroelectric generators. Water is channeled and stored at high higher level then ocean waves. Water is then released and the flow of water from an elevated position to a lower position drives turbines. Advantage of these devices is that cost of installation and maintenance is low.
			In breakwater	Sewave Slot-Cone Generator (SSG) [55]	
			Floating	Wave Dragon [54]	

Studies conducted in the past show that most R&D activity in wave energy has been taking place in Europe, which is mainly because of financial support and coordination provided by the European Commission and also due to the positive attitude adopted by some European national governments. However, in last few years, interest in wave energy utilization has been growing rapidly in other parts of the world as well.

Moreover, it has been found that the development of this concept from commercial stage has been difficult. Although substantial progress has been achieved in the theoretical and numerical modelling of wave energy converters and of their energy conversion chain, model testing in wave basin but is a time consuming and considerably expensive task and is still essential.

Furthermore, the high costs of constructing, deploying, maintaining and testing large prototypes under sometimes very harsh environmental conditions, has hindered the development of wave energy systems; in most cases such operations were possible only with substantial financial support from governments organisations (e.g. EC).

Finally, technology in the area of wave energy converters is still an open area of research that is attracting the attention of academics and inventors. Innovative concepts are surfacing that in the future will enable harvesting of ocean wave energy on a small scale. One such concept is the 'Hybrid Wind and Solar Energy' converter (HWSEC) [56].

To conclude, we would like to note that, in order to maintain an appropriate size of the article, we had to limit the number of referenced studies; hence we apologize to all of those authors which were not cited in this work.

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