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Operating Principle, Performance and Applications of the Wave Mill

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Abstract: The WM (wave mill) is an efficient ocean wave energy converter. This technology will allow generation of electricity from the constant wave actions. The WM made up of multiple OWCs (oscillating water columns) rigidly connected to each other. Each OWC has an inlet and outlet valve. When the water level inside the OWC rises, air is pushed through an outlet valve. When the water level drops, air is sucked in through an inlet valve. A row of OWCs are connected by inlet and outlet air ducts. At the end of each inlet and outlet duct is an air turbine which generates electricity from the airflow created by passing waves. A 30 meter long prototype was tested in Moreton Bay. The measured efficiency from wave to wire was min 12.5% and max 36%. This efficiency is potentially much better than solar or wind power. The wave mill may be seen as a viable green alternate form of energy. The WM is scalable and has other flow-on benefits.

Key words: Renewable energy, wave energy, ocean, oscillating water column, scalable, portable, reduces erosion, constant power.

1. Introduction

The oceans of the world are large and the energy reaches the coasts in the concentrated form of waves. These waves can produce varying levels of energy [1]. The average energy flux (kW/m) per year may be as high as 100 kW/m [2].

WEC (wave energy conversion) is not a new concept. The first patent of a device designed to use ocean waves to generate power was granted in 1799 [3]. Wave energy has been estimated to have the potential to produce 1,000-10,000 GW of power [4].

Four types of WEC will be discussed in this paper.

Point Absorber: is a floating structure that has a vertically submerged float. The float extracts wave energy which can be used as a kinetic, hydraulic or pneumatic energy to drive the generator.

Attenuator: has multiple floats connected together by hinged joints or movable arms. Floats move vertically and laterally with the waves. Hydraulic or pneumatic rams can be used to convert the kinetic energy of this movement to drive electrical generators.

Terminator: OWC (oscillating water column) is a partially submerged chamber open to the sea below, keeping a trapped air pocket above a water column. Oscillating water level inside a chamber acts like a piston, moving up and down, forcing the air out of the chamber and back into it. A bidirectional turbine converts airflow into power.

Overtopping device: continually fills reservoir with incoming waves which is stored above sea level. The ocean water descends through hydro-turbine where the potential energy is converted to useful electricity.

Since the first trail in Australia [5], many designs were built and tested. Why do we not have well proven and commercially successful WEC deployed worldwide [6]?

One of the reasons is a cost of kWh. WEC's construction and deployment is costly. Although the real cost of power unit for the most famous wave power projects were not available, it is possible to

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make estimations based on the size of the construction and measured power output.

Another reason is existing projects could not deliver the claimed output. Often a real output was significantly less and therefore, did not contribute much to the land-based grid.

And probably last but not least is the survivability. Many WECs were lost or damaged in a bad weather.

When the WM (wave mill) project was started, the goal was to overcome all these drawbacks and to build a new type of WEC which can generate commercially usable levels of power.

2. The Wave Mill Concept

When considering the types of WEC, the submerged designs were not included. This was because the capital and operating expenditure of any submerged structure cost much more than that of a similar floating structure.

The overtopping WEC was not considered as it starts up only with a certain height of waves. A complex engineering solution will be needed to adopt overtopping WEC for the wider range of wave conditions.

The point absorber and attenuator were not chosen because of the number of the moving parts. The aim was to find the shortest and simplest way from wave to wire.

The OWC was chosen as a main component because of its simplicity and reliability. However, the OWC cannot produce commercially viable power. Single point absorber and terminator generates power only in interaction with steep fronts and backs of the wave crests, and slows down or idles within the relatively flat top and bottom parts of the wave.

The water inside OWC plays the role of a piston, forcing the air out of the chamber and back into it. With a line of the OWCs perpendicular to the incoming waves, and longer than wave length, the idle period would be overcome. With a line of OWCs longer than wave length there will always be at least one wave crest passing underneath.

Conventional OWC uses bidirectional turbine to convert airflow into power. But unidirectional air flow is the best way to feed air-turbine.

To create unidirectional air-flow in a line of the OWC's alterations to the existing techniques were made.

In the WM, each OWC has an inlet and outlet valve. A row of the rigidly joined OWCs are connected by inlet and outlet air ducts. These are fed air from the OWCs inlet and outlet valves. This solution replaces air-turbines in each OWC within a single air-turbine installed at the end of each inlet and outlet duct. This approach generates electricity from the airflow created by passing waves. If the length of WM is longer than average wave length, the WM will create a constant unidirectional air flow to drive the air turbine.

While one-way valves are used to rectify oscillatory flow to unidirectional flow in other OWC designs [7], the WM appears to be the only concept that could achieve a constant turbine speed for incoming waves which do not vary from wave to wave.

A row of the rigidly joined OWCs works like an air pump constantly pushing air out through the turbine and returning it back to the chambers as shown in Fig. 1.

Fig. 2 shows that the WM is a floating construction which consists of plurality of the rigidly joined OWCs. Each OWC has an inlet and outlet valve. When the water level inside the OWC rises, air is pushed through an outlet valve. When the water level drops, air is sucked in through an inlet valve. A row of OWCs are connected by inlet and outlet air ducts; these are fed air from the OWCs inlet and outlet valves. At the end of each inlet and outlet duct is an air turbine which generates electricity from the airflow created by passing waves. To create a constant air flow to drive the air turbine, the length of WM must be longer than average wave length.

The wave power of a single line of the OWCs perpendicular to the incoming waves depends on the

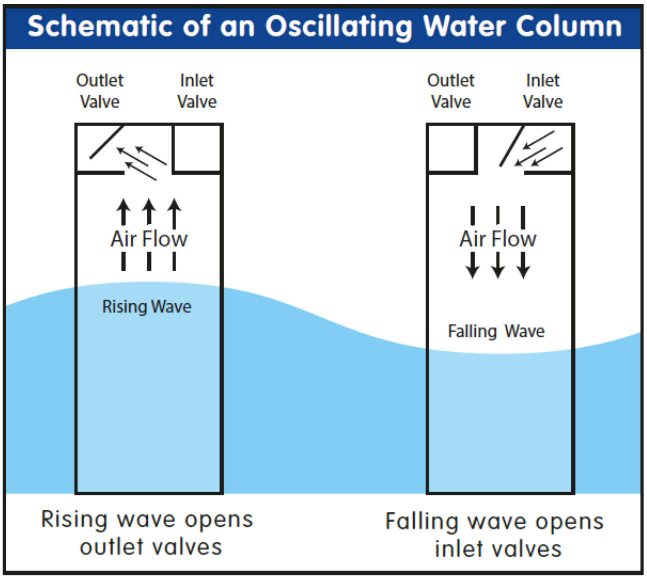

Fig. 1 **OWC with inlet and outlet valves.**

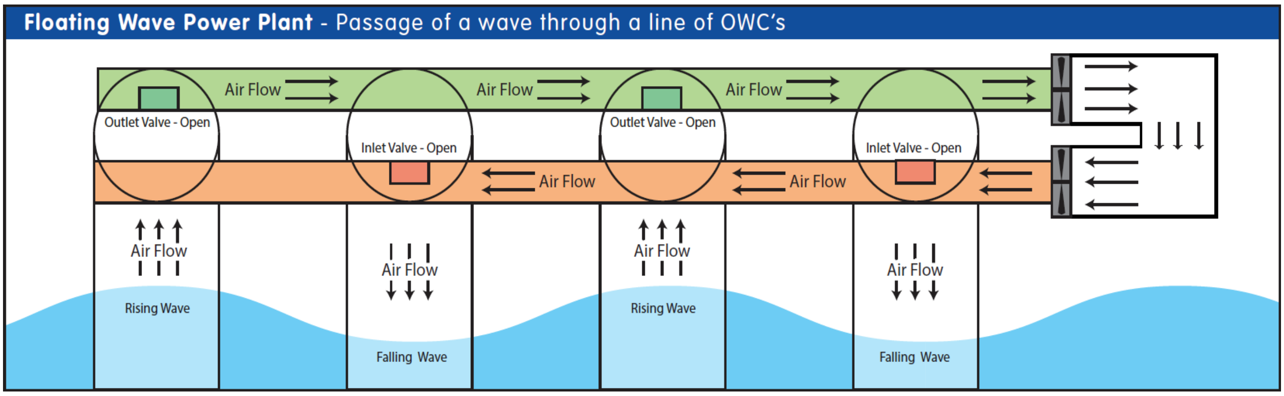

Fig. 2 **A row of the rigidly joined OWCs.**

width of the OWC, the wave speed, the height and the number of the wave crests passing along the line. The wave power, in linear meter kW/m, for one linear meter is given by

$$WP = \frac{1}{2} * H^2 * T \tag{1}$$

where, H is a height (m) and T is period (secs).

The total input from waves in kW is given by

$$P_{total} = (WP) * (WM\ width) * (Number\ of\ Wave\ Crests) \tag{2}$$

where, $(WM\ width)$ is a total width of all OWC lines in metres perpendicular to the incoming waves.

3. Wave Mill Trials

A full scale prototype was built and deployed in Moreton Bay, off Brisbane, Queensland, Australia in 2016 [8]. Table 1 indicates the dimensions of the prototype and Table 2 indicates the wave conditions present at time of testing. Fig. 3 shows the prototype WM ready for testing.

Table 1 **Prototype wave mill dimensions.**

Parameter	Value
Length	30 m
Width	1.5 m
Fan diameter (D)	0.4 m
Generator	600 W in each air duct

Table 2 **Wave conditions.**

Parameter	Min	Max
Measured wave period (T)	2 s	3 s
Measured wave height (H)	0.4 m	0.6 m

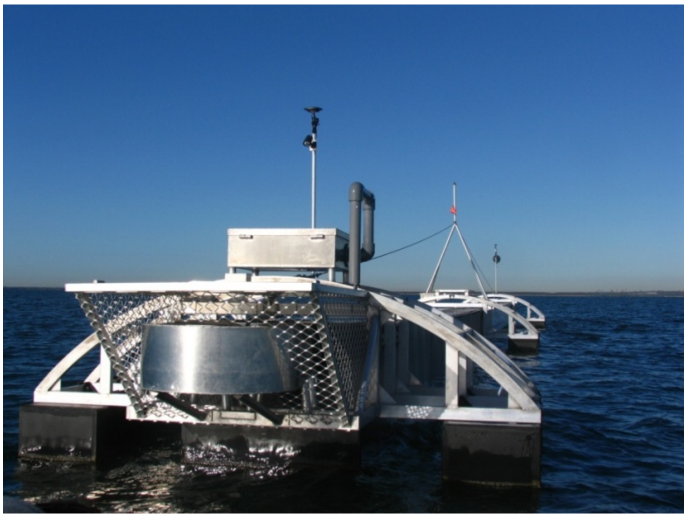

Fig. 3 Full scale prototype. Air turbines inside the U shape duct (in front), connecting inlet and outlet air ducts.

Fig. 4 Two generators, one in each air duct.

Wave mill creates two continuous air-flows simultaneously: one in inlet duct, another in outlet duct as seen in Fig. 4.

4. Wave Mill Performance

Table 3 shows the performance and efficiency of the Wave Mill. As it can be seen in the last entry in efficiency column, the output increases dramatically as the wave period and height increases. The Prototype has been working almost 24 hours a day, 7 days a week. It stopped only in full calm and started up with 0.1 m waves.

Detailed test results and video published on: http://wavepowerengineering.com/home/projects?t=fpp&lang=en-US.

5. How Much Power Can Wave Mill Generate?

The WM output depends only on input from waves and width of the OWCs perpendicular to the incoming waves.

To create continuous air flows, the Wave Mill unit must be longer than average wave length in the mooring location. The width of OWCs defines the

Table 3 Prototype performance.

Wave period, s	Wave height, m	Input from wave, kW	Air velocity inside airduct, m/s	Pneumatic, kW	Output, kW	Efficiency, %
2.0	0.4	0.24	8.0	0.061	0.030	12.5
2.5	0.5	0.47	11.5	0.160	0.096	20.0
3.0	0.6	0.81	15.0	0.404	0.288	36.0

Table 4 Wave conditions.

Parameter	Value
Wave period (*T*)	9 s
Wave height (*H*)	5.0 m
Input for one linear meter wave	72 kW
Output	5.6 MW

Note: The average oil rig dimensions are 200 m × 200 m and power supply is 5 MW.

output. There are engineering limitations for a large floating construction and sometimes instead of building very large unit it is simpler to deploy two or three smaller ones.

The WM deck provides an ideal platform for any custom applications.

The WM can be used as an offshore support facility, a floating foundation for oil rig or for offshore wind projects. Assume we want to use 200 m × 200 m WM unit as a floating foundation in the Bass Strait. Table 4 indicates an example of the wave conditions and expected output power.

6. Cost of Power Unit

The estimated WM lifespan is 50 years. The estimated construction and deployment cost of 200 m × 200 m unit is in the order of $20 M.

Assuming as estimated the operational cost being 10% of the capital expenditure and a lifetime of 50 years produces the following result.

Estimated cost of kWh is $0.05.

7. Mass Production Readiness

The WM has high readiness for a commercial production.

WM unit consists of a structural mesh, a plurality of OWCs are embedded into the mesh connected to air ducts. A set of floats maintains positive buoyancy as seen in Fig. 5.

The WM uses two major materials: steel for construction mesh and HDPE (high-density polyethylene) plastic for OWC pipes.

All parts for structural mesh, HDPE pipes and air-turbines can be bought off-the-shelf.

To assemble the mesh and to install the OWCs, a pipeline arrangement can be used.

8. Applications

There are many applications for the WM such as:

- Power generation for the close to shore communities.
- Offshore support facilities with embedded power supply.
- Floating foundations for offshore projects (oil rigs, offshore wind etc.).
- Coastal protection and beach accretion due to wave attenuation by the wave mill.

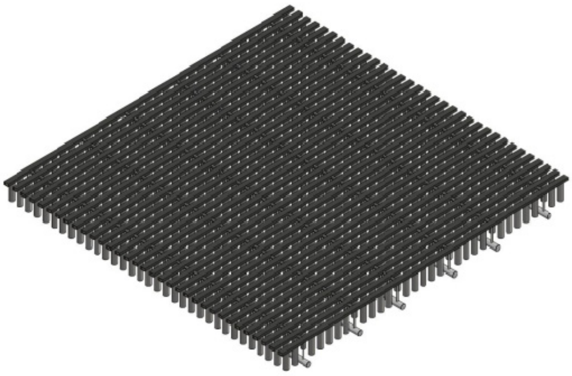

Fig. 5 Multiple rows of OWCs rigidly joined into the one solid floating structure forming the WM.

9. Conclusions

The WM is an innovative and very efficient machine for generating electricity. Its simple operating design lends itself to reliable operation. The WM is a scalable and modular construct which can be easily adapted to meet most power generation requirements where grid power is difficult to access. The end result is a very low cost per kWh for the electricity generated by the WM.

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