Resonant Wave Energy Converters: Concept development

The Resonant Wave Energy Converter (REWEC) is a device for converting sea wave energy to electrical energy. It belongs to the family of Oscillating Water Columns and is composed by an absorbing chamber connected to the open sea via a vertical duct. The paper gives a holistic view on the concept development of the device, starting from its implementation in the context of submerged breakwaters to the recently developed vertical breakwaters.

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■ *F. Arena, G. Barbaro, V. Fiamma, V. Laface, G. Malara, A. Romolo, F.M. Strati*

Introduction

Nowadays, the wave energy resource is accepted for being a remarkable source of energy. In this regard, recent global estimates show that the theoretical potential for ocean energy technologies is between 20,000 and 90,000 TWh/yr (consider that in 2004 world's electricity consumption was less than 20,000 TWh/yr) [1]. In this context, the energy from sea waves is the most conspicuous form of ocean energy. The total theoretical wave energy potential is approximately 32,000 TWh/yr [2]. In the last decades, the wave energy resource was mapped in several areas. For instance, Liberti *et al.* [3] and Arena *et al.* [4] investigated the wave energy potential in the Mediterranean Sea with an emphasis on the Italian coasts. They showed that the most energetic area of the Mediterranean Sea is Alghero (Sardinia, Italy).

■ **Contact person: Felice Arena**
arena@unirc.it

A large number of concepts defining different Wave Energy Converters (WEC) were developed to harvest the energy from ocean waves. More than 1000 wave energy devices were patented all around the world. One of the fundamental aspects that need to be taken into account in the development of the conversion technology is linked with the remarkable variability of energy and of time scales. The conversion is established through the so-called power take-off (PTO) system. Commonly, turbines or hydraulic motors provide the mechanical component, which converts the alternate motion of the waves into a continuous one-directional motion. The PTO mechanism is usually coupled with a control system in order to optimize the performance of the device under a range of operating conditions. Then, cables and an electrical infrastructure connect the power output from the device to the electric grid.
Several methods were proposed to classify the WECs [5-8]. Specifically, a classification based upon the operating principle of the device distinguishes among: Overtopping devices; Oscillating Bodies; and Oscillating Water Column (OWC).

- ***Overtopping.*** An overtopping device is wave terminator that converts wave energy into potential energy by collecting surging waves into a water reservoir above the mean water level. This device can be either floating or fixed to the shore. The PTO component usually is an axial turbine. See e.g. Margheritini *et al*. [9].
- ***Oscillating bodies***. Oscillating bodies can be classified with respect to the motion in: heaving, pitching, surging and rotating mass.

Heaving oscillating devices are characterized by a linear oscillatory motion of the immersed, or floating body. These mechanical and/or hydraulic devices convert the vertical motion due to the waves into linear or rotational motion to drive an electrical generators. See e.g. Archimede Wave S. [10].

Pitching devices oscillate around the horizontal axis in the direction perpendicular to the incident wave. These devices usually consist of a number of floating bodies hinged together across their beams. The relative motions between the floating bodies are used to pump high pressure oil through hydraulic motors, which drive the electrical generators. These devices can be ether: submerged or semi-surface type. See e.g. Aquamarine Power Oyster, Wave Roller.

Surging devices are characterized by the horizontal motion of an immersed body in the direction of its longer extension. If the body, such as an axisymmetric body, has predominant direction, the direction for surge motion may be specified as the direction of wave incidence. See e.g. Pelamis [10].

Rotating mass devices drive an eccentric weight or a gyroscope thanks to the heaving and swaying motion of the incoming wave. See e.g. ISWEC [11]

- ***Oscillating Water Column (OWC).*** OWCs are the most popular wave energy devices. They are composed by a structure with an upper air chamber, which is exposed to the action of the sea waves. The water column inside the chamber oscillates because of the incident wave action. The air into the upper chamber flows through an air turbine coupled to an electrical generator, which converts the kinetic energy into electricity. The air turbine rotates in the same direction, regardless of the flow. A scheme is shown in Figure 1.

Heath [12] defines the major advantages of OWCs, with respect to others WECs:

- There are few moving parts;
- There are no moving parts in the water;
- The use of an air turbine removes the need for gearboxes;
- It is reliable;
- It is easy to maintain;
- It uses sea space efficiently.

Among this, the possibility of being embodied into a conventional breakwater must be mentioned. Indeed, such a solution has several advantages: the construction costs of a breakwater are only slightly increased, and the access for construction, operation and maintenance of the wave energy plant become much easier [6].

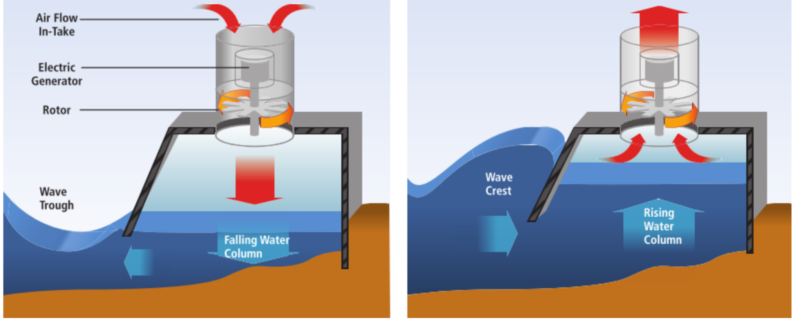

FIGURE 1 Scheme of an OWC during the crossing of a wave through (left) and of a wave crest (right)
Source: Lewis et al. [8]

The eigenperiod of oscillations inside OWCs is typically smaller than the period of the incident waves; with conventional OWC is not possible to modify this eigenperiod, therefore some complex devices where proposed for phase control in order to reach the resonance condition (latching control) [13].

Starting from the ’90, several full-size OWC prototypes were built all around the world. Examples are [10]: the installation of Pico (1999) in the Azores (Portugal), equipped

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with a Wells turbine whose capacity is of 400 kW; the installation of LIMPET (Land Installed Marine Power Energy Transformer) (2000) in Islay Island, Scotland (UK), containing three water columns, with an installed capacity of 250 kW. The integration of an OWC wave energy converter into a conventional vertical breakwater has been done for the first time in the harbor of Sakata, Japan (1988), whose installed power was of 60 kW. The first prototype of a "multi-chamber OWC breakwater" was made in the port of Mutriku (Spain) (2009) [14]. The installed power is of 296 kW, with 16 Wells turbines of 18.5 kW each, spread over 16 distinct rooms.
Recently, Boccotti [15-21] proposed a new kind of OWC, called U-OWC or REWEC. REWEC is the acronym of "Resonant Wave Energy Converters". This device removes some limitations of classical OWCs, such as the small eigenperiod of the water column oscillations, or the low connecting point to the open wave field. In the next sections, the features of this device are discussed by disseminating the experiences conducted at the Mediterranea University of Reggio Calabria in the last 10 years.

Development of the REsonant Wave Energy Converters (REWEC)

The REWEC has been conceived as a way for connecting the traditional need of protecting a certain area to the opportunity of harvesting energy from sea waves. In this regard, it is worth-mentioning that the traditional approach of marine engineering is to utilize massive structures at the borderlines of the area. Structures like vertical breakwaters and submerged barriers are all devoted to this task. Considering the fact that they are expected to withstand the continuous action of sea waves, the idea of incorporating wave energy converters is not surprising. In this context, the family of REWEC devices is an example of successful application of the principle of reaching two objectives by one unique structure. Boccotti and his research group at the Mediterranea University developed it in the past 10 years from both a theoretical and an experimental perspective. The development stages and the related major findings are disseminated by reference to the evolution of the REWEC system.

REWEC: an invisible barrier for protecting a coastal area

The first model of REWEC was conceived as a modification of a classical submerged breakwater (Fig. 2). Such a structure is composed by 3 elements: an air pocket, a vertical duct and an air feed. In this system, the water waves are partially reflected by the structure and partially transmitted, while the opening at the top of the vertical duct allows the system interacting with the environment. Specifically, the interaction involves the absorption of sea wave energy.
The REWEC dynamics was investigated by Boccotti [15]. He verified via a small-scale field experiment that the device has the unique feature of being able to reach the resonance condition with the incident waves. Such a possibility relates to the fact that the eigenperiod of the system can be tuned by changing the volume of the air pocket. By doing so, the device is able to absorb a remarkable quantity of wave energy. Thus, reducing the transmission of incident waves.
The experimental activity has also assessed the reliability of the mathematical model used for describing the REWEC dynamics. Indeed, the fluctuations of the inner water surface can be predicted quite well from a time history of the pressure fluctuation at the top of the vertical duct. In this regard, the formulation of the proposed equation of motion is the following:

$$\frac{c-\xi}{g}\frac{d^2\xi}{dt^2}+\frac{l}{g}\frac{du}{dt}=h_1-h_2-h_f \qquad (1)$$

where the symbols are shown in Figure 2, u is the water particle velocity in the vertical duct, g is the acceleration due to gravity, h_1 is the total head at point 1, h_2 is the total head at point 2 and h_f are head losses. Thus, Eq. (1) is a nonlinear second order differential equation, where the nonlinarity is due mainly to the head losses, which are of a drag type.
Based on the small-scale field experiment, the performance of the REWEC at full scale can be predicted. By assuming a REWEC exposed to wind-generated waves with a JONSWAP [22], it is seen that the plant can absorb up to 45% of the incident waves.

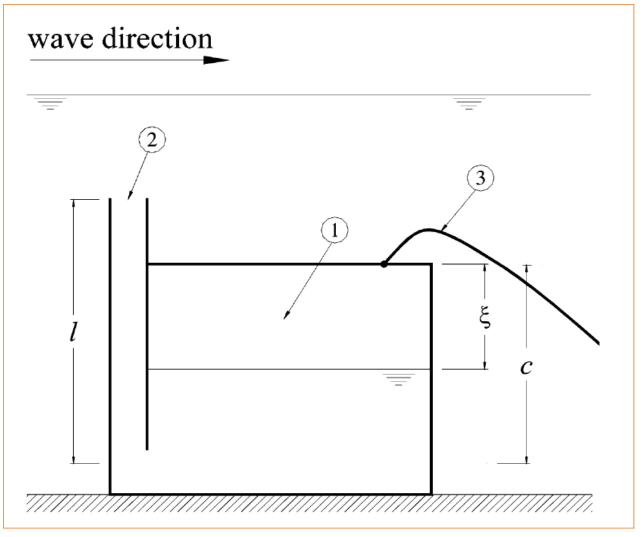

FIGURE 2 Scheme of a REWEC including an air pocket (1), a vertical duct (2) and an air feed (3)
Source: Boccotti [15]

REWEC2/3: a vertical breakwater incorporating a wave energy converter

In parallel to the REWEC system, a second wave energy converted (REWEC2) was proposed by incorporating the vertical duct-air, pocket-air feed system into a vertical breakwater (Fig. 3). This second system was proposed as an alternative to the classical vertical breakwaters employed for creating a save basin.
Obviously, in this condition the open wave field has only a reflected wave field, which is modified by the absorption of wave energy. The mathematical description of the REWEC2 dynamics is quite similar to the REWEC1. In this situation, the relevant difference relates to the possibility of employing a bidirectional turbine for converting the absorbed wave energy to electrical power.
The working principle of the device is analogous to the one of the REWEC. Indeed, by controlling the air pocket volume the eigenperiod of the system is appropriately tuned. It is worth-mentioning that this feature allows implementing a real time control strategy for optimizing the performance of the plant in variable climatic conditions. Indeed, sea waves are expected to have a time-varying peak spectral period. Therefore, resonance can be reached by adjusting the air pocket volume. Predictions based on a Froude similarity have shown that this plant can absorb 40-55% of the incident wave energy. Further, by equipping the air duct with a monoplane Wells turbine, such a plant can produce an average electrical power up to 500 kW.
In addition to that, the plant has some good features from a global stability perspective. Indeed, the safety factors against sliding and overturning are slightly larger (nevertheless, quite close to) than the ones of a classical vertical breakwater.
It may be recognized that optimizing the performance of the REWEC2 requires a sophisticated real time system. Therefore, to remove this critical requirement of the device, a simplified version of the device has been proposed: the REWEC3 [16]. This system is shown in Figure 4. In this system, the air pocket is below the mean water level and the air pressure in still conditions is the atmospheric pressure. Resonance is still reached by the system, but the eigenperiod must be selected a priori during the design stage. Specifically, starting from the identification for the most relevant sea states from an energetic perspective, the eigenperiod is matched to a related peak spectral period. In this situation, the system is tuned by changing the length and the width of the vertical duct.
In 2005 a REWEC3 was installed at the natural laboratory of the Mediterranea University of Reggio Calabria. That experimentation has been pursued with the objective of validating the available hydrodynamic model and of monitoring the performance of the system in random sea waves [17, 18]. The key results of the experimentation relates to the definition of reliable tools for designing a REWEC3 plant, and also to the observation that waves in front of the structure can be amplified remarkably in case of swells. The experimentation emphasized also the capability of the plant in absorbing wave energy. Indeed, measurements showed that the plant is able absorb even 90% of the incident wave energy, resulting in a beneficial action from the perspective of wave energy conversion, as well as on improving vessel navigation.
The theoretical development around the device is interesting, as well. Indeed, starting from the model described via Eq. (1), the REWEC3 description is obtained by coupling the equation of motion to the air pocket dynamics. In this regard, a common

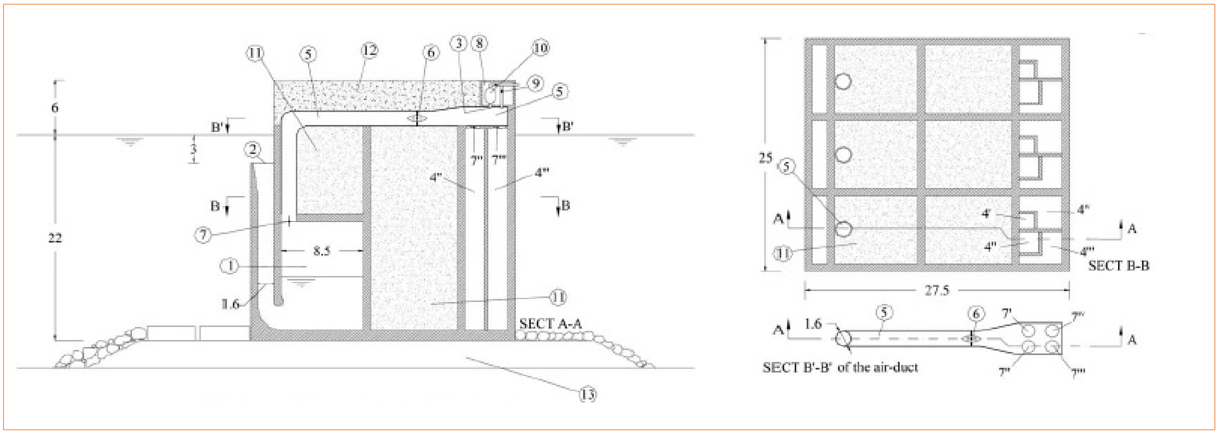

FIGURE 3 Example of REWEC2. 1 air pocket; 2 outer opening; 3 air feed; 4 air reservoir; 5 air duct; 6 Wells turbine; 7 butterfly valve; 8 service room; 9 exhaust valve; 10 compressor; 11 sand filling; 12 superstructure cast in concrete; 13 rubble mound foundation; volumes of reservoirs: 4I, 55 m³; 4II, 110 m³; 4III, 220 m³; 4IV, 275 m³
Source: Boccotti [15]

assumption is to consider the underlying thermodynamic process as isentropic. In parallel, the description of the modification of the surrounding wave field is pursued by an iterative approach based on the maximization of the ratio between the energy per unit width and the wave power. The relevant aspect is that the procedure can be implemented for designing the device based on a single parameter: the resonance index. It is calculated by the equation,

$$R = \frac{4\,T^*}{T_P} \qquad (2)$$

where T_p is the peak period of the spectrum of the wave pressure at the upper opening of the vertical duct (Δp) and T^* is the abscissa of the first maximum of the following cross-correlation function:

$$\psi(T) = <\Delta p(t) \cdot \xi(t+T)> \qquad (3)$$

Such an index is 1 close to resonance. Therefore, at the design stage, the plant is designed to reach resonance (that is, to have R = 1) at the desired sea state.

Conclusions

The paper has disseminated the main characteristics of the Resonant Wave Energy converter (REWEC). It has shown the historical development of the device considering the various concepts proposed by Boccotti in the past decade, starting from a device incorporated into a submerged breakwater to the case in which it is incorporated into a vertical breakwater.
The past small-scale field experiments pursued at the NOEL laboratory of the Mediterranea University

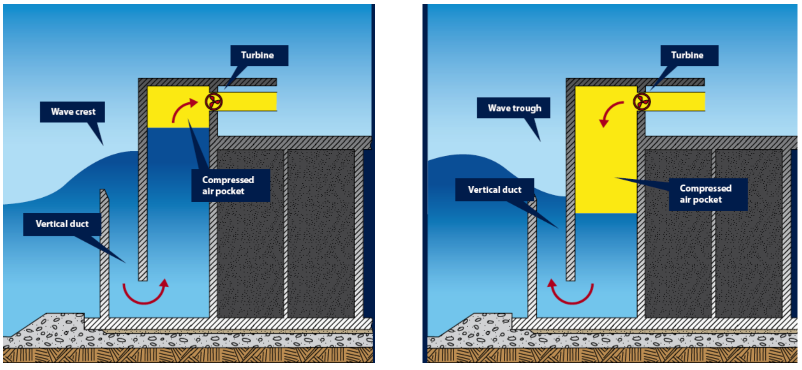

FIGURE 4 Scheme of a REWEC3 plant. Left panel: plant behaviour during a wave crest; right panel: plant behaviour during a wave trough

of Reggio Calabria has shown that the device has some peculiarities providing better performances in comparison with other devices belonging to the Oscillating Water Column family. Specifically, the REWEC is able to reach naturally the resonance condition with the wave pressure exciting the system for the desired sea state. Thus, maximizing the absorption of the wave energy.

The future development of the device relates to the investigation of a REWEC3 small-scale model equipped with a turbine and to full-scale prototype. These future works are discussed in the second part of the paper, which reports the recent experiences in the context of the POSEIDONE project and of a modular REWEC3 developed in collaboration with ENEA. The REWEC3 under construction at the Civitavecchia port will be described.

Felice Arena, Giuseppe Barbaro, Vincenzo Fiamma, Valentina Laface, Giovanni Malara, Alessandra Romolo, Federica Maria Strati
University of Reggio Calabria "Mediterranea", Italy

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