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Review

# Oscillating-water-column wave energy converters and air turbines: A review

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ABSTRACT

The ocean waves are an important renewable energy resource that, if extensively exploited, may contribute significantly to the electrical energy supply of countries with coasts facing the sea. A wide variety of technologies has been proposed, studied, and in some cases tested at full size in real ocean conditions. Oscillating-water-column (OWC) devices, of fixed structure or floating, are an important class of wave energy devices. A large part of wave energy converter prototypes deployed so far into the sea are of OWC type. In an OWC, there is a fixed or floating hollow structure, open to the sea below the water surface, that traps air above the inner free-surface. Wave action alternately compresses and decompresses the trapped air which is forced to flow through a turbine coupled to a generator. The paper presents a comprehensive review of OWC technologies and air turbines. This is followed by a survey of theoretical, numerical and experimental modelling techniques of OWC converters. Reactive phase control and phase control by latching are important issues that are addressed, together with turbine rotational speed control.



**Contents**



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**Nomenclature**

*Roman letters*

| | |
|---|---|
| $A$ | added mass |
| $B$ | radiation force coefficient |
| $c$ | blade chord (Section 3) |
| $D$ | turbine rotor diameter |
| $E$ | energy per unit mass (Section 3) |
| $f_e$, $f_r$ | excitation force, radiation force |
| $F_e$, $F_r$ | complex amplitudes of $f_e$, $f_r$ |
| $g$ | acceleration of gravity |
| $G$ | radiation conductance |
| $H$ | radiation susceptance |
| $k$ | polytropic exponent |
| $m$ | mass |
| $p$ | pressure |
| $P$ | complex amplitude of $p$ |
| $P_t$ | turbine power |
| $q$ | volume flow rate |
| $Q$ | complex amplitude of $q$ |
| $S$ | inner free-surface area |
| $t$ | cascade pitch (Section 3) |
| $t$ | time |
| $T$ | torque |
| $U$ | blade velocity |
| $V$ | absolute flow velocity (Section 3) |
| $V$ | air chamber volume (Section 4) |
| $w$ | mass flow rate |
| $x$ | vertical coordinate |
| $X$ | complex amplitude of $x$ |

*Greek letters*

| | |
|---|---|
| $\alpha$ | absolute flow velocity angle |
| $\beta$ | relative flow velocity angle |
| $\eta$ | turbine efficiency |
| $\Pi$ | dimensionless turbine power |
| $\rho$ | density |
| $\sigma$ | standard deviation (or rms) |
| $\phi$ | flow rate coefficient (Section 3) |
| $\Phi$ | dimensionless flow rate |
| $\psi$ | pressure coefficient (Section 3) |
| $\Psi$ | dimensionless pressure head |
| $\omega$ | radian frequency |
| $\Omega$ | rotational speed |

## 1. Introduction

The ocean waves are an important renewable energy resource that, if extensively exploited, may contribute significantly to the electrical energy supply of countries with coasts facing the ocean [1]. A wide variety of technologies has been proposed, studied, and in some cases tested at full size in real ocean conditions [2–5]. The mechanical process of energy absorption from the waves requires a moving interface, involving (i) a partly or totally submerged moving body and/or (ii) a moving air–water interface subject to a time-varying pressure. In the latter case, there is a fixed or oscillating hollow structure, open to the sea below the water surface, that traps air above the inner free-surface; wave action alternately compresses and decompresses the trapped air which forces air to flow through a turbine coupled to a generator. Such a device is named oscillating-water-column (OWC). Although the concept was already known in the 1940s, this designation seems to have appeared for the first time in published paper form in 1978 [6] and has been widely used ever since, even if the moving water inside the structure is far from shaped like a column. Before that, this type of wave energy converter (WEC) was sometimes known as the Masuda device. The main advantage of the OWC versus most other WECs is its simplicity: the only moving part of the energy conversion mechanism is the rotor of a turbine, located above water level, rotating at a relatively high velocity and directly driving a conventional electrical generator. OWCs are a major class of wave energy converters, possibly the class that has been most extensively studied and with the largest number of prototypes so far deployed into the sea.

In almost all OWCs, the air alternately flows from the chamber to the atmosphere and back, although in some concepts the flow is in closed circuit. Unless rectifying valves are used, which is widely regarded as unpractical except possibly in small devices like navigation buoys, the turbines are self-rectifying, i.e. their rotational direction remains unchanged regardless of the direction of the air flow. Several types of such special turbines have been developed. The axial-flow Wells turbine, invented in the mid-1970s, is the most popular self-rectifying turbine, but other types, namely self-rectifying impulse turbines, have also been proposed, studied and used.