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Self-rectifying air turbines for wave energy conversion: A comparative analysis

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ABSTRACT

The oscillating water column (OWC) with an air turbine is a major class of wave energy converter that has been object of extensive research and development effort over many years, including the deployment of prototypes into the sea. In an OWC, the air alternately flows from the chamber to the atmosphere and back. Unless check valves are used, the turbines are self-rectifying, i.e. their rotational direction remains unchanged regardless of the direction of the air flow. The paper presents a comparative study of the performance of various types of self-rectifying air turbines and their suitability to different OWC applications and energy levels of the local wave climate. The study is based on available information on results from laboratory testing at Reynolds numbers high enough to make those results representative of full-sized machine performance under real operating conditions. Average values of flow rate, pressure head and efficiency are used in the comparisons, based on a stochastic approach in which the pressure oscillations in the OWC air chamber are assumed to be a random Gaussian process.

1. Introduction

The oscillating water column (OWC) is a major class of wave energy converters that has been object of extensive research and development effort over many years, including the deployment of prototypes into the sea [1]. A major advantage of the OWC as compared with most other wave energy converters is the simplicity of the energy conversion mechanism: the only moving part is the rotor of a turbine, located above water level, rotating at a relatively high velocity and directly driving a conventional electrical generator. OWC converters have been installed on the shoreline, standing near shore on the sea floor, incorporated into breakwaters or deployed offshore as floating structures (Fig. 1).

In almost all OWCs, the air alternately flows from the chamber to the atmosphere and back through a self-rectifying turbine whose rotational direction is independent of the direction of the air flow.

Several types of self-rectifying turbines have been developed. The axial-flow Wells turbine, invented in the mid-1970s, is the most popular, but other types have also been proposed, studied and used [1–4]. Information on air turbine performance has been published in a large number of papers. The range of model sizes and testing conditions, the various ways in which the results have been presented, and the different definitions of dimensionless variables used in the plots, explain why comparisons are difficult and scarcely available, especially if they involve different types of turbines. In most cases, the plotted results concern instantaneous flow conditions. However, it should not be forgotten that the turbines have to operate under oscillating and largely random conditions in terms of pressure head and flow rate, and so averaged results are of special interest in the comparisons. The knowledge of how the different types of air turbines compare with each other, and of their limitations and their relative advantages, is essential for developers and designers of wave energy converters of OWC type, many of whom are not experts in turbomachines in general and air turbines in particular. The aim of the present paper is to provide suitable information on this respect.

The paper presents a comparative study of the performance of various types of self-rectifying air turbines and of their suitability to different OWC applications and energy levels of the local wave climate. The study is based on available information on the aerodynamic performance of the various types of air turbines, especially results from laboratory testing at Reynolds numbers high enough to make those results representative of full-sized machine performance under real operating conditions. Average values of flow rate, pressure head and efficiency are used in the comparisons, based on a stochastic approach in which the pressure oscillations in the OWC air chamber are assumed to be a random Gaussian process.

The basic assumptions and the application of dimensional analysis are presented in Section 2, together with the stochastic approach to the turbine aerodynamic performance analysis under random sea

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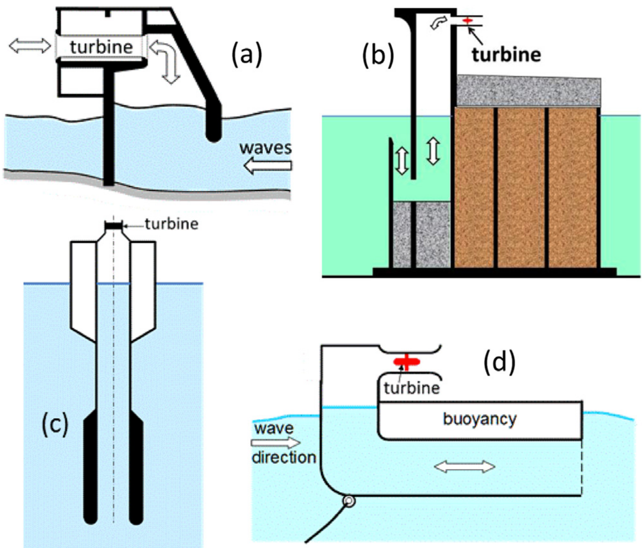

Fig. 1. Various types of OWC wave energy converters: (a) bottom-standing; (b) integrated into breakwater; (c) OWC spar-buoy; (d) backward-bent-duct-buoy (BBDB).

conditions. Axial-flow Wells turbines, and radial- and diagonal-flow variants, are analysed in Section 3, followed, in Section 4, by self-rectifying impulse turbines. Section 5 is devoted to comparisons between the different turbines from various points of view. Conclusions are drawn in Section 6.

2. Basic assumptions

2.1. Dimensional analysis

It is usual to apply dimensionless analysis to the performance study of turbomachinery [5]. This has the advantage of extending the applicability of the results from the testing of a given machine to geometrically similar machines of different sizes, at various rotational speeds and with different fluid densities. The consideration, in the present analysis, of the Reynolds number and the Mach number raises difficulties. This is due to the fact that experimental results are in general obtained from model testing in which both Mach number and Reynolds number are significantly lower than in full-sized machines operating under real sea conditions. This is more critical in the case of Wells turbines: they are known to be more sensitive to changes in Reynolds number and Mach number than self-rectifying turbines whose rotor configuration derives from conventional axial-flow and radial-flow turbines of impulse or reaction types. For this reason, in the present comparative study, preference is given to experimental results available in the literature from the testing of the larger models at sufficiently high rotational speeds. Significant air compressibility effects in the flow through self-rectifying turbines are known to take place at Mach numbers that rarely have been reproduced in laboratory testing. For these reasons, the effects of Mach and Reynolds numbers are in general ignored in the present comparative study.

We introduce the following dimensionless variables (see e.g. [5])

$$\Psi = \frac{p}{\rho\,\Omega^2 D^2},\quad \Phi = \frac{Q}{\Omega\, D^3},$$
$$\Pi = \frac{P}{\rho\,\Omega^3 D^5},\quad \eta = \frac{\Pi}{\Phi\Psi}. \tag{1}$$

Here Ψ is dimensionless pressure head, Φ is dimensionless flow rate, Π is dimensionless power output, η is efficiency, p is pressure head (pressure in air chamber minus atmospheric pressure), Q is volume flow rate (positive for outward flow), P is turbine power output, Ω is rotational speed (in radians per unit time), and ρ is air density. Note that, in real sea applications, p, Q, Ψ, Φ are alternately positive and negative.

If the effects of change in Reynolds number and Mach number are neglected, dimensional analysis allows us to write (see [5])

$$\Phi = f_\Phi(\Psi),\quad \Pi = f_\Pi(\Psi),\quad \eta = f_\eta(\Psi). \tag{2}$$

In the published literature, experimental results are, in many cases, made non-dimensional, and plotted, in ways that are different from what appears in Eqs. (1) and (2). In such cases, they were converted to the formats specified by these equations.

2.2. Stochastic approach

The water surface elevation of real-sea waves as well as the air pressure oscillation in the OWC chamber may be regarded as random processes. For most engineering purposes, the sea surface motion may be considered as a Gaussian process [6,7]. The same may be said of the air pressure oscillation, provided that the OWC converter is a linear system. More precisely, (i) if linear water wave theory is applicable to the hydrodynamic process of wave energy absorption; (ii) if the oscillations in air pressure p are (in modulus) small compared with the atmospheric pressure; and (iii) if the turbine is linear (flow rate proportional to pressure head). For details, see [8]. This is applicable with fairly good approximation to Wells turbines (which are known to be approximately linear at constant rotational speed) in moderately energetic seas. For the purpose of comparisons, we will assume here that, in the case of other types of self-rectifying turbines, the inner air pressure oscillations p are also approximately Gaussian.

Let σ be the standard deviation or root-mean-square (rms) of p. If the pressure oscillation p is Gaussian, then its probability density function $f(p)$ is

$$f(p) = \frac{1}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{p^2}{2\sigma^2}\right). \tag{3}$$

Let us assume that the rotational speed Ω is kept constant. The averaged values (denoted by an overbar) of the air flow rate Q, of the turbine power output P, and of the power available to the turbine $P_{avai} = pQ$ are given by

$$\{\bar{Q}(\sigma),\,\bar{P}(\sigma),\,\bar{P}_{avai}(\sigma)\} = \int_{-\infty}^{\infty} f(p)\{Q(p),\,P(p),\,P_{avai}(p)\}\,\mathrm{d}p \tag{4}$$

or

$$\{\bar{Q}(\sigma),\,\bar{P}(\sigma),\,\bar{P}_{avai}(\sigma)\} = \frac{1}{\sqrt{2\pi}\,\sigma}\int_{-\infty}^{\infty}\exp\left(-\frac{p^2}{2\sigma^2}\right)\{Q(p),\,P(p),\,pQ(p)\}\,\mathrm{d}p. \tag{5}$$

This may be rewritten, in dimensionless form, as

$$\{\bar{\Phi}(\sigma_\Psi),\,\bar{\Pi}(\sigma_\Psi),\,\bar{\Pi}_{avai}(\sigma_\Psi)\} = \frac{1}{\sqrt{2\pi}\,\sigma_\Psi}\int_{-\infty}^{\infty}\exp\left(-\frac{\Psi^2}{2\sigma_\Psi^2}\right)\{f_\Phi(\Psi),\,f_\Pi(\Psi),\,\Psi f_\Phi(\Psi)\}\,\mathrm{d}\Psi, \tag{6}$$

where

$$\bar{\Phi} = \frac{\bar{Q}}{\Omega D^3},\quad \bar{\Pi} = \frac{\bar{P}}{\rho\,\Omega^3 D^5},\quad \bar{\Pi}_{avai} = \frac{\bar{P}_{avai}}{\rho\,\Omega^3 D^5}, \tag{7}$$

and $\sigma_\Psi = p/(\rho\,\Omega^2 D^2)$ is the dimensionless value of the standard deviation (or rms) of the pressure oscillation p. The average efficiency in oscillating flow is

$$\bar{\eta}(\sigma_\Psi) = \frac{\bar{\Pi}(\sigma_\Psi)}{\bar{\Pi}_{avai}(\sigma_\Psi)}. \tag{8}$$

In the calculations, the infinite limits of integration are replaced by finite ones.

In what follows, 15 turbines, numbered 1–15, are analysed and compared.