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Wave radiation of a cycloidal wave energy converter

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ABSTRACT

Numerical results from a three-dimensional radiation model are presented where a cycloidal wave energy converter (WEC) is interacting with an incoming straight crested airy wave. The radiation model was developed in response to experimental observations from 1:10 scale experiments which were conducted in the Texas A&M Offshore Technology Research center wave basin. These experiments were the first investigations involving a WEC where three dimensional wave radiation effects were present due to the fact that the span of the WEC was much smaller than the width of the basin. The radiation model predicted the observed surface wave patterns in the experiment well, and showed that radiation induced wave focusing increased the recoverable wave power beyond the two-dimensional predictions for small WEC spans, while approaching the two-dimensional limit for very large spans. The numerical model was subsequently used to investigate the sensitivity of the WEC to misalignment between the incoming waves and the WEC shaft as well as the impact of a gap in the blade setup of a double WEC. For misalignment, the loss in efficiency was found to be strongly dependent on the ratio between WEC span and incoming wavelength, where short spans (on the order of one wavelength or less) which are realistic for actual ocean deployment showed only minor reductions in efficiency, while very long spans were found to be more sensitive to misalignment. The blade gap in a double WEC setup was found to have a relatively minor effect (up to 30%) on efficiency. Efficiency was found to either increase or decrease depending on the size of the gap.

1. Introduction

Among alternative energy sources, wave power is one of the most abundant sources on earth. The World Energy Council according to [1] has estimated the world wide annual amount of wave energy at 17.5 PWh (Peta Watt hours = 10^{12} kWh). This amount of energy is actually comparable to the annual world wide electric energy consumption, which is currently estimated at 16 PWh. Thus, wave energy has the potential to provide a large portion of the world's electric energy needs, if it can be harnessed efficiently. In addition to the energy availability, wave energy has other advantages. Since a large portion of the world's population lives close to the ocean shores, the distance between energy production and consumption is small, which reduces transmission losses and necessary investments in transmission lines. As opposed to other alternative energy sources like wind, stream and solar energy, the installation of wave power devices does not require use of already precious real estate. This makes wave energy an ideal energy source for efficiently providing renewable energy to densely populated coastal areas. Thus ocean waves have a tremendous potential to provide clean renewable energy. Further engineering aspects of wave power as an energy source are appealing as well. While the power density of both solar and wind in typical favorable sites is in the order of 1 kW m^{-2} [2], wave power in a typical North Atlantic wave that was considered in a related paper [3] (wave height of $H = 3.5$ m and period of $T = 9$ s) yields 108 kW m^{-1} of wave crest. As shown there, a device extending about 40 m in the vertical direction can extract almost all of this wave energy, yielding a power density of about 2.7 kW m^{-2} or more than two and a half times that of wind or solar power. If one considers the theoretical inviscid conversion limits for waves and wind, which are 100% for waves [4] and 59% for wind [5], the accessible power density of waves is more than four times as large as that of wind. Furthermore, wave energy is available on a more consistent basis and can be better predicted in advance, therefore mitigating the need to back up a wave power plant with other conventional power sources, such as solar and wind energy.

2. Motivation and objectives

Given the attractive features of wave energy as an alternative energy source, it has received significant attention in the scientific community over time. While a comprehensive review of all relevant publications would be prohibitively long, the reader is instead referred to comprehensive reviews published by McCormick [6],

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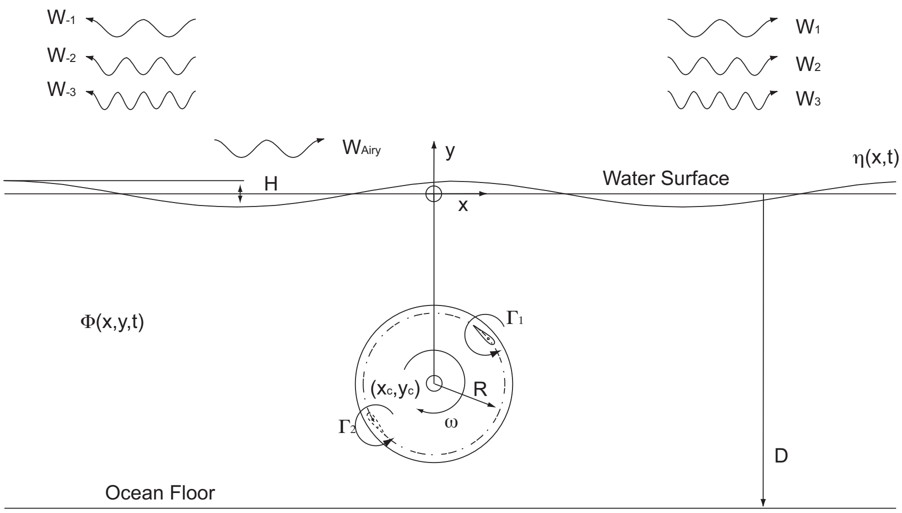

Fig. 1. Cycloidal wave energy converter geometry and generated waves.

Mei [7] or, most recently, Cruz [8]. The following discussion will instead focus only on select sources most pertinent to the current work.

While wave energy as a resource may be free, the construction effort to harness it is a major expense and to a large degree determines the cost of energy being produced. As a less efficient WEC will need to be larger in size to extract the same amount of energy as a more efficient one, cost of energy is directly related to efficiency. Arguably, the most efficient WEC is one that can extract all of the energy from an incoming wave, and the class of wave energy converters that is able to achieve this is commonly referred to in literature as wave termination devices. There have been various wave termination designs reported in literature, with the most well known devices being the Salter Duck [9] and the Bristol or Evans Cylinder [10]. Both consist of a series of elements which are aligned parallel to the wave crests, in the case of the Salter Duck these are cam-shaped and floating on the surface, while the Bristol Cylinder is fully submerged. Both have been shown to be able to absorb an incoming wave completely. The wave energy is converted to electric power by means of a power-take-off system that is hydraulic in both cases. As both devices move at approximately the wave induced water velocity, the devices need to feature a large surface area to convert appreciable amounts of power. This increases construction cost, reduces storm survival odds and has ultimately motivated the investigation of the Cycloidal WEC described here. The fact that both devices require mooring to the ocean floor also hampers storm survival odds and precludes installation in very deep water.

A typical cycloidal wave energy converter as considered in this paper is shown in Fig. 1. It features one or more hydrofoils attached eccentrically to a main shaft at a radius R. While the shaft rotates, the pitch angle of the blades may be adjusted. This device operates at a rotational speed of the hydrofoil that is typically an order of magnitude larger than the wave induced water velocity, and employs the lift force of the hydrofoil to generate shaft torque directly. Using lift allows for a much smaller hydrofoil plan form area to be employed compared to the cross sectional areas of Duck and Cylinder, and generating shaft torque directly eliminates the need for a costly and inefficient hydraulic or linear generator type power take off system.

A single rotating hydrofoil was first investigated by Hermans et al.[11] both numerically and experimentally. While Marburg [12] reported very low wave energy conversion efficiencies (on the order of a few percent) in these experimental investigations, Siegel et al. [13] were able to show in simulations that with improved sizing of the WEC as well as by using synchronization of the rotation of the foil with the incoming wave, wave termination with better than 99% inviscid efficiency was possible. These numerical findings were confirmed by 1:300 scale experiments in 2011, as reported by Siegel et al. [14] where invisicid conversion efficiencies of greater than 95% were achieved. Both of these initial studies performed synchronization of the WEC with a numerically generated harmonic wave, or a paddle wave maker, respectively. Thus they did not require a feedback controller and estimator to succeed. A controller and estimator were for the first time successfully implemented by Jeans et al. [15] for irregular waves in a numerical simulation. Typical conversion efficiencies in this study were beyond 90% for a superposition of two harmonic waves, and around 80% for irregular waves following a Bretschneider distribution. At the same time, the controller and estimator were successfully tested in an experiment as reported in [16] where harmonic waves with different wave heights and frequencies were successfully cancelled, achieving efficiencies comparable to the earlier synchronization experiments that had a priori knowledge of the incoming wave. The performance of the feedback controller and estimator could thus be experimentally verified for the first time. Next, the WEC investigations were advanced by experimentally canceling both a superposition of two harmonic waves, as well as irregular waves following a Bretschneider distribution. This has been done in simulations reported by Jeans et al. [15], as well as experimentally validated by Siegel et al. [17] in a small 2D wave flume.

The first wave cancellation experiments in a wave tank where the span of the WEC was far smaller than the width of the tank were conducted in 2012 at the Texas A&M Offshore Technology Research Center and established successful electricity production for the first time, see Fagley et al. [18]. Experimental observations also indicated the presence of 3D radiation effects, and an initial version of a numerical model described in Fagley et al. [18] found good agreement between experiment and numerical model. In this work, the radiation model is further improved and used to investigate the sensitivity of the WEC to angular offsets between WEC shaft and wave crest direction. It is of importance to predict the possible efficiency reductions as a result of this type of misalignment. It is also necessary to quantify the necessary accuracy of wave measurement equipment employed for alignment of WEC and incoming wave.

A second focus of this work is the investigation of the impact of a blade gap on the performance of the WEC. For a WEC attached to a monopile, as shown in Fig. 2, a gap between the left and right