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Experimental wave termination in a 2D wave tunnel using a cycloidal wave energy converter

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ABSTRACT

A lift based cycloidal wave energy converter (CycWEC) is investigated in a 1:300 scale two-dimensional wave flume experiment. This type of wave energy converter consists of a shaft with one or more hydrofoils attached eccentrically at a radius. The main shaft is aligned parallel to the wave crests and submerged at a fixed depth. The operation of the CycWEC both as a wave generator as well as a wave-to-shaft energy converter interacting with straight crested waves is demonstrated. The geometry of the converter is shown to be suitable for wave termination of straight crested harmonic and irregular waves. The impact of design parameters such as device size, submergence depth, and number of hydrofoils on the performance of the converter is shown. For optimal parameter choices, experimental results demonstrate energy extraction efficiencies of more than 95% of the incoming wave energy. This is achieved using feedback control to synchronize the rotation of the CycWEC to the incoming wave, and adjusting the blade pitch angle in proportion to the wave height. Due to the ability of the CycWEC to generate a single sided wave with few harmonic waves, little energy is lost to waves radiating in the up-wave and down-wave directions.

1. Introduction

Among renewable energy, wave power is one of the most abundant sources on earth. The World Energy Council, according to Boyle [1], has estimated the world wide annual amount of wave power energy at 17.5 PWh (Peta Watt hours = 10^{12} kWh). This is comparable to annual worldwide electric energy consumption, which is currently estimated at 16 PWh. Thus, wave power has the potential to provide a large portion of the world's electric energy needs if it can be tapped efficiently. Other advantages of wave power include its power density, predictability, and location. Since a large portion of the world's population lives close to ocean shores, the distance between energy production and consumption is minimized, reducing transmission losses. Thus, wave power is an ideal energy source for efficiently providing renewable energy to densely populated coastal areas.

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 [2], Mei [3] or, most recently, Cruz [4]. The following discussion will instead focus only on select sources most pertinent to the current work.

There have been various wave termination designs reported in literature, with the most well-known devices being the Salter Duck [5] and the Bristol or Evans cylinder [6]. 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 power 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, which is typically an order of magnitude smaller than the celerity, 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.

Initial investigations of lift based wave energy conversion by means of a single hydrofoil were performed at TU Delft as early as the 1990s, both experimentally by Marburg [7] and numerically by van Sabben [8]. As noted by Hermans et al. [9], a major advantage of this approach over traditional wave energy converters is that the wave energy can be converted directly into rotational mechanical energy. This initial work demonstrated the feasibility of the approach, as well as the ability of a CycWEC to self-synchronize with the incoming wave in terms of rotational phase. However, the conversion efficiencies found both in the theoretical work and the wave tunnel experiments conducted at TU Delft were very small, in the order of few percent in experiments, with a theoretical maximum of 15%.

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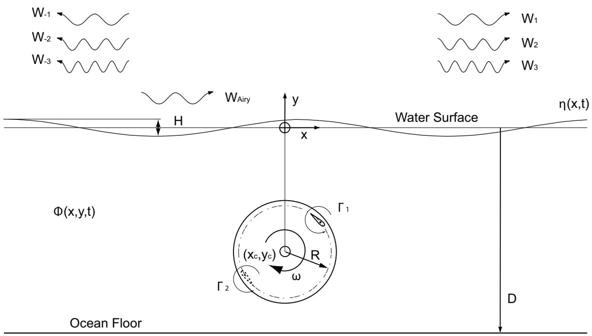

Fig. 1. Cycloidal wave energy converter geometry and generated waves.

Pinkster and Hermans [10] also demonstrated the use of a cycloidal turbine as a means of detecting wave direction and period with good accuracy.

A typical cycloidal WEC, as considered in this paper, is shown in Fig. 1. It features one or more hydrofoils attached parallel to a horizontally oriented main shaft at a radius R, rotating clockwise at angular speed ω, and submerged a depth y_c, which is measured relative to a Cartesian coordinate system with $y = 0$ being the undisturbed free water surface. The hydrofoils are assumed to have a large span compared to their chord c, which is approximated by a large aspect ratio, which is the ratio between span and chord length. They are also assumed to be aligned parallel with the incident wave crests. The orientation (pitch) of each hydrofoil may be adjusted to produce the desired amount of wave height, which is proportional to the angle of attack as will be shown.

Based on the sketch in Fig. 1, a number of non-dimensional quantities emerge. The basic size of the wave energy converter is denoted by $2R/\lambda$, where the wave length λ is the fundamental length scale. Consequently, the vertical position of the main shaft is denoted by y_c and the wave height by H. It is also convenient for parameter studies to compare different size wave energy converters while keeping the distance between the water surface and the topmost point of the CycWEC foil path fixed, that is $|y_c + R| = const$. At any point on the free surface the vertical elevation is η and peak-to-peak amplitude of the resulting wave field is denoted by H. The incoming wave W_{Airy} is assumed to travel left to right, and waves generated by the cycloidal WEC traveling in the direction of the incoming wave receive a positive index (e.g., W_1) and are considered traveling down-wave; while waves traveling in the opposite direction are considered traveling up-wave and receive a negative index (e.g., W_{-1}).

The aim of the present work was to extend the experimental work presented at conferences in the recent past [11,12], as well as to compare the experimental results qualitatively and quantitatively to the results from numerical potential flow simulations as reported by Siegel et al. [13] and Jeans et al. [14]. This is done for operation of the CycWEC as both a wave generator as well as a wave energy converter following the rationale that efficient wave termination requires single sided wave generation. The results presented investigate the range of wave lengths for which a CycWEC of fixed size can efficiently generate and cancel incoming waves. This is of importance since in any real wave climate the wave height and frequency varies both from wave to wave, as well as from season to season. The impact of all design parameters, in particular submergence depth y_c, radius R, number of blades and pitch angle of the blades is investigated in detail and compared to simulation results. The parameter studies are conducted for rotation of the CycWEC with a fixed rotational period, or harmonic incoming waves of constant wave height, respectively. Thus, no feedback control is required and the CycWEC is operated with a fixed but adjustable phase shift relative to the incoming waves for wave cancellation. In further experiments, a feedback controller was employed to enable efficient interaction between the CycWEC and irregular waves. The feedback controller employed the signal of a single wave gauge located up-wave of the CycWEC in order to control rotation and pitch of the CycWEC blades based on this measurement in real time. Irregular waves were synthesized from simple harmonic waves with the wave power of each wave component determined from a Bretschneider distribution. The feedback controller employed the signal from a wave gauge positioned up-wave from the WEC, and controlled both rotation and blade pitch of the WEC. It is shown that efficient wave cancellation of irregular waves is possible with this setup.

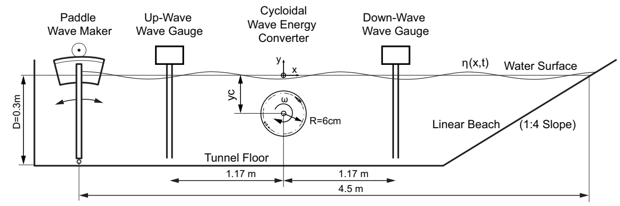

Fig. 2. Wave tunnel schematic – not to scale.

2. Experimental setup

The tunnel used for testing the CycWEC was a 2D wave tunnel designed to provide a 1:300 scale model of a deep ocean wave. The full scale design deep ocean wave investigated numerically in [13] had a period of $T_{Airy} = 9$ s, a wave length of $\lambda_{Airy} = 126.5$ m, a wave height of $H = 3.5$ m, and power per meter of wave crest of $P = 105$ kW/m. It was represented in the present setup by a wave with a period of $T_{Airy} = 0.5$ s and wave length of $\lambda_{Airy} = 0.39$ m; at a typical wave height of $H = 20$ mm the scaled wave carried approximately $P = 192$ mW/m of wave power.

2.1. Wave tunnel

The wave tunnel is shown in a conceptual sketch in Fig. 2. The tunnel was designed for the generation and dissipation of waves with a period between $T = 0.2$ s and $T = 1.15$ s at wave heights up to $H = 5$ cm.

It had an overall length of 5 m, where 4.50 m were usable for wave experiments between the flap wave maker and the beach, a width of 0.55 m and a design water depth of 0.3 m. The width of the tunnel was increased by 50 mm on each side in the center test section, which allowed the drive system of the CycWEC to be placed outside of the wave testing area by means of false walls. At the right end of the tunnel, there was a linear beach with a 1:4 slope. For the design wave of $T = 0.5$ s and $H = 20$ mm, the reflection coefficient of the beach was measured by traversing two wave gauges using the approach described in [6] and found to be $C_r = 0.106$.

2.2. Irregular wave synthesis

The irregular incident wave field was created using a linear superposition of a finite number of linear Airy wave components using a flap type wave maker hinged at the bottom of the tunnel. The resulting surface elevation for a unidirectional deep ocean wave propagating in the x-direction and satisfying the linearized free surface boundary conditions was given in [15] to be

$$\eta_I(x,t) = \sum_{i=1}^{N_I} \frac{H_i}{2} \cos(k_i x - \omega_i t + \theta_i), \quad (1)$$

where N_I was the number of regular wave components used to represent the irregular wave field, and H_i, k_i, ω_i and θ_i were the wave height, number, frequency and phase for component i, respectively.