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ABSTRACT

This work discusses a new wave energy converter (WEC) design that, when deployed in waves, performs unidirectional rotation about a vertical shaft. The uniqueness of this new WEC design is on utilizing omnidirectional water flow generated by waves to drive a rotor to perform unidirectional rotation about a vertical axis. This unique feature circumvents the frequency-dependent issue of common WECs, and eliminate realignment needs to cope with dynamically changing wave propagation directions. The key component of the WEC is a rotor, which has a vertical shaft with a number of blades mounted to it. Each blade has a hydrofoil-shaped cross section and is in a bent shape along its span. The spanwise bending of the blades makes the rotor capable of gaining a unidirectional driving torque about the vertical shaft no matter in which spatial direction the local water is passing by. For validating the WEC design and gaining preliminary understanding, a very first rotor model without any parametric optimization was built. Two types of experiments were then carried out by employing this model. In the first type, the model was translated (with the shaft vertically aligned all the time) in still water along a horizontal direction (back and forth), a vertical direction (up and down), and a circular orbit in a vertical plane. In the second type, the model was exposed in waves generated in a wave flume. In all the experiments, well-established unidirectional rotation of the rotor about its vertical shaft has been observed. The hydrodynamic performance of the rotor in waves was further characterized through systematic experiments under various conditions.

Key words: wave energy converter, WEC, vertical axis, unidirectional rotation

1. INTRODUCTION

Ocean waves carry huge amount of energy. In typical waves, water particles perform omnidirectional motion. Such three dimensional unsteady flow behavior makes energy extraction from waves much more difficult than from winds (nearly unidirectional to individual wind turbines). For this reason, typical wind turbines perform unidirectional rotation in nearly unidirectional approaching winds; whereas most of wave energy converters (WECs) being explored to date perform various types of reciprocating motions such as heave, pitch, sway, reciprocating bending or curving, etc [1]. Reciprocating motions make a WEC's efficiency strongly wave-frequency dependent. In contrast, ocean waves have daily changing frequency with a broad-band spectrum. Obviously, reciprocating WEC designs are not well-suited for the broad-band waves towards high efficiency on energy extraction.

Among a vast amount of WEC designs there is a very small group that behaves differently. Specifically, WECs in this group perform unidirectional rotation in waves. Representative WEC designs of this type include a Savonius WEC [2], a cycloidal WEC [3], and a wave rotor [4]. Unidirectional rotation allows a WEC to circumvent the frequency dependent nature possessed by reciprocating WECs, hence it is advantageous in making the WEC broadly adaptive to widely spread wave frequencies with no needs of any frequency-tuning mechanisms. This very small group of unidirectional WECs can be further categorized into two types according to the orientation of the axis of rotation – horizontal-axis WECs [2, 3] and vertical-axis WECs [4].

For a horizontal-axis WEC, the axis needs to be aligned along the wave crest direction for the best efficiency. Making such alignment is possible in well-organized swells, but not in ill-defined seas. Besides, dominant waves do change propagation directions frequently. Therefore, a dedicated mechanism in the WEC for its dynamic realignment is very likely a necessity, which greatly complicates the WEC structure and thus significantly weakens the WEC robustness, at a high cost. In comparison, a vertical-axis WEC does not have the realignment needs; waves from any direction just work well. Design of the vertical-axis WEC, however, is challenging from the hydrodynamics perspective. It demands omnidirectional water flows due to waves to drive a rotor, as a part of the WEC, for unidirectional rotation about a vertical axis.

Obviously, if an omnidirectional-flow-driven unidirectional rotor with a vertical axis can be realized, it will be greatly suited for wave energy harvesting. The WaveRotor design [4] has made an attempt along this direction. According to the developer, however, it works well in tidal flows superimposed with waves, but does not work in irregular waves alone. Most recently, the authors demonstrated a new WEC design of this type [5]. Cup-shaped blades were employed in configuring the unidirectional rotor, which rotates well about a vertical axis in waves.

In the present work, the authors discuss another unidirectional vertical-axis rotor design. Differing from the earlier rotor with cup-shaped blades (the drag type), the present rotor employs hydrofoil blades (the lift type).

2. CONCEPTUAL DEVELOPMENT

In simple waves water particles perform orbital motion superimposed with a Stokes drift [6]. In irregular seas, coexistence of multiple dominant-frequency components or a broad-band frequency distribution [7] in conjunction with various wave propagation directions makes local water flows even more complicated. Therefore, for a WEC deployed in the ocean, surrounding water flows can be in any spatial directions that are continuously changing. To use this type of omnidirectional flows to drive a rotor for unidirectional rotation about a vertical axis, hydrodynamic design plays a critical role.

Figure 1 illustrates the conceptual design of the rotor, which is employed in the present research. It consists of multiple sets of blades along a vertical shaft; each set has multiple blades evenly distributed circumferentially. Two sets of three-blade rotor configuration were adopted in this proof-of-concept research. Each blade has a hydrofoil-shaped cross section in a NACA0021 profile. The blade has three segments along the span: a vertical segment, a horizontal segment, and a smooth bend in between. Focusing on an assembled set of blades, the vertical layout represents a typical Darrieus H-rotor [8], and the horizontal layout is essentially a Wells' rotor [9].

The Darrieus H-rotor has long been applied to vertical axis wind turbine designs. It performs unidirectional rotation about its shaft when winds are blowing in any direction normal to the shaft but not along the shaft. In contrast, a Well's rotor is specifically designed to realize unidirectional rotation about its shaft in bidirectional flows along the shaft but not normal to the shaft. By combining the two rotor designs as shown in Fig. 1, the vertical layout is responsive to flows normal to the shaft with low resistance to flows along the shaft, whereas the horizontal layout is responsive to flows along the shaft with low resistance to flows normal to the shaft. As a result of the combination, the newly formed rotor is expected to perform unidirectional rotation no matter in which spatial direction a flow passes by. Such a unique behavior of the rotor would be perfect for energy harvesting from ocean waves.

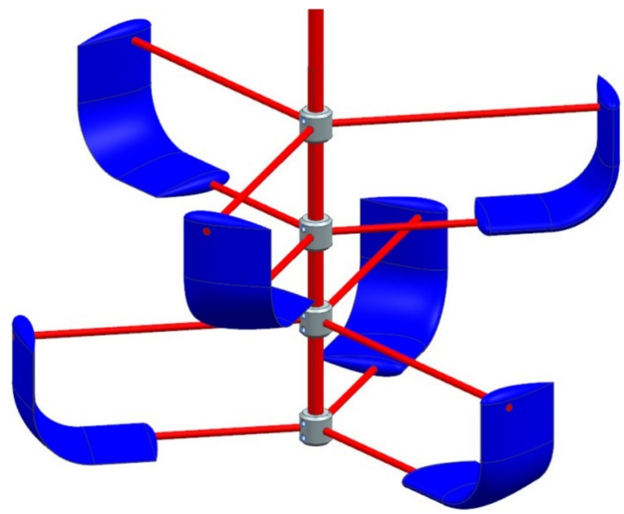

Figure 1: Rotor configuration.

In an attempt to make the rotor motion as smooth as possible in dynamically changing flow directions, three considerations are implemented in the rotor design. First, multiple sets of blades with reduced dimensions over a single set of blades of relatively large dimensions are employed. It is expected to cope well with the flow non-uniformity, particularly in irregular waves. Second, there is an offset angle along the rotation direction between two adjacent sets of blades. Such arrangement should help on reducing interaction between the two sets and, thus, gaining energy absorption efficiency. Third, a bend is used between the vertical and horizontal portions of each blade for a smooth transition. The bend is intended to improve the rotor responsiveness during the time with inclined flows transitioning between horizontal and vertical directions.

Flow interaction with the rotor is highly nonlinear. Therefore, the effectiveness of the above three considerations needs to be validated as a part of the optimization process. In the present work, the authors have focused on the proof-of-concept study of utilizing omnidirectional flows to drive the rotor for unidirectional rotation. Optimization of any type, including validation of the three considerations, was not carried out yet in this initial approach.

3. EXPERIMENTAL SYSTEM

All experiments were carried out in a wave flume of inner dimensions 15m (L) × 1m (W) × 1.3m (H). To directly validate the rotor's capability on performing unidirectional rotation about a vertical axis in waves, one type of experiments was to expose the rotor in simple waves; the rotor has only one degree of freedom (DOF) – rotation about its vertically mounted shaft. To gain fundamental understanding on the rotor's responsiveness in some specified flow directions, another type of experiments was also carried out by moving the rotor in still water in a controlled manner. Specifically, three motion modes of the rotor were examined: horizontal oscillation, vertical oscillation, and circular orbital motion in a vertical plane. In all these three modes, the rotor shaft was always aligned vertically and was performing translation only. The orbital motion of the rotor in still water was used to approximate a fixed rotor (with one DOF) in simple deep waves where water particles perform circular orbital motion (drift was neglected) [6].

To translate the rotor in still water, a custom-designed machine has been built, as shown in Fig. 2. The machine sits on top of the wave flume. The machine has a servo motor to translate, through a gearbox and cam, a slider along a circular orbit in a vertical plane. Both the radius of the orbit and the revolving speed of the slider are adjustable. By directly fastening the rotor holder to the slider, the rotor translates along a circular orbit. By fastening the rotor holder to the vertical rail, the rotor performs horizontal oscillation. By turning the whole machine by 90° about the crossover beam (with an added supporting beam, not shown in Fig. 2) and by fastening the rotor holder to the same vertical rail (now horizontal) with the rotor shaft vertically aligned, the rotor performs vertical oscillation. The rotor holder holds the rotor shaft in place via two sleeve bearings, giving the rotor one DOF – rotation. For the case of testing the rotor in waves, the machine simply functions as a non-moving support.

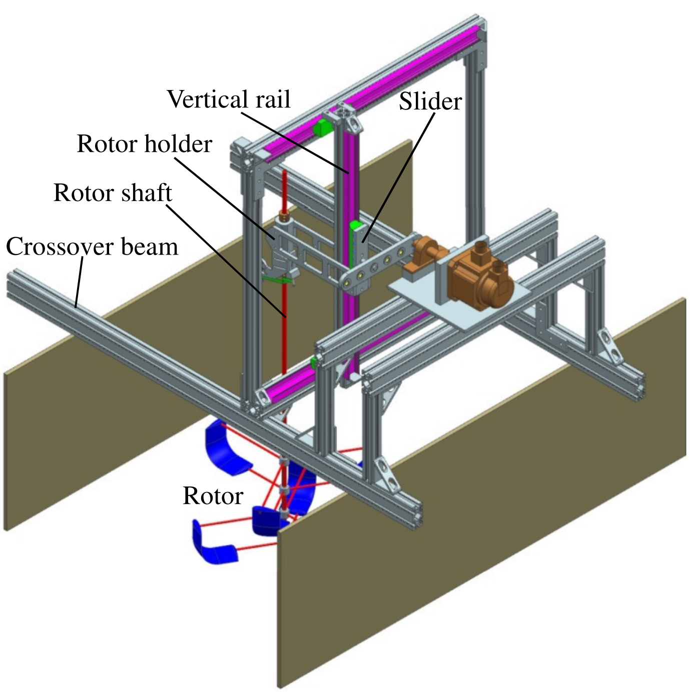

Figure 2: Experimental setup.

A model rotor (Fig. 1) has been fabricated for testing. It has a rotor diameter of D = 0.5 m (the diameter of the largest circular swept area). Individual blades are all identical. Each blade has a hydrofoil (NACA0021) cross section with a chord length of 76.2 mm. Along the curved span the blade consists of a straight 50.8-mm long vertical segment, a straight 50.8-mm long horizontal segment, and a circular bend of radius 50.8 mm (for the central curved plane) in between. The two extreme ends of the blade are rounded by revolving the hydrofoil cross section about its centerline. Two sets of blades, with each having three blades evenly distributed circumferentially, are fastened to the rotor shaft in series. From the highest point of the lower set of blades to the lowest point of the upper set of blades there is a spacing of 30 mm along the shaft. Between the two sets there is also an angular offset of 60° about the shaft.

For the three types of still water experiments, the pick-to-pick amplitude of oscillation (H) or the diameter of the circular motion (also H) for the rotor has been examined at three different values, H = 114 mm, 216 mm, & 318 mm. At each value of H, the oscillating frequency (f) or circulating frequency (also f) were also varied at three different values, f = 0.5 Hz, 0.75 Hz, & 1 Hz. For wave experiments, only one combination of wave parameters is explored: wave height H = 223 mm, wave frequency f = 0.593 Hz. In this case, the water depth in the wave flume was 1 m, and the rotor was submerged with the highest point of the blades to be 100 mm beneath the free surface in still water.

To obtain time traces of the rotor's angular velocity under various conditions, a dial was coaxially fixed to the rotor shaft from the top end, and an iPhone 6 Plus was employed to videotape the dial rotation. Videos were then manually processed to extract angular information. All the planned experiments were repeated three times during data acquisition.

4. RESULTS AND DISCUSSION

The experimental exploration started with the still water approach. Due to the long lasting periodic motion (e.g., oscillation or circular motion) of the rotor in a confined water body, the rotor kept passing through its own wake generated from earlier cycles. Therefore, the water flow around the rotor was highly chaotic and turbulent rather than still. Yet, such complex flow conditions have never stopped the rotor from performing unidirectional rotation about its vertically aligned shaft while translating in any directions. Specifically, profound and consistent unidirectional rotation has been observed all the time with the rotor oscillating in horizontal and vertical directions, and orbiting along circular paths. By directly exposing the rotor in waves, smooth unidirectional rotation was also clearly demonstrated.

Time traces of the instantaneous angular velocity ω for four typical cases are shown in Fig. 3 in a dimensionless form ω_Π. Detailed experimental conditions are specified in the figure. The angular velocity ω was normalized as

$$\omega_\Pi = \omega\ D/(2\pi f H)\,. \quad (1)$$

It represents the ratio of two tangential speeds: one is the rotor's tip speed due to rotation, and the other is either the maximum translation speed of the rotor in still water or the free-surface water speed along a circular orbit in deep waves. The mean angular velocity $\overline{\omega}$ and the fluctuation magnitude $\Delta\omega$ were normalized in exactly the same way; they were denoted as $\overline{\omega}_\Pi$ and $\Delta\omega_\Pi$ upon normalization.

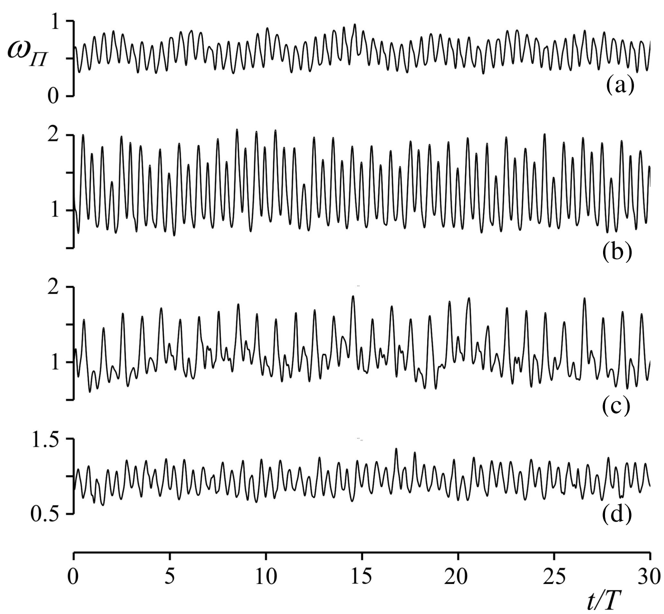

Figure 3: Time traces of the normalized angular velocity ω_Π within 30 periods (T) for four cases: (a) horizontal oscillation of the rotor, (b) vertical oscillation of the rotor, (c) orbital translation of the rotor along a circular path, and (d) the rotor in waves. For (a) through (c), H = 216 mm, f = 0.75 Hz (T = 1.33 s). For (d) H = 223 mm, f = 0.593 Hz (T = 1.69 s).

As shown in Fig. 3, for both horizontal and vertical oscillations, unidirectional rotations of the rotor are evident. In both cases the angular velocity fluctuates at a dominant frequency that is two times of the oscillation frequency. The average value and fluctuation level of the angular velocity for the vertical oscillation (Fig. 3a) is much higher than that for the horizontal oscillation (Fig. 3b). Such behavior has also been reflected in the orbital motion (Fig 3c), where the peak velocity gained during nearly vertical phases is much greater that that during nearly horizontal phases. The velocity discrepancy can be fixed by increasing the length of the vertical portion of each rotor blade. For the rotor in waves (Fig. 3d), however, the discrepancy is hardly noticeable. This was mainly due to the fact that the waves generated in the wave flume for this testing case were intermediate waves rather than deep waves. As a result, water particles move along elliptical paths with the major axis in the horizontal direction, which makes the water flow stronger horizontally than vertically.

Figure 4 compares the relative fluctuation of the angular velocity, $\Delta\overline{\omega}_\Pi / \overline{\omega}_\Pi$, among the four cases discussed in Fig. 3. $\Delta\overline{\omega}_\Pi$ is evaluated by calculating the standard deviation of a time trace of ω_Π. Obviously, the rotor in waves presents the smoothest rotation with the lowest fluctuation level.

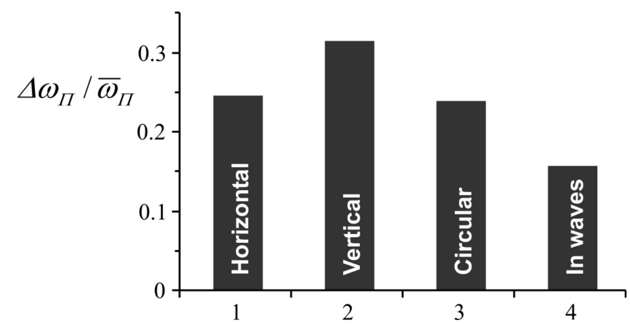

Figure 4: Comparison of the relative fluctuation of the angular velocity among the four cases in Fig. 3.

To better understand the rotor responsiveness to flows from different directions, a parametric study has been conducted by moving the rotor in still water. Fig. 5 presents the frequency effect on the average velocity $\overline{\omega}_\Pi$ in three specified motion types. $\overline{\omega}_\Pi$ was calculated by averaging three repetitive runs for each parametric combination; every run provided a 75-second record of instantaneous angular velocity. As shown in Fig. 5, at a fixed H, increase of the frequency led to nearly linear increase of $\overline{\omega}_\Pi$ in all the three motion types. It is very interesting that the

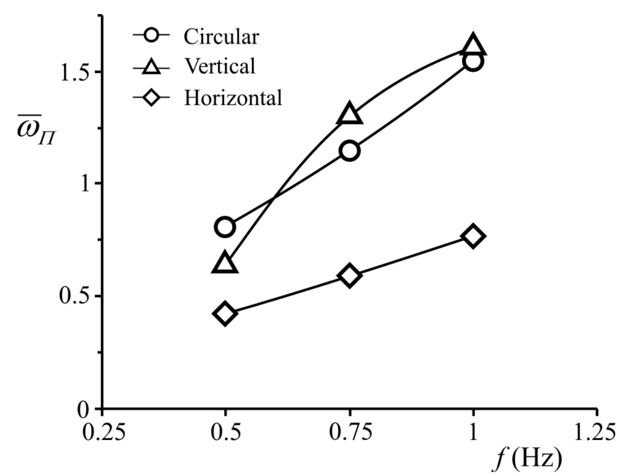

Figure 5: Effect of the frequency change on the normalized average angular velocity. For all the examined cases, H = 216 mm.

vertical oscillation achieved angular velocities close to, and some time even higher than, the circular motion. The horizontal oscillation, on the other hand, was not as strong as the other two in making the rotor rotate.

At a fixed frequency f and with varying value of H/D (normalized H), the averaged velocity $\overline{\omega}_{\Pi}$ for the three motion types were plotted and compared in Fig. 6. Similar to Fig. 5, the values of $\overline{\omega}_{\Pi}$ for the vertical oscillation and circular motion are quite close to each other in the examined range of H/D, and the corresponding values for the horizontal oscillation are much lower. It is noteworthy that increase of H/D only caused a mild increase of $\overline{\omega}_{\Pi}$ in all the three types of motion. That is in comparison with a much rapid change in Fig. 5.

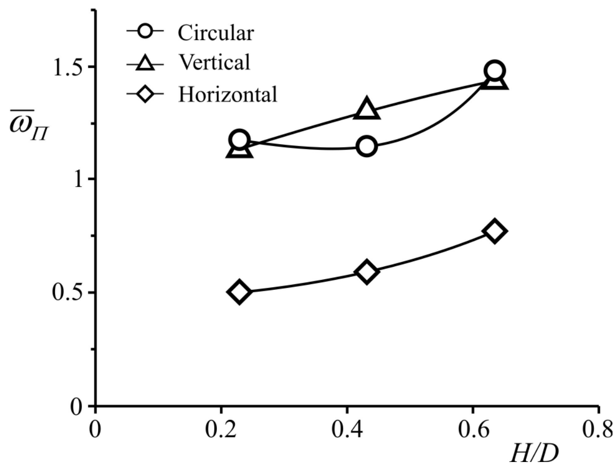

Figure 6: Effect of *H/D* on the normalized average angular velocity in three specified motion types. For all the examined cases, $f = 0.75$ Hz.

5. CONCLUSIONS

A new rotor design has been investigated for wave energy conversion. The rotor employs hydrofoil blades with a spanwise bend. It performs unidirectional rotation about its vertical shaft in omnidirectional flows generated by waves. The unidirectional behavior of the rotor has been characterized by moving the rotor in still water. Three motion types have been applied on the rotor: horizontal oscillation, vertical oscillation, and circular motion. The two oscillation types were used to identify the sensitivity of the rotor to flow directions. The circular motion was employed to simulate the relative motion between the rotor and deep waves. The rotor has also been tested in waves, and smooth and profound unidirectional rotation of the rotor was observed.

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