Investigating of Helmholtz wave energy converter

Y. Saadat^{a,1}, Nelson Fernandez^a, Alexei Samimi^a, Mohammad Reza Alam^b,
Mostafa Shakeri^b, Reza Ghorbani^a

^aDepartment of Mechanical Engineering, University of Hawaii at Manoa, Honolulu, HI 96822, USA

^bDepartment of Mechanical Engineering, University of California, Berkeley, CA 94720, USA

ABSTRACT

This study examines a new concept of wave energy conversion inspired by natural wave pools which are able to trap ocean wave energy into a basin. A novel wave energy converter that uses the Helmholtz resonance frequency is introduced. This device which is called Helmholtz wave energy converter (HWEC) amplifies the oscillation amplitude of a fluid in a basin that is connected to the sea through a narrow channel. The main focus of the current study is to understand the mechanism of wave amplification at Helmholtz resonance frequency in a basin and experimentally investigate the geometry of an ideal wave pool in a wave tank utilizing the theoretical method previously has been done on tidal Helmholtz resonance. The geometry causes amplification in oscillating fluid velocity within the channel at the Helmholtz frequency. Geometric characteristics of HWEC were experimentally studied to determine the dimensions of the basin for inducing Helmholtz resonance. A 1/25th and a 1/7th scale models were used to correlate the Helmholtz frequency with the device geometry. In addition, the effects of the device's basin length and angle of winglets at the inlet of the channel were explored. Furthermore, Particle image velocimetry (PIV) technique was used to determine the velocity fields through the channel of the 1/25th scale model. The results suggest that reducing the angle of the winglets leads to fewer higher order harmonics resulting in better performance of the device in extracting the energy of the incoming waves. It is also shown that the alignment of the axis of the device relative to the incoming waves plays an important role in the overall efficiency of the device. The results of the current study can be used to optimize the design of HWEC devices for extracting wave energy. Moreover, the results reveal that resonance in the channel results in amplification of wave height relative to incoming waves and the corresponding wave power available for absorption. Appropriate location of the power take-off (PTO) in the channel can be empirically determined using PIV data. However this work does not examine the effect of the PTO in the device's energy absorption performance.

Keywords: Helmholtz resonance mode, Wave energy converter, Power take-off, Particle image Velocimetry (PIV), Wave power absorption.

¹ Corresponding author: Department of Mechanical Engineering, University of Hawaii at Manoa, Honolulu, HI 96822, USA.

Email address: yaldas@hawaii.edu (Y Saadat) & rezag@hawaii.edu (R. Ghorbani).

1. Introduction

Increases in energy demand in conjunction with recent concerns regarding climate change, dependence on fossil fuels for energy production, and trends in high oil prices demand that we develop reliable alternative energy technologies that utilize the diverse global energy resources available. One such resource—wave energy—has until now remained relatively untapped. This readily available and inexhaustible source of energy has, in recent decades, garnered global attention, and is a significant field of research for renewable energy. While the idea of converting wave energy to electricity is relatively new, it was referenced in France as early as 1799 with the Girard brothers inventing a Wave Energy Converter (WEC) [1]. Nonetheless, it was not until the 1970's, due to the energy crisis in 1973, that considerable exploration occurred with wave energy, launching a great frontier of the energy industry.

At this time, studies were aimed at a furthering knowledge of wave power in order to find a reliable and economical method to convert wave energy into electricity. Many intriguing theories regarding wave energy emerged, along with several types of WEC designs, which were effectively established; pioneers of such models and concepts include Masuda [2], Salter [3], Mei [4-6], Flans [7,8], Newman [9], Bubal [10], Evance [11,12], Fujita [13], Drew [14]. Thus, diverse methods of wave energy extraction have arisen: Scotland's Pelamis Wave Energy Converter [15], Oyster [16], Sweden's Lysekil Project [17], Duck wave energy converter [3], Aqua Buoy [18], Limpet [19], Wave Dragon [20], and many other are notable designs.

While more than a thousand WEC's have already been designed, there is still a need to develop WEC devices that are more efficient and economical with minimal environmental impacts. Although many factors influence the efficiency of WEC devices, one of the most important factors is the geometry of the device. A more precise design in geometry can enable efficient energy conversion from waves power. This study introduces a novel concept of a WEC device referred to as a Resonator; this device is inspired by natural wave pools ubiquitously referred to as "toilet bowls" and blowholes—a geological phenomenon formed as sea channels grow landwards into a water basin, which can result in a high pulsating current within the channel and a heaving water surface within the basin. The resonance of water inside the basin produced by asymmetry of its narrow water channel allows for the capture of Helmholtz mode of the waves, which is the dominant mode of oscillation as it consents the device to attract the most energy. Figure. 1 depicts an example of the toilet bowls within Hawaiian coastal region.

In principle HWEC, operates similar to OWEC [21], in which the water oscillates in a chamber. However, the geometry of HWEC is designed to utilize the water velocity in the channel in order to extract power using a water turbine as a PTO. This design no longer results on high-pitched noise caused by the air turbine used in all OWC devices. The HWEC has a simple design, contains no moving parts except for PTO unit, requires low cast material, possesses a relatively small form factor, and the coastal location would lead to low power transition costs after conversion to electricity. Thus, it maximizes wave energy available for capture while minimizing maintenance and operational costs. The concept is perspicuous: the narrow channel, basin and specific connection between them along with specific geometry such that allow an augmented quantity of incoming wave power to be captured.

Fig. 1: Natural Resonator at Hanauma Bay, Hawaii.

In this study two different scale models are utilized; a $1/25^{\text{th}}$ scale device in a wave tank at the University of Hawaii at Manoa and a $1/7^{\text{th}}$ scale device at the Richmond Field Station of University of California, Berkeley. The surfaces elevation profiles were collected at various points to identify resonance conditions. Following this study, the $1/25^{\text{th}}$ scale device was observed with a two-dimensional Particle Image Velocimetry instrument (PIV) to determine the instantaneous velocity field through the channel of the model.

This paper is organized as follows. Section 2 presents the equations governed in this article. Section 3 presents the experimental set up and results. Lastly, Section 4 discusses the conclusion.

2. Governing Equations

The Helmholtz mode equations that govern this project utilize theoretical methods for tidal waves from studies by Doleman and Mass [22, 23]. This study experimentally validates the application of tidal generated waves' Helmholtz frequency toward wind-generated waves' Helmholtz frequency. Thus, the analysis given below will be helpful for future investigations. In Fig. 2, the top view of a basin is illustrated with maximum depth H and horizontal area A^* , which depends on Z^*/H the non-dimensional depth of water, and is connected to the sea by a narrow strait of width B and depth H . Z^* is the vertical coordinate which is measured from the mean-water level upwards.

Fig. 2: Top view of a basin with narrow channel

Maas carried out the theoretical method to examine the tidal Helmholtz resonance in the basin, assuming that the strait's length L , as well as the basin's length scale $A_0^{1/2}$, are much smaller than the tidal

wavelength in the basin, λ . Thus, the tidal wave travels through the basin momentarily, Here $A_0 = A_*(0)$. Equation (1) defines the wavelength that determine by the lunar semi-diurnal tidal frequency such that:

$$\lambda = 2\pi c / \sigma_e \quad (1)$$

Where σ_e is equal to $1.4 \times 10^{-4} \text{ rad s}^{-1}$ and “c” is the long-wave speed defined as Eq. (2):

$$c = \sqrt{gH} \quad (2)$$

Where g is the gravitational acceleration and H is the basin depth.

Turbulence and frictional effects are negligible for the case where the width of the basin is much greater than the width of the channel. However, this is not applied to Resonator by means of geometry and PTO in which the energy is extracted. This part can be further studied. In a relatively broad basin, since the external tide elevation at sea $\zeta_e(\sigma_e, t_*)$ is defined as a periodic function of time t_* , and the velocity and frictional effects are small, thus the momentum equations in the basin will reduce to the lowest order, stating that horizontal pressure gradients are equally negligible. Thus, the uniform Helmholtz modes are the dominant modes in the basin. In addition, the tide's state in the basin can be explained by a single time dependent parameter, like the surface elevation, ζ_i , or the volume. The excess of the volume contained in the basin is approximately given in Eq. (3):

$$V_* \equiv \int_0^{\zeta_i} A_*(Z_*/H) dZ_* \quad (3)$$

The change in the excess volume is a mass flux function that is defined in Eq. (4):

$$\frac{dV_*}{dt_*} = -u_0(H + \zeta_0)B \quad (4)$$

Where $u(x; t_*)$ is the depth-averaged flow and $\zeta_*(x; t_*)$ is the surface elevation within the strait. ζ_0 happens in the entrance of the basin ($x=0$). The flow through the strait, as derived from the momentum equation, is shown in Eq. (5):

$$\frac{\partial u}{\partial t_*} = -\frac{\partial}{\partial x} \left(g\zeta_* + \frac{1}{2}u^2 \right) - \frac{k}{\zeta_* + H} |u| u \quad (5)$$

Where Coriolis effects are ignored and k is a bed stress coefficient.

It was assumed that the flow is uniform downstream of the channel where the width increases due to the basin, and the elevation decreases linearly over the length of the channel. It was also assumed that the change in the surface elevation is much smaller than the depth of the system. Integration the flow equation along the length of the channel yields to Eq. (6):

$$L \frac{dU}{dt_*} = g(\zeta_i - \zeta_e) + \frac{1}{2}(u_i^2 - u_e^2) - L \frac{K}{H} |u| u \quad (6)$$

Where subscript “i” refers to a variable's value in the basin's interior whereas the subscript “e” refers to the exterior of the basin. After several simplifications the excess volume changes in the basin can be calculated as Eq. (7):

$$\frac{dV_*}{dt_*} = -uHB \quad (7)$$

There is a dynamic pressure difference between outflow and inflow, with the inflow proportional to the channel flow $u_i = (1-\delta)u$ and the $u_e = u$, where δ denotes an empirical proportionality constant and considering $u > 0$. Thus, for small δ we can rewrite $\frac{1}{2}(u_i^2 - u_e^2)$ as $(-\delta u^2)$ or $(-\delta |u|u)$. This pressure drop between inflow and outflow, the bottom friction in the channel, and wave radiation during the water oscillation in the basin all lead to a damping process in the Helmholtz oscillator. Due to this damping process, the length of the channel is effectively increased, as the water excess outside the strait takes part in the oscillation. Thus, the effective length becomes as Eq. (8):

$$L_E = L - \frac{B}{\pi} \left[\ln\left(\frac{\pi B}{\lambda}\right) + \Gamma - \frac{3}{2} \right] \quad (8)$$

In which $\Gamma = .5772$ signifies Euler's constant. Hence, the total oscillating fluid's mass increases and therefore the Helmholtz frequency decreases.

In a non-dimensionalized formula for Helmholtz frequency, that the assumptions are: $Z^* = H_z$, $\zeta_i = H\zeta$, A^* (Z^*/H) = $A_0(A(z))$, $V^* = A_0 H V$, thus, dimensionless excess volume is shown in Eq. (9):

$$V = \int_0^{\zeta} A(z) dz \quad (9)$$

Where, $\zeta_e = H Z_e$, and $t^* = t / \sigma_H$.

Thus, the tidal Helmholtz frequency is defined as Eq. (10):

$$\sigma_H^2 = gHB / A_0 L_E \quad (10)$$

Considering the scales and eliminating u by combining with the linear damping term and employing equation (10) into equations (6) and (7), the Helmholtz resonator due to excess volume $V(t)$ is derived such that is shown in Eq. (11):

$$\frac{d^2 V}{dt^2} + \zeta(V) = Z_e(\sigma t) - r \frac{dV}{dt} - \gamma \left| \frac{dV}{dt} \right| \frac{dV}{dt} \quad (11)$$

When the sea level oscillation within the basin is amplified with respect to its value at sea the basin will lose some energy by radiating wave back in to the sea. Here, $r = \sigma B / 2L_E$ denotes the radiation damping coefficient, and $\gamma = (\delta / L_E + k / H) A_0 / B$ signifies the aggregate of quadratic damping coefficients. The forcing parameters and damping parameters r and γ are independent quantities. Also, $\zeta(V)$ is the restoring term and it is a function of excess volume. The forcing by the external wave is shown in Eq. (12) and is characterized by its amplitude F and scaled frequency $\sigma = \sigma_e / \sigma_H$.

$$Z_e = F \cos \sigma t \quad (12)$$

This study experimentally validates the application of “tidal generated waves Helmholtz frequency” toward “wind-generated waves Helmholtz frequency”. Thus, the equations 11 and 12 will be helpful to model the physics of resonance for future investigations.”

The experimental work in this article validates the application of Helmholtz equations which is explained in previous section. In fact the experiments validate the application of tidal generated wave Helmholtz equations for wind generated wave resonance under the following assumptions:

- The square-root of the basin's area is much smaller than the wavelength of incoming waves.
- The effective channel's length is equal to the length of the channel.

- The Froude number can be applied to the Helmholtz resonance mode. This allows a geometric factor, λg , of 25 and 7 to be applied to the Helmholtz frequency, σ_H , scaling it by $\frac{1}{\sqrt{\lambda g}}$.
- The surface elevation for a progressive periodic wave is sinusoidal and is a function of position x and time t that is indicated in Eq. (13):

$$\eta(x, t) = a \cos(kx - \omega t) \quad (13)$$

Where a is the wave amplitude and $k=2\pi/L$ denotes the wave number. The angular frequency is $\omega = 2\pi/T$, where T is the wave period.

- The time averaged power of the incoming wave into the device of width W_f is shown in Eq. (14):

$$P_1 = \frac{1}{2} W_f \rho g \zeta_e^2 C_g \quad (14)$$

Where, C_g is the group velocity and $C_g = (gH)^{0.5}$.

- The power at the channel is defined as Eq. (15):

$$P_c = \frac{1}{2} \rho B H U^3 \quad (15)$$

- The power in the basin is calculated by Eq. (16):

$$P_2 = \frac{1}{2} W_f \rho g \zeta_i^2 \sigma_H. \quad (16)$$

- Thus, the ratio of power in the basin to the power of the incoming wave is defined as Eq. (17):

$$\frac{P_2}{P_1} = \left(\frac{\zeta_i}{\zeta_e} \right)^2 \sqrt{\frac{W_b B}{W_f H L}} \quad (17)$$

Where W_b is the length of a square shaped basin, assuming the square profile.

3. Experimental Setup and Results

As introduced earlier, the theoretical model above is examined through two different experiments, using wave gauges in wave tank for 1/25th and 1/7th scales, measuring the surface elevations of the waves by means of wave gauges and channel flow fields by means of PIV instrumentation. All the experiments are fully described and the results are clearly discussed herein.

3-1. 1/25th scale set-up

In the case of the 1/25th scale experiment, the wave flume was 0.15 m wide and sufficiently long for the experiment in order to allow waves to fully develop before interacting with the model. The channel width was 0.05 m and the water depth was 0.2 m. Views from the top and side of the proposed design are shown in Fig. 3, however this design is modified after the preliminary results.

Fig. 3: (a) Top-view and (b) side-view schematic diagrams of the 1/25th experimental setup.

Wave height was measured using three JFE Advantech high sensitivity capacitive wave level sensors (ACH-600RS) with a resolution of 0.1 mm (0.0001 m) and an accuracy of ± 0.03 mm (± 0.00003 m). Data collection was at a nominal 100 Hz. The third wave gauge (WG3) was positioned as the center of the basin to measure surface elevation within. The first wave gauge (WG1) was positioned at a distance greater than three water lengths from the wave maker and a wavelength multiple from WG3, measuring the fully developed incident wave height. The second wave gauge (WG2) was placed at the mouth of the channel to measure the surface elevation where flow encounters its first change. Comparing WG1 and WG3 measurements were used to determine the phase-shift between basin free surface and incident waves. Wave gauges locations are shown below in Fig. 4.

Fig. 4: Location of the three wave gauges

Periodic, linear, intermediate waves were produced using a computer-controlled wave maker in the flume. Target ocean wave periods of 4.5 to 7.5 seconds were scaled to 0.9 to 1.5 seconds using a geometric

factor of 25, and wave height was 20% of the water depth. The resonator basin channel was oriented parallel to the direction of travel of the incident waves. The transition of flow boundary from flume wall to channel wall was accomplished using angled winglets, whose lengths and related angles were varied. Using this set-up, two sets of experiments were conducted, and in each case the area of the basin was adjusted by moving a flat plate at the backside of the basin to match the Helmholtz resonance to the incoming wave frequency.

The first set of trials tested the full period range (0.9 to 1.5 seconds) with single winglet configuration and fix geometry of the basin. The purpose of this experiment was to determine the Helmholtz frequency of the HWEC. For each incoming wave, the distance between WG1 and WG3 are kept equal to the incoming wavelength. At Helmholtz frequency, the wave amplitude at the basin (WG3) is in phase with incoming wave (WG1) and the wave amplitude is maximized at the basin. The first trial resulted in correlation between the wave period and Helmholtz resonance. The second set of trials tested range of winglet angles with a static period of 1.4 seconds. The winglet angles ranged from 60 to 25 degrees, as measured from the flume wall. It was found that a lower reduction angle corresponded to a reduction of higher harmonics, allowing more energy to be transmitted to the basin.

The experiments above resulted in fabricating and testing the final device for 1/25th scale. This device has the lower reduction angle that means $\Theta = 30^\circ$ and also, the winglets are curved causing much more efficient device with lower energy dissipation. The final device diagram is shown in Fig. 5.

Fig .5: Top view of the length and angle of winglets

Figure 6 illustrates the correlation between experimental and theoretical Helmholtz frequencies. Much of the discrepancy seen may be attributed to viscous losses.

Fig. 6: Theoretical and Experimental Comparison of Helmholtz Mode.

As shown in the slope of the lines, the 29% increase in natural frequency of the basin can be attributed to increase the channel length affected by the winglets.

Finally, an obstruction was placed at the mouth of the channel to simulate a power take-off. The one-way gate was employed to induce exit flow past the location of the power take-off. Three different blockage ratios of 40%, 60%, and 80% of the channel cross-sectional area were used. These blockages did not significantly affect the dynamics of the system since no significant phase shifting occurred. However, it was seen that, the 80% blockage caused the greatest magnitude of reflected waves. This directly affected the energy transmitted and the flow velocity in the channel. Conversely, the 40% blockage had the smallest effect on flow velocity and resulted in the lowest magnitudes of reflected waves. More detailed results may be found in [24]

3-2. 1/7th scale set-up

Two wave gages were used in this setup. The first was positioned at a distance greater than three water depths from the wave maker, to measure fully developed waves, and one wavelength from the second wave gage, in order to determine phase shift between incidence waves and the basin free surface. The second wave gauge was suspended in the middle of the basin.

The wave periods tested were scaled using a geometric factor of 7, such that the target oceanic periods of 4.5 to 7.5 seconds were scaled to 1.7 to 2.84 seconds. The basin was built to resonate at 2.4 seconds,

therefore testing was done primarily at this frequency. The device was constructed using plywood panels on a frame of aluminum extrusions, with dimensions of 1 meter wide by 1 meter tall by 1.3 meters long and with the channel width of 0.3 meters and the winglet angles $\Theta=30^\circ$ that is resulted as the most efficient angle from previous experiment for $1/25^{\text{th}}$ scale. The device is shown in Fig. 7. Also the flume was 2.46 meters wide and 1.99 meters tall and adequately long for experiment.

Fig. 7: The experimental device at $1/7^{\text{th}}$ scale.

In addition to the goal of validating the theoretical model on a larger scale, these experiments examined the effect of angle of incidence on internal wave height. The basin was rotated by 15 degree increments from 0 degrees to 45 degrees relative to the flume wall. 0 degrees produced the greatest basin wave height, as expected. A plot of both incoming wave height and basin wave height for a 3 second period at 0 degrees can be seen in Fig. 8.

Fig. 8: 1/7th scale model of the Resonator with response plot.

For this scale, the ratio of power in the basin to incoming wave power [Eq. 17] reduces to $\frac{P_2}{P_1} = .5 \left(\frac{\zeta_i}{\zeta_e} \right)^2 = 4.5$.

It was found that power addition to the resonator basin decreased exponentially from 100% at $t=0s$ to 0% (steady state) at $t= 20s$. This is assumed to be due primarily to radiation and friction damping of the resonator.

The power ratio versus wave number data for each of the three angles of incidence is shown in Fig. 9. Again, it can be seen the energy absorption of the resonator saturate at around 20 wave cycles. It is thus between the interval of 1 and 20 wave cycles that a power take-off (PTO) should be engaged, so as to avoid energy extraction in a saturated system. Note that a PTO will affect the response and oscillation amplitude of the system—something to be investigated in further studies. More detailed can be found in [25]

Fig. 9: Power ratios of basin wave heights to incoming wave heights for three angles of incidence, from top to bottom: 0° , 15° , and 30° .

3-3. PIV experiment

A flow measurement technique known as 2D Particle Image Velocimetry (PIV) was used to determine the instantaneous velocity field through the scaled model. Use of optical measurement methods for flow measurement for scaled models has several advantages.

One advantage of optical measurements is the ability to measure flow without interference. Unlike mechanical measurement probes that occupy a space within the flow, optical methods view the flow through the implementation of tracers. Another advantage, in the case of optical measurements via PIV, is a flow field is established. This is useful for flow visualization as well as flow field quantification, unlike the flow visualization methods whose characteristics are solely qualitative.

For this experiment, it was essential to use optical methods of measurement because the small size of the model restricts the use of mechanical-type probes. Second, a flow field throughout the model's channel was sought to determine the HWEC effects when interfering with wave induced flow.

3-3-1. Experimental Equipment

The experiment was conducted using a commercially available PIV system from TSI, Incorporated. The components of the system were the laser, camera, synchronizer, and software.

The laser subsystem was a pulsed Dual Nd: YAG laser operating at 532 nm. The laser emits 100 mJ/pulse for a duration of 6 ns. The flashlamps of laser operate at a maximum frequency of 15 Hz. The dual laser system allows the system to then sample at 30 Hz as the two lasers operate in an alternating pulse pattern.

The PowerView HS-560 camera was used. The CCD array allows for 1280 x 1024 pixel images (1.3 mega pixels). The pixel size is 12 μm (H) x 12 μm (V), allowing for an image size of 15.4 mm (H) x 12.3 mm (V). The frame straddling interframe time of this camera model has a minimum of 75 ns, sufficient for these experiments.

The lens used was a Sigma 105mm F2.8 macro lens. The magnification of the lens is 1:1 and provides the appropriate particle clarity and depth of field for the desired results.

The synchronizer was TSI's LaserPulse Synchronizer model number 610035 which allows the computer to interface with the dual laser system, camera, and computer.

The software used was Insight 3G for data acquisition and analysis. Tecplot and Matlab were also used for processing the data provided from Insight 3G.

Additional equipment used was a light arm, cylindrical lens, and spherical lens. The light arm allowed the laser sheet to be oriented in any manner required by routing the laser through a fiber channel. The cylindrical lens used had a -50 mm focal point. The spherical lens used had a focal length of 200 mm.

3-3-2. Experimental Method

A diagram of the experimental setup is shown in Fig. 10. The optical method of 2D PIV utilizes a thin laser sheet to illuminate the 2D plane under investigation. However, water is transparent so tracer

particles were required to diffract laser photons to the camera. The tracer particles used were neutrally-buoyant silver-coated glass spheres. Seeding particles mixed in the fluid are illuminated when passing through the laser sheet.

Fig. 10: PIV Experimental Setup

The photons are captured by a 1.3 megapixel CCD camera with a line of sight orthogonal to the light sheet. The camera exposure straddled the laser pulse in order to determine the direction of the particles resulting in two images per frame. The scaled model was fabricated from plexiglass. The model was transparent and allowed the camera to view directly into the channel capturing the flow field.

3-3-3. Experimental Conditions

The model was 50 mm in width at the channel. The light sheet was positioned in the middle of the channel such that light sheet was parallel to the channel walls. The light sheet was produced from an 8 mm laser beam emanating from the laser housing.

The laser beam was modified using a cylindrical lens and spherical lens, respectively. The cylindrical lens diverged the laser beam in one direction (height) while maintaining the beam dimension in the other direction (width). A light sheet of approximately 40 mm was created using a -50 mm cylindrical lens. The spherical lens determines the focal distance of the waist, the minimum laser thickness (<1mm). The spherical lens used had a focal length of 200 mm.

The seeding of the fluid was accomplished using silver-coated glass spheres. The mean thickness of these spheres was 10 microns and a specific gravity of 1.03, very similar to the fresh water used for the experiment. Because the two materials were close in specific gravity the translations of particles due to buoyancy was small relative to the translation due to the waves.

The camera's lens aperture ($f/\#$) that f is focal length and $\#$ is f-stop set to 100/16. This yielded a diffraction limited spot size of 20.8, based on $Diff\ Spot = 2.44 * \lambda * f/\#$ where λ is the laser

wavelength, $f/\#$ as discussed is the lens aperture, and Diff Spot is the resulting diffraction limited spot size. The depth of field is expressed as $DOF = 2 * D^2 * \frac{\beta}{A}$ where D is the object distance, A is the lens aperture, and β is the angular blur defined as $\beta = \frac{B}{\text{ImgD}}$ where ImgD is the image distance and B is the acceptable blur size on the CCD chip. The image calibration was determined to be $198.8 \mu\text{m}/\text{pixel}$

The wave periods under investigation ranged from 0.9-1.5 seconds. This period range was determined through the use of the geometric scaling factor of 25. The water depth was a constant 200 mm for all tests and the wave height was a constant 20 mm for all periods.

Figure 11 shows a snapshot of the $1/25^{\text{th}}$ scale results during the PIV experiment. This image corresponds to period of 1.5 seconds for a basin length of 220 mm.

Fig. 11: Top view and side view of device, the bottom figure is PIV image for $T = 1.5$ Sec.

The PIV camera is able to record the velocity vectors, and provide us sufficient information to meaningfully interpret the results. The images of group velocity vectors at constant wave length with a period of 1.5 second are shown in Fig. (12-a -12-h) for a short range of times.

408

Fig. 12-a: Velocity vectors after 1/6 sec.

Fig. 12-b: PIV Velocity vectors after 1/3 sec.

Fig. 12-c: Velocity vectors after 1/2 sec.

Fig. 12-d: PIV Velocity vectors after 2/3 sec.

Fig. 12-e: Velocity vectors after 5/6 sec.

Fig. 12-f: Velocity vectors after 1 Sec.

Fig. 12-g: Velocity vectors after 1 1/6 sec.

Fig. 12-h: Velocity vectors after 1 1/3 sec.

It may be observed that the direction of the velocity vectors reverses between $\frac{1}{2}$ seconds and $\frac{2}{3}$ seconds, and again between $1\frac{1}{3}$ seconds and $1\frac{1}{2}$ seconds, at the instances when average velocity is zero. Maximum velocity is seen to occur at $\frac{5}{6}$ seconds with a magnitude of 0.48 m/s, occurring exactly at a time equal to $T/2$, and at a distance of 0.1 meters from the water surface.

Additionally, the maximum magnitude of average velocity occurred at the same time, with a value of 0.19 m/s. The curves for maximum and minimum particle velocities over time, plotted along with the curve for average velocity in the channel over time, are shown in Fig. 13.

Fig. 13: Average velocity in whole channel, and maximum particle velocity at each instantaneous time in the channel

Figure 13 also illustrates the result that, when the system approaches Helmholtz resonance, the two velocities follow expected behavior such that their peak values coincide at the appropriate time, a small shift between them is because of flow velocity. However, when the system is not at resonance, the two velocity measures do not agree. In this case, the average velocity does indeed show the entire water mass oscillating back and forth, in addition, the particles' maximum velocity in the same frequency as the average velocity. Experimenting with the Helmholtz resonance basin has illustrated a means of increasing magnitude of average velocity of the system, corresponding to an increase in available power to be extracted.

In addition, in Fig. 14 the axial velocity as a function of the water column(Y) is shown. By inspection of the data, the location of the optimal axial velocity profiles occur 10% into the channel measured from the side of incident waves. It can be seen that the maximum velocity consistently occurs at 40% of the water column as measured from the bottom boundary; a significant observation is that the exit flow from the basin yields a greater velocity than the entrance flow, an effect of the basin resonance which has the potential to yield more power for extraction.

Fig. 14: Average velocity in whole channel, and maximum particle velocity at each instantaneous time in the channel

4. Conclusion

The application of the theory of Helmholtz resonance used for wind-driven ocean waves was explored in both 1/25th scale and 1/7th scale experiments, and in both cases the experiment supports the theoretical conclusions of Section 2. The 1/25th scale device was tested with a two-dimensional Particle Image Velocimetry instrument (PIV) to determine the instantaneous velocity field through the scaled model. The first two PIV experiments demonstrated the sensitivity of the device to the channel's width and the basin area. The area of the basin had to be adjusted to match the Helmholtz resonance of its geometry to the

incoming wave frequency. Fluid boundary from flume wall to channel wall transitioned through the utilization of winglets, with the winglet angle affecting the performance of the device such that for angles above 30 degrees (relative to the flume wall), the performance of the device declined, causing flow to change abruptly and leading to larger amplitude of reflected waves at the face of the channel, thereby reducing wave energy transmitted to the basin. It was also found that curved winglets allowed for a much more efficient device with lower energy dissipation.

Channel blockages of 40%, 60% and 80% yielded expected results whereby the lowest blockage had the smallest effect on flow velocity and caused the lowest magnitude of reflected waves, suggesting highest performance gains when a turbine is implemented and the channel is partially blocked.

Resonance in the channel resulted in an amplification of wave height in the basin relative to incoming waves, and thus a corresponding amplification of power within the basin. This suggests that the power take-off (PTO) should be engaged in the part of the channel where the system isn't saturated, rather than where the ratio of amplified waves in the basin to incoming waves is no longer increasing.

Three different angles of attack, $\beta = 0^\circ$, 15° , 30° as measured between the WEC axis and incoming wave direction of travel were tested, with the ideal power ratio found to occur at $\beta = 0^\circ$, as expected. The power ratio in this case is 4.5, which is 1.6 times greater than $\beta = 15^\circ$ and 3.75 times greater than $\beta = 30^\circ$. Thus, the basin must be placed with the WEC axis parallel to the incoming waves for best performance.

The last experiment that utilized the two-dimensional Particle Image Velocimetry instrument (PIV) was carried out with the following results: The average velocity was plotted along with the maximum and minimum particle velocities over time. The instant of maximum average velocity, and corresponding maximum current and maximum power, were compared to the instants when maximum and minimum particle velocities peak. An analysis of all collected data indicated that the location of maximum velocity occurred at the middle height of the channel, suggesting an ideal location for PTO placement.

5. Acknowledgement

We would like to express our gratitude to the Renewable Energy and Island Sustainability (REIS) program, which is funded in part by the US Department of Energy Grant, DE-OE0000394. Also, we are grateful to Tyler Thornbrue for editing this article.

6. References

- [1] Clement, A., 2002, "Wave energy in Europe: current status and perspectives". *Renewable and Sustainable Energy Reviews* 6 (5): 405–431.
- [2] Masuda, Y., 1972, "Study of Wave Activated Generator and Future View as an Island Power Sources," 2nd International Ocean Development Conference.
- [3] Salter, S.H., 1974, "Wave Power," *Nature*., 249:720-723.
- [4] Mei, C.C., 1976, "Power Extraction from Water Waves," *Journal of Ship Research*., 20(2):63-66.
- [5] Mei, C.C., and Newman, J.N., 1979, "Wave Power Extraction by Floating Bodies," *Symposium on Ocean Wave Energy Utilization*., 1-28.
- [6] Mei, C.C., 1989, "The Applied Dynamics of Ocean Surface Waves," *World Scientific*.
- [7] Falnes, J., and Budal, K., 1978, "Wave-Power Conversion by Point Absorbers," *Norwegian Maritime Research*., 6(4):2-11.
- [8] Falnes, J., 2007, "A Review of Wave Energy Extraction," *Marine Structures*., 20:185-201.
- [9] Newman, J.N., 1977, *Marine Hydrodynamics*, M.I.T, Press.
- [10] Budal, K., and Falnes, J., 1978, "Wave-Power Conversion by Point Absorbers," *Norwegian Maritime Research*., 6(4):2-11.
- [11] Evans, D.V., 1976, "A Theory for Wave-Power Absorption by Oscillating Bodies," *Journal of Fluid Mechanics*., 77(1):1-25.
- [12] Evans, D.V., 1979, "Some Theoretical Aspects of Three-Dimensional Wave-Energy Absorbers," *Symposium on Ocean Wave Energy Utilization*., 78-112.
- [13] Fujita, R.M., and Pelc, R., 2002, "Renewable Energy from the Ocean," *Marine Policy*., 26:471-479.
- [14] Drew, B., Plummer, A.R., and Sahinkaya, M.N., 2009, "A Review of Wave-Energy Converter Technology," *Journal of Power and Energy*., 223:887-902.
- [15] Yemm, R.9. (2008). "Full-scale WECs: Pelamis. in *Ocean Wave Energy* ". (J. Cruz, ed.), pp. 304-321.
- [16] Aquamarine Power. Available from <http://www.aquamarinepower.com/> (access date April 2013).
- [17] http://www.el.angstrom.uu.se/forskningsprojekt/WavePower/Lysekilprojektet_E.html (access date April 2013)
- [18] Wachter, A. Neilsen, K. (2010). "Mathematical and Numerical Modeling of the Aqua Buoy Wave Energy Converter". Volume 2, pp. 16-33.
- [19] Limpet, http://www.wavegen.co.uk/what_we_offer_limpet.htm (access date April 2013)

- [20] (WA 2013) Wave Dragon. Available from <http://tinyurl.com/wavegen1/> (access date April 2013).
- [21] Evans, D.V. 1978, "The Oscillating Water Column Wave-Energy Device," J. Inst. Math Applies 22,423-433.
- [22] Doelman, A., and Koendrink, A., and Maas, L.R.M., 2002,"Quasi-periodically forced nonlinear Helmholtz Oscillatots," Physica D: Nonlinear Phenomena., 164 (1-2), pp.1-27.
- [23] Maas, L.R.M., 1997, "On the nonlinear Helmholtz response of almost-enclosed tidal basins with sloping bottoms," J. Fluid Mech., 349, pp. 361-380.
- [24] Saadat, Y., Fernandez, N., and Ghorbani, R. 2013, "The Wave Energy Converter Based On Helmholtz Mode, Inspired By nature," 32nd international conference on ocean, offshore and arctic engineering, Nantes, France.
- [25] Saadat, Y. Fernandez, N. Samimi, A. Alam, M. Shakeri, M. Ghorbani, R. 2013 "Helmholtz Resonance Mode For Wave energy Extraction". 10th European wave and tidal energy conference, Alaborg, Denmark 2013.