A Parametric Experimental Study of the 2D Performance of a Ducted Wave Energy Converter

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Abstract

Offshore Wave Energy Limited's "OWEL" wave energy converter is a novel design that uses the forward surging motion of deep water waves to capture and compress air. Uni-directional compressed air flow is used by the device to drive a turbine and generator to produce electricity. Previous experimental studies provided useful initial information about the general operating principles and basic trends in device performance. This paper serves as a progress update of the small scale, 2D experimental work being carried out at the University of Southampton. Testing has investigated the relationships between device performance and wave characteristics as well as trialling a series of different geometric configurations of the model.

Keywords: Wave Energy, OWEL, Experimental, Small Scale Model

Nomenclature

OWEL = Offshore Wave Energy Limited
P = Wave power (kW/m)
β = Orifice constriction ratio
T = Wave period (s)
H = Wave height (m)
Q = Air flow rate ($m^3 s^{-1}$)
C_D = Orifice Coefficient of Discharge
P = Pressure ($N m^{-2}$)

1 Introduction

Numerous wave energy converters operate using air as an intermediate in the generation of electricity. Various different oscillating water columns for example have been developed over the past few decades but few have performed to expectation. The majority of these types of devices have been designed to capture lower energy, shallow water waves.

The "OWEL" wave energy converter has a novel design that uses the forward surging motion of waves captured within a duct to compress air. The device is designed to operate offshore to capture high energy, deep water waves and it is hoped to overcome some of the limitations experienced by other devices. A number of ducts could be combined to form a single platform, on a similar scale to 'Wave Dragon' [1], as this would provide more stability and higher capacity.

Previous 1:10 and 1:100 scale model tests have been performed with promising outcomes. The results and findings have been used to validate various mathematical models [2] and to develop a better understanding of the hydrodynamics. This has helped to optimise the design of the device however, for further optimisation a better understanding of the fundamental principles is required.

Small scale 2D model testing has been carried out in a wave tank at the University of Southampton. Preliminary results were reported by Leybourne et. al [3] and highlighted trends in performance which enabled the design of a more thorough round of testing. Experiments commenced in late 2008 with the intentions of using the model to fully determine the relationships between wave characteristics and the device hydraulic - pneumatic efficiency. A series of different geometric configurations were also tested to examine their effects on performance.

2 Principle of Operation

The converter is essentially a floating duct which is open at one end to capture incident waves. The sides and floor are angled inward to induce a rise in wave height within the duct. As a wave enters the device, it creates a seal with the roof creating a trapped pocket of air ahead of the wave front. As the wave progresses, the air is compressed and passes through a non-return valve and most likely into a pressure reservoir where it can be stored. A schematic of this process is shown in figure 1. This proposed method will generate uni-directional air flow meaning standard air turbines can be used instead of the less efficient bi-directional turbines used in oscillating water columns.

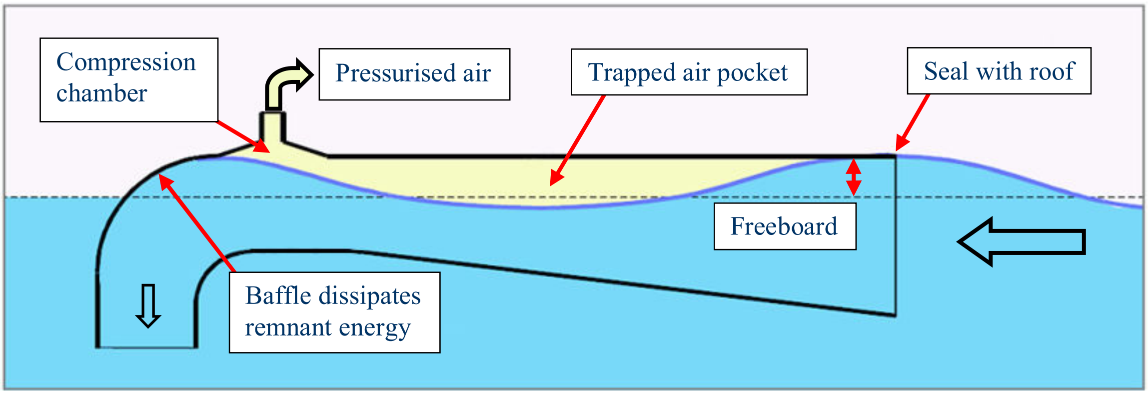


Figure 1: Schematic of the device operation.

3 Experimental Methodology

Testing Facilities

The model was tested in a narrow wave tank at the University of Southampton. The tank was 15m in length, had a water depth of 0.7m and a width of 0.42m. The model was fixed in the water at 8m downstream of the wave-maker to ensure waves were fully developed when arriving at the duct mouth. The support system allowed the model to be raised and lowered to vary the freeboard. Wave period and height were measured using two resistive wave probes ahead of the model.

Model

The model was constructed using clear Plexiglas for the side walls, floor and roof and aluminium sheet for the baffle. Figure 2 shows the completed model in the wave tank during a test. A plastic cone was used for the 'compression chamber' which exited into a straight Perspex pipe. The pipe contained an orifice plate arrangement which was used to simulate the power take-off and measure air flow out of the model. To represent a 2D case, the duct spanned the entire tank width and did not have inclined side walls which would be found on a 3 dimensional device.

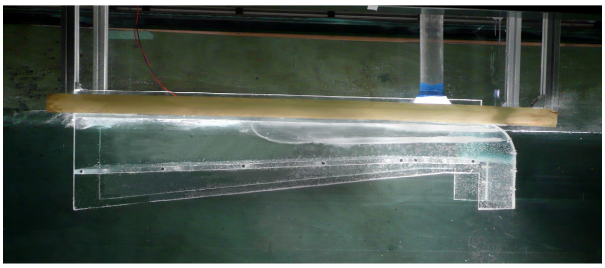


Figure 2: Model being tested in the wave tank with a wave travelling along the duct.

Power Take-off

The power take off was modelled using a simple orifice arrangement. Orifice plates are fairly common practice having been implemented previously to model power take off systems on small scale OWC tests such as those reported by Sarmento [4] and Forestier et. al.[5].

The orifice was employed to provide a purely comparative measure of performance and was not, at this stage, intended to simulate a full scale power take off as this was deemed beyond the scope of these tests.

The British Standard [6] for measuring flow with orifices was used to specify the arrangement of the orifice assembly and is summarised in figure 3. The most suitable orifice tested had a constriction ratio of 0.4 of the pipe diameter and was cut into a single brass plate. It was centred in the Perspex pipe and positioned 5 pipe diameters downstream of the compression funnel to ensure steady flow. Two pressure tappings were positioned either side of the plate and a differential pressure transducer was connected across them to measure the pressure drop across the orifice.

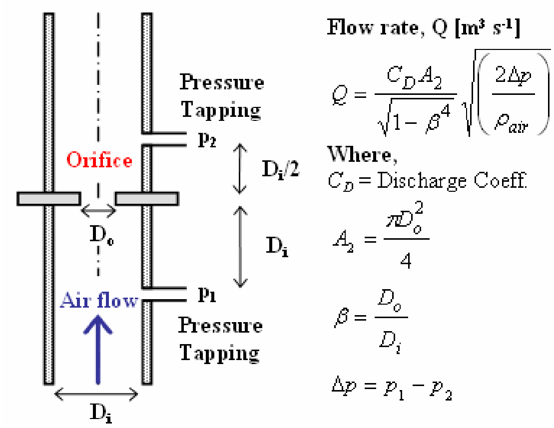


Figure 3: A summary of the orifice arrangement with related equations and notations.

Experimental Procedure

The wave spectra used in the tests was derived from Orkney wave data recorded by EMEC [7] over a 14 year period. Figure 4 is a contour plot showing the typical available yearly wave energy distribution per metre width of wave crest. This has been plotted in terms of wave height and wavelength, non-dimensionalised by characteristic device lengths scaled at 1:56 from the model dimensions. The suggested testing conditions from HMRC [8] were also taken into account and included in each run. To achieve greater detail, models were tested with up to 300 different

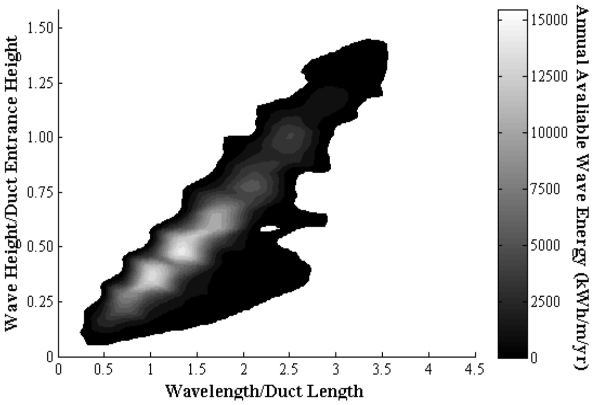


Figure 4: Typical yearly wave energy available at Orkney [7]

waves with periods ranging from around 0.5 – 2.2 seconds.

A number of different scales for the wave regime were considered and examined during the testing including 1:80, 1:36, 1:16 and 1:56. The intentions were to match the device peak performance to the peak available energy and key wave type at a typical North Atlantic site such as that in Orkney.

A series of different model configurations were tested all with the intention of reducing the wave reflections in the device. Other alterations thought to improve performance were also examined. In total, 7 different geometric model configurations were tested.

The full scale converter will feature adjustable ballast tanks allowing the freeboard to be varied to match the incident wave conditions. Three different freeboard levels were tested for some of the model configurations to investigate the concept of matching the freeboard to suit wave height.

Tests were run using an automated system which, for the most extreme example, allowed a set of 300 different wave types to be tested in around 18 hours.

4 Results

Device power output was calculated from the product of the pressure differential across the orifice and the air flow rate through the orifice. Performance was determined by the duct's hydraulic – pneumatic efficiency, deemed as the ratio of air power to incident wave power, where wave power is given by equation 1.

$$P_{wave} = \frac{\rho_{water} g^2 H^2 T}{32\pi} \quad \textbf{(1)}$$

Due to the large size of the data sets, contour plots appeared the most convenient way of comparing different experimental parameters. It was also useful to plot the axes with wavelength and wave height non-dimensionalised by the model's characteristic lengths of duct length and entrance height respectively.

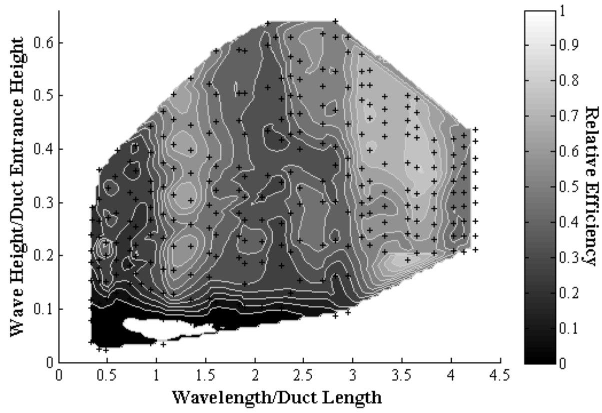


Figure 5: Performance contour plot for model configured with a small freeboard height.

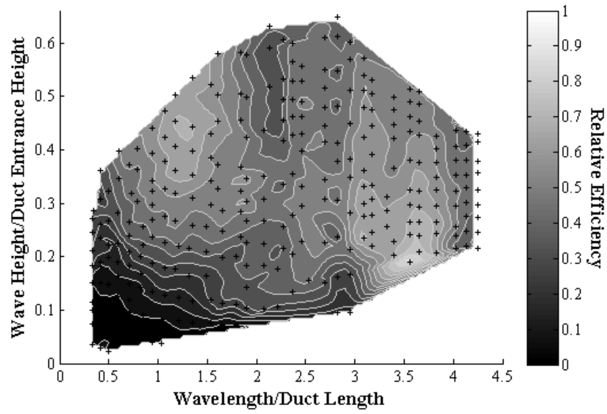


Figure 6: Performance contour plot for model configured with a moderate freeboard height.

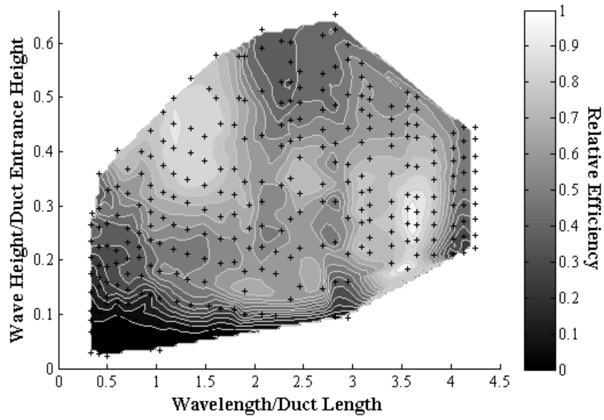
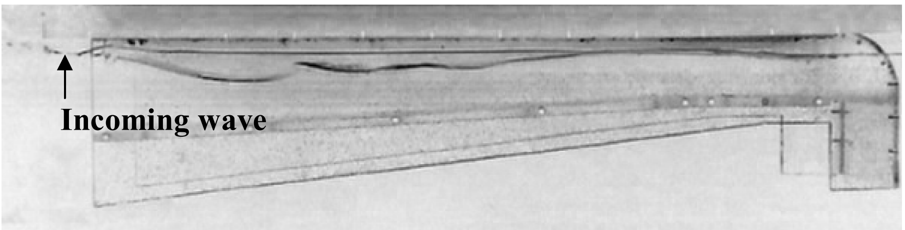
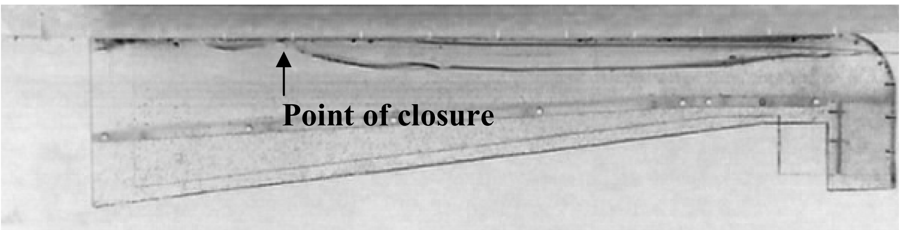


Figure 7: Performance contour plot for model configured with a large freeboard height.

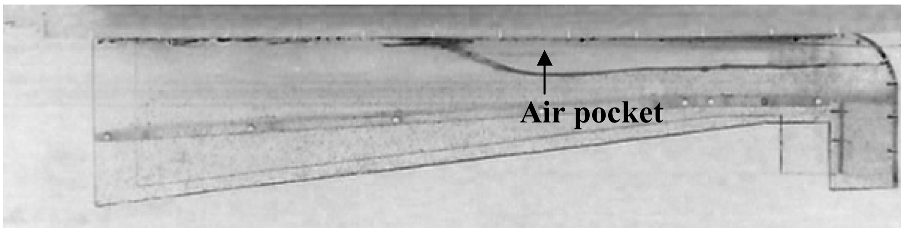
Figures 5 - 7 show the results for one particular model configuration tested with 3 different freeboard heights over a large range of waves. The efficiencies have all been non-dimensionalised by the maximum efficiency recorded within the three presented data sets. It is clear from the three plots that two regions of peak performance exist: One between wavelength to duct length ratios of 1 to 1.5 and the other at longer wavelengths at around a ratio of 3.5.



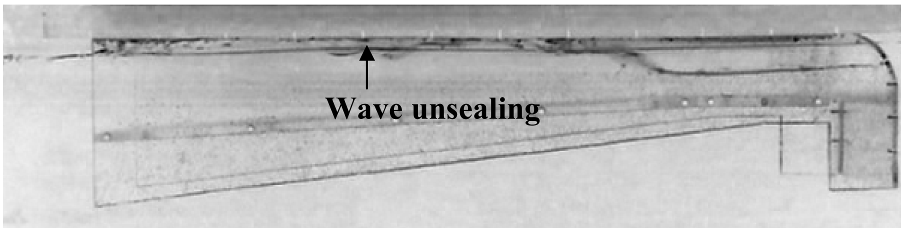
Frame A. Incoming wave prior to first closure – (Time = 14.1 sec)



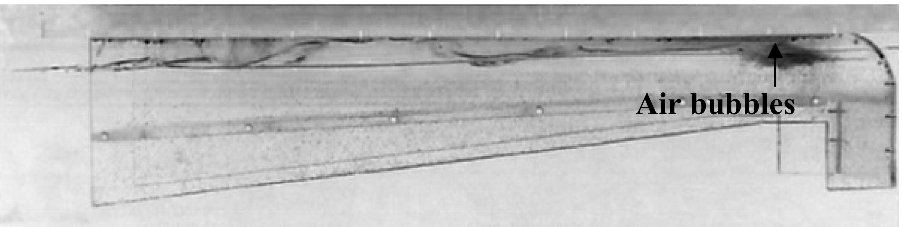
Frame B. Wave just sealed at front of duct – (Time = 14.4 sec)



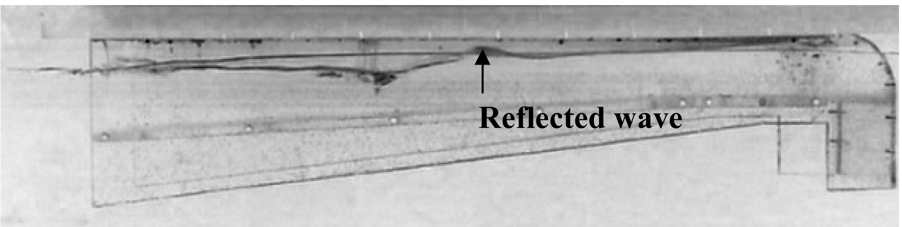
Frame C. Sealed wave front half way along duct – (Time = 14.8 sec)



Frame D. Wave beginning to un-seal at the duct entrance – (Time = 15.1 sec)



Frame E. Reflected wave delays the unsealing – formation of air bubbles at the baffle end (Time = 15.4 sec)



Frame F. Reflection passing back through the duct – (Time = 15.8 sec)

Figure 8: Series of 6 frames (A-F) over a wave cycle showing the sealed wave passing into the duct. (Wave Height / Duct Entrance Height = 0.4 and Wavelength / Duct length = 3.85)

The plots show that the device performs well over a fairly broad range of wavelengths and wave heights. For this model configuration, a larger freeboard generally gave the greatest performance as waves were able to compress a greater volume of air rather than over topping the duct. This indicates the need for the full scale device to have a variable freeboard in order to optimise the volume of air available to the incident waves.

In addition to the numerical results, a number of the runs were filmed at 30fps to gain a better insight into the shape of the wave front as it passed through the duct. Figure 8 shows a series of sample frames (A-F) taken from a wave case with a relatively long wavelength and moderate height. It can be seen that for these conditions the wave creates a good seal with the duct roof. The stills also show, fairly clearly, the behavioural characteristics of the wave in the duct.

If the model scale is considered to be between 1:50 and 1:60, it allows the region of peak performance to be shifted to match the region of available energy. For example, figure 4 shows that the greatest wave energy is provided by waves with a wavelength to duct length ratio of between 1 and 1.5 and a wave height of around half of the duct entrance height. Comparing this with figure 7 shows that the first region of peak performance coincides with the maximum energy available. Similarly it is also possible to alter the scale so that the second area of peak performance coincides with the maximum energy.

It was initially thought that wave reflections from the baffle at the end of the duct were detrimental to the device performance. However, after trialling various designs to reduce wave reflections, it was found that the reflections aid the resonant characteristics of the device and actually increase performance. It is thought that at duct resonance, the wave reflections cause constructive supposition with the incident waves thus increasing wave height within the duct, creating a better seal with the roof.

OWCs with a pneumatic power take off have an optimum power take-off impedance, as shown by Falnes [9]. To examine the sensitivity of the device to impedance different orifice sizes were tested. It was found that the device has a high sensitivity to power take-off impedance therefore it is intended that the next experimental study will determine the optimum impedance.

Overall, conversion efficiencies have been significantly improved over previous testing. One model configuration, for example, performed 93% better than the original baseline design for the same wave conditions.

These results will be used to design a series of tests to be conducted in a wave basin, for an intermediate scale, multi-duct model.

5 Conclusions

A successful test schedule has provided a valuable set of results. Peak efficiencies were significantly improved over previous testing and it is hoped that the knowledge gained in these tests will result in further improvements in other scale tests in the future.

Wave reflections from the baffle aid the resonant characteristics of the duct and lead to increased performance.

Resonant regions of peak performance have been identified.

Peak performance occurs for wavelengths between 1 - 1.5 duct lengths and 3.5 – 4 duct lengths and for waves that are 0.25 – 0.5 of the duct entrance height.

The results have provided useful information for designing future models and show that the OWEL is a promising WEC for use as a large scale offshore device.

Future Work

A number of steps have been highlighted necessary for the future progression of the OWEL project. The foremost task is to model the device using CFD and validate the simulation using results from the set of experiments reported in this paper.

Using the knowledge gained from the experimental and CFD results, a 3D wave basin test study will be undertaken. This will examine both fixed and floating models under regular and irregular wave regimes. The purpose of these tests will be to measure performance and loads on the structure for the different wave conditions.

It is then likely that a mathematical model will be developed to scale up results with the main project aims of creating a sea-going demonstrator to help create a full scale design and techno-economic model.

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