Experimental and Computational Modelling of the OWEL Wave Energy Converter

M. Leybourne[1], W. Batten[1], A.S. Bahaj[1], N. Minns[2] and J. O'Nians[2]

[1] University of Southampton, Sustainable Energy Research Group
School of Civil Engineering and Environment
Southampton, SO17 1BJ. UK
E-mail: `mark.leybourne@soton.ac.uk`

[2] IT Power Ltd.
St Brandon House
29 Great George Street
Bristol, BS1 5QT. UK
E-mail: `ned.minns@itpower.co.uk`

Abstract

This paper presents the findings of the experimental testing and computational modelling of a novel, ducted wave energy converter known as OWEL. Extensive wave basin testing was conducted with a floating, multi duct model at around 1:100 scale. Measurements of performance, motions, structural and mooring loads were taken in order to inform the design of a future device demonstrator.

A simplified device configuration was computationally modelled using ANSYS CFX. This comprised a single, stationary duct and was run with various monochromatic waves relating to those tested in the wave basin study. The model was validated using the results from the experimental testing. Simulations were used to predict the full scale output of a multi-megawatt OWEL device.

The results from this phase of the development of OWEL demonstrate the potential of the device and are being used to design a benign test site demonstrator that is hoped to be deployed within the next few years.

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

1. Introduction

The OWEL (Offshore Wave Energy Limited) wave energy converter is a floating, moored device designed to be deployed in highly energetic deep water locations. The device concept has been in development for a number of years and is now at an important stage in its progression. To date two stages of research have been completed, these completed steps have proved the concept and its ability to scale giving the confidence to continue the research programme.

The work reported in this paper is the result of a 12 month project supported by the South West Regional Development Agency (SWRDA). This latest phase of development follows on from the previous testing and research programmes [1-2] and had the overall specific aim of generating an accurate Techno-Economic model for a large scale OWEL device. The discussion presented here however, focuses largely on the technological aspects of the latest development.

The dominant aspect of the project was the extensive wave basin testing which was designed to assess the performance of a small scale, multi-duct model over a range of both idealised and scaled, realistic conditions. Results from these experiments fed directly into the creation of the techno-economic model and are central in the design of the large scale, ocean demonstrator.

The initial experimental testing was conducted by Leybourne et. al. [3] at the University of Southampton and studied a number of wave conditions and geometric configurations of a simplified model in a 2D wave flume. The tests determined the optimum geometric configuration of the duct and identified the relationships between the duct length and wave period to access the regions of peak performance. These results were directly used to inform the design of the 3D basin model.

A computational model was developed in parallel with the basin testing and was by the 3D physical test results. The model was used to investigate the effects of scale on the performance for a number of different sized geometries. These results were also incorporated into the techno-economic model in order to help estimate scaled output. Work is ongoing to further advance the model and improve the agreement between the computational and experimental results.

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

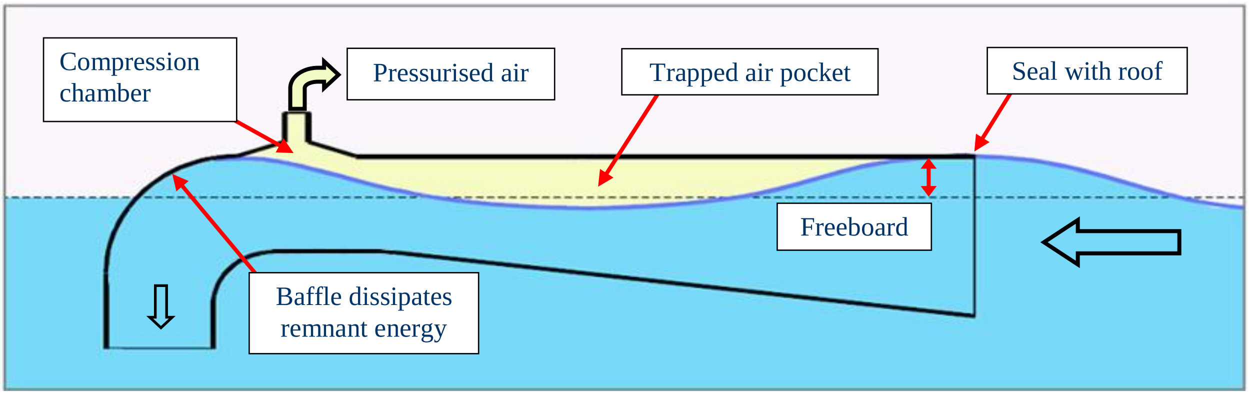

Figure 1: Schematic of the device operation.

air is compressed and passes through an exit pipe to the power take-off system. A schematic of this process is shown in Fig. 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.

3. Wave Basin Testing

The main objectives of the basin testing were to;

1. Assess performance sensitivity to parameter changes such as fixed/floating model.
2. Confirm calculated resonant periods of the motions
3. Produce results to validate numerical models
4. Generate scalable power data

Experimental Set-Up

Experimental testing of the 5 duct, ~1:100 scale OWEL was carried out at the Hydraulics and Maritime Research Centre (HMRC) in Cork, Ireland. Testing occurred over two periods in October and December 2009, with a break for initial analysis to help better utilise the second testing period.

The testing programme was designed using guidance from work by Holmes [4] and split into two phases of investigation; fixed and floating conditions. The fixed tests were used to assess the performance and characteristics of the model under idealised conditions.

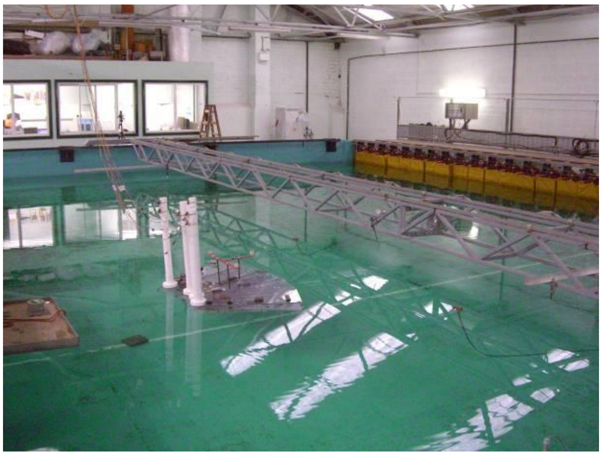

Figure 2: Floating model in the wave basin at HMRC, Cork

The floating model provided information about how the device would perform under a more realistic environment with scaled Bretschneider sea states. The HMRC wave basin is 25m long, 18m wide and 1m deep therefore, able to produce a mixture of intermediate depth and deep water waves. The wave generation system consists of 40 flap type, wedge shaped aluminium paddles attached to the 18m side of the tank.

Both mono- and polychromatic seas were able to be generated by the wave makers. Spreading functions applied to the input wave spectrum allowed short crested, directional seas to be produced, best representing real sea conditions.

The model was positioned in the centre of the tank as shown in Fig. 2. For the static tests, a rigid metal frame with adjustable height was used to hold the model in place. A scaled and slightly simplified mooring system was used for the floating tests.

As with previous experimental testing of OWEL, orifice plates were used to simulate a power take-off in order to calculate pneumatic power. The orifices were positioned in the white exit pipes 10D downstream of the compression chamber to ensure a more steady flow.

Four types of instrumentation were used:

- Differential pressure sensors to measure the pressure drop across the orifice plates in the exhaust pipes in order to calculate pneumatic power.
- Strain gauges to measure the deflection of components of the model and calculate structural loads.
- Load cell to measure mooring forces.
- Motion sensor system to record the motions of the floating platform.

Fixed Tests

The first testing phase was designed to characterise the device in simple terms using monochromatic waves and to provide data to validate the computational model. Results were also used to compare with the previous 2D flume tests in order to assess the impact of multiple ducts and 3D effects on performance.

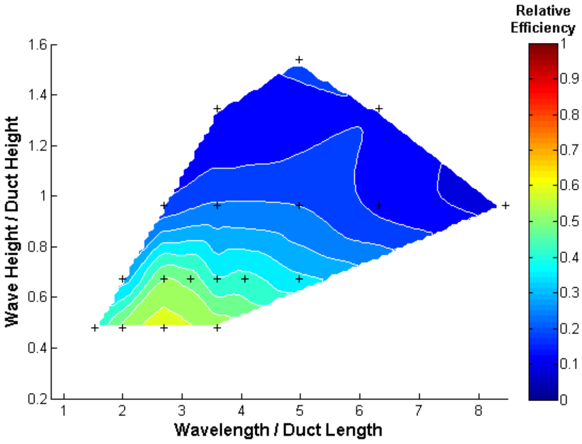

Figure 3: Performance contour plot for fixed model with monochromatic waves.

The pneumatic conversion performance of the model is presented here in the form of contour plots in order to make the large amount of data readily comparable. The plots in Figs. 3 to 6 show efficiency data for one of the ducts in the platform, for four different tests each with around 20 sea states. The pneumatic efficiency is displayed relative to the maximum efficiency recorded in these four tests. The axes are characterised by the duct length and entrance height to provide useful design ratios.

Fig. 3 shows the performance of the model with monochromatic waves whilst it was rigidly fixed in the tank. Peak performance occurs at a wavelength to duct length (λ/DL) ratio of around 2-3. An image showing this configuration under test is shown in Fig. 7. In general, it was found that performance was decreased in comparison to the 2D model. The basin model was smaller than the flume model and suffered more from the effects of surface tension. For this reason, the freeboard and orientation of the model with the free surface could not be set correctly. This led to a reduction in the compression available and more significant impact from viscous losses. The surface tension effects were even more problematic for the floating tests as the model was frequently held to the water surface.

Fig.4 shows performance, again for a fixed model, but with polychromatic, short-crested sea states. It is clear that performance in short-crested seas for a fixed model was better than for regular waves. For many of the sea states, the spectral components present contained waves with periods that coincided with the device's natural period, meaning performance was increased across a wider range of wave periods.

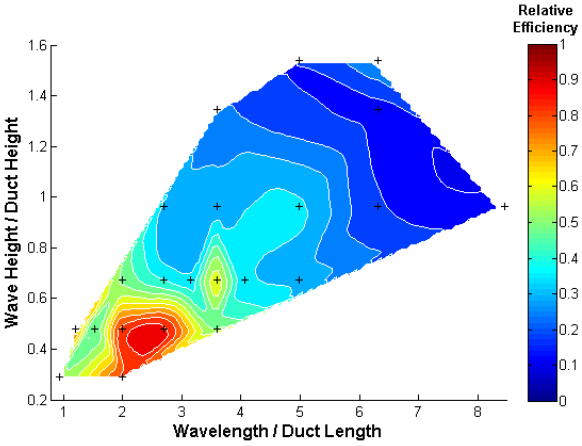

Figure 4: Performance contour plot for fixed model with directional, polychromatic waves.

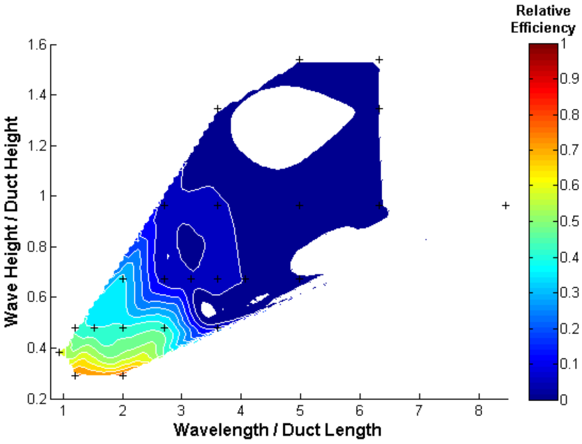

Figure 5: Performance contour plot for floating model with monochromatic waves.

Floating Tests

Following the first set of tests, the second phase of investigation was intended to replicate the motion and performance of OWEL in a real sea state. The motion of the floating model influences the conversion performance as the entry freeboard to the duct, a fairly critical parameter, varies through a wave cycle and is dependent on the model's pitch and roll.

The performance of the floating model with regular waves is shown in Fig. 5. The peak performance shifted to a smaller λ/DL ratio due to the effect of motions and was a similar magnitude to the fixed case. However, for the larger seas, performance was somewhat reduced due to the large motions induced by regular waves.

The most realistic test was the floating model in short crested seas, the performance of which is shown in Fig. 6. The peak performance also remains at a smaller ratio, as with the monochromatic floating conditions. However, the overall performance across all of the sea states was much improved.

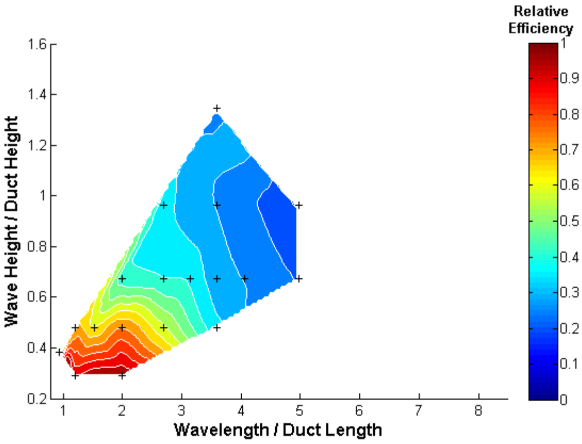

Figure 6: Performance contour plot for floating model with directional, polychromatic waves.

This is an encouraging result as it demonstrates that the device is able to perform to expectations in scaled, realistic seas.

Some floating trials were conducted during the first phase of testing however, the motions of the model were found to be detrimental to performance. By re-assessing the position and amount of ballast and buoyancy for the model, it was possible to alter the metacentric height and moments of inertia to stabilise the model for certain sea states and enhance the motions for others.

For all of the wave cases, the frequency of the pitch and surge motions were equal and were 180° out of phase, meaning that the model's bow pitched upward whilst simultaneously surging backward. This suggests a strong coupling between pitch and surge which can be beneficial to the performance.

In the second phase of testing, with a slightly redesigned model, it was found that at the design wave, the phase relationship between the incident wave and pitch and surge was such that the model pitched bow down and surged forward into the incident wave. The pulse of power occurred at around a 90° phase lag to the pitch which is thought to be optimum. At the design wave, the motions resulted in a 20% increase in performance over the fixed configuration. This ideal response improves the capture performance of each duct through better wave sealing and air compression within it. This relationship can be seen in the time series motions and power plot in Fig. 8. The power, which can be thought of as the duct intercepting the incident wave, occurs as the model pitches down and surges forward.

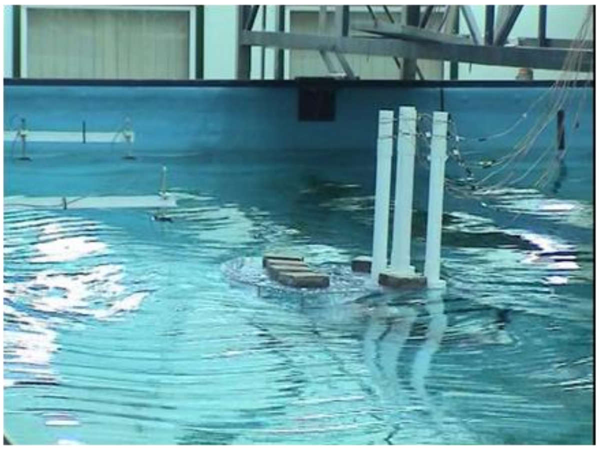

Figure 7: Fixed model under test with monochromatic waves

The roll was damped by careful positioning of reserve buoyancy and ballast at the extremities of the model however, it was found that roll was not as detrimental to performance as initially perceived. Frequency domain analysis of the motions indicated that roll and sway were also very closely coupled.

Due to the sheer number of variables and degrees of freedom present in the system, it was difficult to ascertain strict relationships and the influence of each factor. However, the main trends and characteristics were identified.

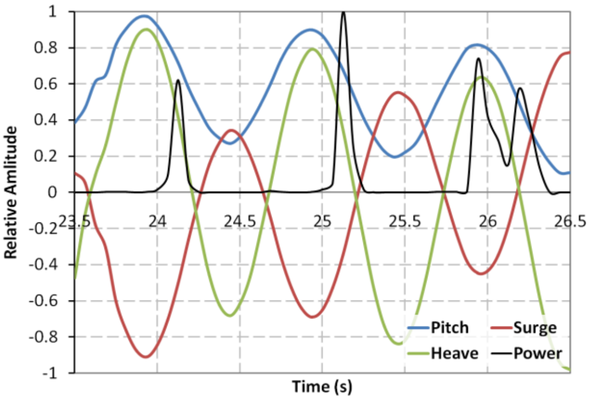

Figure 8: Example of motions and power time series for the floating model with monochromatic waves.

Whilst it is slightly beneficial overall to mount OWEL statically at model scale, performance of the floating model was increased over the fixed condition for the design wave and shorter period waves. This was because the magnitude of the motions in smaller seas was relatively small. As the wave period was increased, the model was found to follow the contour of the waves so that pitch and heave became in phase with the incident wave. This is advantageous for storm wave survivability at full scale as the device captures far less energy in the much larger, more energetic waves. This also helps to limit the pneumatic power output of each duct, meaning that energy supplied to a power take-off will be better matched to the rated turbine output.

4. Computational Modelling

Computational modelling is a useful tool in the development of WECs as it allows for concepts and optimisations to be studied without the need to physically construct or test them, saving both time and money. The complex nature of wave energy conversion limits the level of detail practically achievable by these methods. It was therefore only practical to investigate a single, fixed duct in simplified monochromatic waves rather than the whole domain of a floating, multi-duct simulation in real seas.

The commercial CFD program, ANSYS CFX™ was used in the creation of a computational model similarly to that in work conducted by Westphalen et. Al [5]. Initially, a simple transient simulation was set up with a 2D geometry, with the purpose of being a development platform that could be run with minimal computing time in order to assess boundary and initial conditions.

Input boundary conditions were used to set the fluid velocity and volume fraction at the inlet to the domain. By assigning the X and Y velocity components of the water to behave as those stated in the linear wave theory, the fluid acts as it would in an idealised monochromatic wave. The boundary conditions for the domain are summarised in Fig. 9.

Once the boundary and initial conditions were determined and tested, the model geometry and mesh were developed and then refined. In order to reduce computational time, the duct was split along the longitudinal plane and a symmetry boundary was used to represent the other half of the duct and domain.

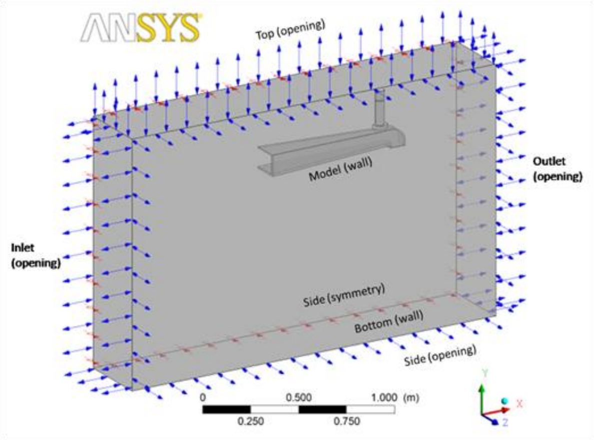

Figure 9: Computational domain showing boundary conditions.

Eventually, a fine mesh comprising 1.1 million nodes was used for both the small and full scale simulations. Ordinarily this would have taken many days to run on a standard desktop computer, we however were able to run the simulations in parallel on the University of Southampton's high performance computing cluster called IRIDIS in about 30 hours per simulation. A number of monochromatic waves were run in the model in order to compare time series results with the experimental, fixed model results. The water volume fraction for an example, typical wave entering the duct is shown in Fig. 11. The pressure evolved in the computational model was sampled at the same geometric locations as they were in the physical model tests, those being one pipe diameter upstream and half a pipe diameter downstream of the orifice plate. This was the key comparison parameter between the physical and computational models.

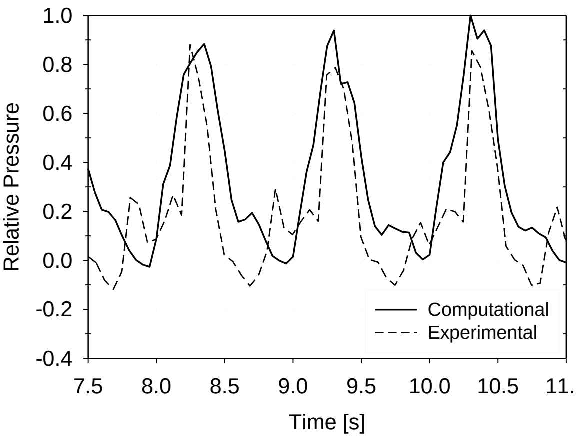

Figure 10: Comparison of computational and experimental orifice pressures for a typical wave

An example comparison between computational and experimental differential pressure is shown in Fig. 10. The graph shows a section of time series data of the differential pressure, relative to the maximum pressure in the data set, measured across the orifice for two data sets generated by a typical, regular wave. The computational result is for a slightly coarser mesh with 660,000 nodes. The other is from experimental results taken from the first a testing period at HMRC Cork.

Whilst the agreement between computational and experimental results was generally fairly reasonable, the computational model over predicted the developed pressures, flow-rate and pneumatic power. As Fig.10 shows, peak pressures were similar but the areas under the experimental curves were much smaller than the computational and so higher flow rates were predicted. As the model is further refined and improved, it is expected that the agreement between the results will become better.

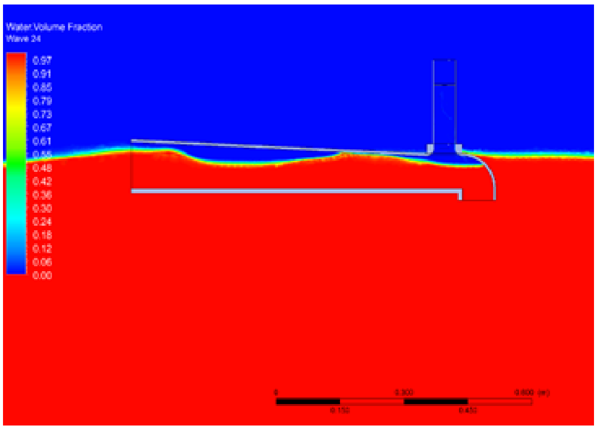

Figure 11: Typical wave entering the duct of the computational model.

One of the main deliverables of the computational modelling was scaling data to be used to predict the full scale output of an OWEL device. Various different sizes of model geometry were used in the simulations to provide an idea of how performance varies with scale. Fig. 12 shows the results of this analysis along with a theoretical estimate of the performance at different scales. The theoretical estimate is based on simple Froude scaling laws combined with reduction factors to take into account losses likely to be experienced at larger scales. These include effects such as compressibility with this factor derived from the work by Weber [6].

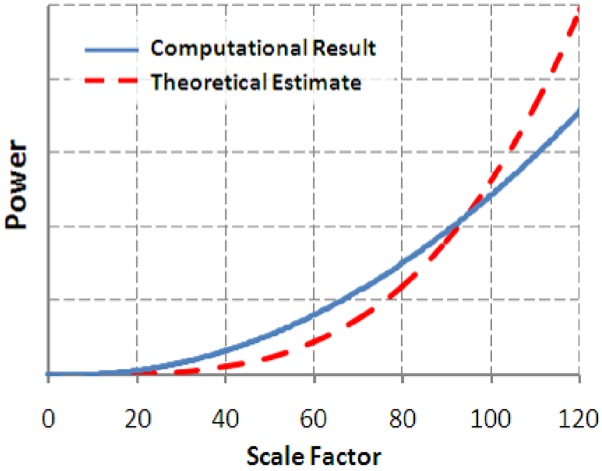

Figure 12: Computational and theoretical scaled power.

5. Conclusions

A fundamental and detailed understanding of OWEL was gained, including performance, motion and loading characteristics.

In depth knowledge of performance sensitivity to parameter changes (e.g. monochromatic / polychromatic waves, fixed / floating model) has been attained and can be used to develop the next generations of the device with a high degree of confidence.

The motions of the OWEL platform were measured in realistic, scaled sea states and their effect on performance analysed. The naval architectural and platform dynamics and their effect on power production are well understood and can be used to design the next generations of OWEL. It is now possible to design OWEL with specific dynamic and static properties to enhance performance and survivability.

The validated computational model will be a useful design tool to assess new design features and optimisations in the future. This will also be used for further investigation of scaled performance.

6. Future Work

A techno-economic model and outline design for a 1:2, ocean deployed demonstrator has been developed using the results of this development phase.

A series of strategic partners have been gathered together as a result of this project and it is the intention of the consortium to pursue the development of OWEL to the commercial stage. Between them, all of the skills exist to drive the development forward, and produce a viable commercial device.

In addition, this phase of development has identified several aero- and hydrodynamic design details that can be improved and these will be prioritised in the next developmental stage as they are likely to increase performance further.

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