The design and commissioning of the first, circular, combined current and wave test basin.

David Ingram*, Robin Wallace†, Adam Robinson‡ and Ian Bryden§
*Institute for Energy Systems
School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, United Kingdom Email: david.ingram@ed.ac.uk
†Institute for Energy Systems
School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, United Kingdom Email: robin.wallace@ed.ac.uk
‡Institute for Energy Systems
School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, United Kingdom Email: adam.robinson@ed.ac.uk
§The University of the Highlands and Islands
11B Ness Walk, Inverness IV3 5SQ, United Kingdom Email: ian.bryden@uhi.ac.uk

***Abstract*—In 2010 Bryden, Ingram and Wallace applied to the UK Engineering and Physical Sciences Research Council (EPSRC) for funding to construct the *all waters combined current and wave test facility*. Funding was awarded and over the next three years the FloWave TT facility was constructed. At its heart is a 25m diameter, circular basin, equipped with 168 force feedback wave makers, 28 bidirectional impellers and a liftable floor. The 2m deep test section is designed to generate currents (at 0.8m/s) and 700mm high, 2s period, waves from any relative directions. Allowing a model to be subjected to scale tests over the full tidal ellipse simultaneously with multi-directional waves.**

Construction of the facility was completed in November 2013, and calibration is currently in progress. Initial work has shown that maximum flows of 2ms^{-1} can be achieved across the test section, while the circular wave maker array allows very large focused waves to be created.

This paper describes the FloWave facility, its construction and commissioning and presents some preliminary results.

I. Introduction

FloWave (Figure 1) is the first basin in the world to allow the combination of waves and currents in any relative direction. It has been designed to provide a proving ground and development facility for ocean energy devices (including fixed and floating offshore wind turbines. and wave and tidal energy converters). The basin has been sized to allow small arrays of machines to be tested and also to allow testing of installation and maintenance operations. Figure 1 shows the flap-type, dry back, wave makers in red and immediately beneath them the raisable tank floor and flow induction system. Each of the 28 flow drive units has a 48kw motor connected to a five bladed, symmetric, $1.7m$ diameter impeller. Between the impeller and the tank wall is a $90°$ turning vane and, at tank floor level, a set of turning vanes and flow conditioning material to introduce/extract water from the test section. To the left of the picture is the quayside workshop area and above it the facilities offices with good sight lines onto the surface of the tank. A $32\mathrm{m}$, 5 tonne, beam crane is installed in the roof which has access to the entire tank hall. The central floor section of the tank is a buoyant moored platform which, while locked down for testing, can be raised to allow model installation. The floor is hauled up and down on cables attached to a hydraulic cylinder and acts as a tension leg platform.

II. FloWave construction

A. Design

The design of the facility was inspired by a combined current and wave test basin design described by Salter [1] (Figure 2) but never constructed. Salter's basin utilised a giant Voith-Schnider impeller with undershot wave makers. in contrast, the FloWave basin uses 28 independently controlled 1.7m diameter impellers. Rather than under shooting the wave makers flow is introduced in front of the wave makers using shaped transition vanes to generate a region of quiescent water in front of the wave makers bounded by a strong turbulent shear layer [2]. The basin is designed to operate at scales of between 1:20 and 1:40. This region is chosen because the performance (with respect to Reynolds number) of tidal rotors under such conditions are comparable (in terms of tip speed ratio and coefficients of power) to full scale rotors (see Figure 3).

The most energetic sites for tidal energy extraction in the UK (in the Orkney Islands, the Pentland Firth, Strangford Narrows and the Sound of Islay) are characterised by water depths of between $20\mathrm{m}$ and $70\mathrm{m}$ with current velocities in excels of $5\mathrm{ms}^{-1}$. Richmond et al report that the turbulence intensities for flows in tidal channels are around 15% [3] . Wave devices are typically deployed in water depths of between $10\mathrm{m}$ and $100\mathrm{m}$ with wave heights of up to $30\mathrm{m}$. Large atlantic swell waves at such sites can wave have periods in excess of 20s. Applying Froude scaling, we determine that the basin should:

- achieve flow speeds of $0.8\mathrm{ms}^{-1}$ with an associated turbulence intensity of circa 7%,
- provide waves of $700\mathrm{mm}$ with periods of $2\mathrm{s}$, and
- have a water depth of between $2 - 2.5\mathrm{m}$.

The decision to require low turbulence intensity levels of 7% is to allow higher levels of turbulence to be provided in experiments as "designer" turbulence. This is done by placing structures in front of the tidal rotors to create large scale, or high intensity, eddy structures, much in the same way as is done in wind tunnels.

Fig. 1. Section through the Flowave TT facility (courtesy of Bennets Associates)

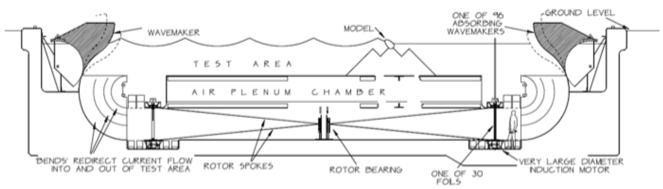

Fig. 2. Section through a proposed circular combined current and wave tank, reproduced from [1].

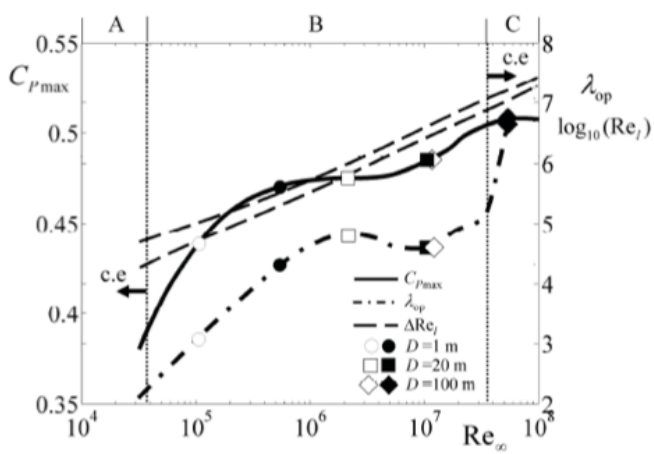

Fig. 3. Variation of power coefficient, C_P, and tip speed ratio, γ, with Reynolds number for turbines with length scales of 1, 20 and 100.

1) Flow conditioning: The use of a strong shear layer to create a quiescent region in front of the wave makers is critical to the successful operation of the facility. The wave makers deployed in the FloWave basin use force-feedback [4], [5] absorb incoming waves and the presence of flowing water in-front of the wave makers will modify the force, causing wave absorption to fail. It is therefore critical that the wave makers are located in quiescent water. One of the main deficiencies of the under-shot "race-track" design proposed by Salter [1] is that the wave makers are not isolated from the current. Robinson et al [6], [2] suggested the use of a strong turbulent shear layer in-front of the wave maker to create a quiescent

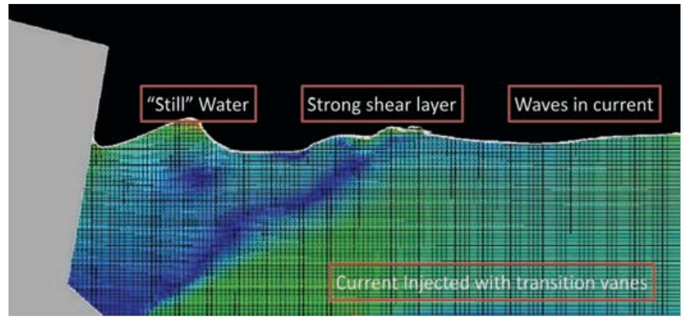

Fig. 4. CFD simulation of a wave maker with current using a strong shear layer, computed using Flow3D. Their is a region of quiescent water in front of the flap-type wave maker which is isolated from the flowing water region by a strong shear layer.

Fig. 5. Initial excavation of pit for the containment tank with the steel frame of the building erected before excavation commenced.

region. This proposal is based on a comprehensive series of computational fluid dynamics (CFD) simulations and experiments conducted both in the curved wave basin at Edinburgh University and in a specially constructed wave/current flume. Figure 4 shows a single frame from a transient CFD calculation performed using Flow3D to illustrate the concept. The wave maker is isolated from the flowing water by a strong-shear layer, beyond which the transformation of the waves, due to Doppler shifting, is clearly visible. The CFD simulations have been validated using PIV and ADV measurements and the shear-layer method is shown to work at both the inflow- and outflow- ends of wave-current flume (Full details are given in [2]).

2) Plane waves in circular tanks: The, so-called, snake theory which allows the generation of plane waves at an angle to a segmented wave maker [7], [8] is simply extended to circular wave tanks and has been used in both the Japanese AMOEBA tank [9], [10] and the NMRI deep sea basin in Tokyo Japan. Whilst the AMOEBA basin is very small (Ø= 1.6m), the NMRI basin has a diameter of 15m, just over half that of FloWave.

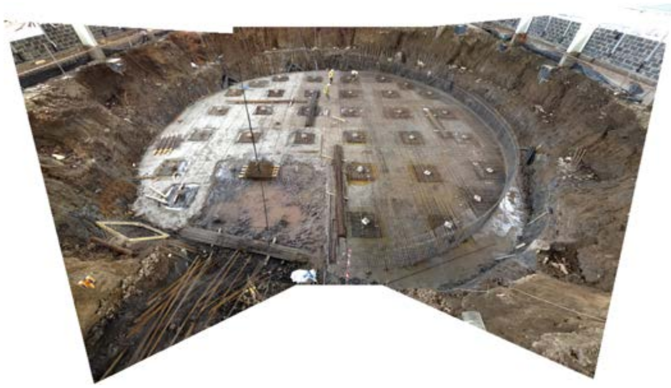

Fig. 6. Installation of the re-bar for the containment tank floor showing the rock anchors into the basalt and the start of the re-bar work for the, 25m diameter, lower tank wall.

Fig. 7. Shuttering in position for pouring the lower tank wall and the installation of rebar for the step which supports the wave makers and the, 30m diameter, upper tank wall.

B. Civil Construction

The civil works were conducted by the UK Construction firm Graham (`www.graham.co.uk`). The approach taken was novel in that the building was erected first and then the pit for the containment vessel was dug. The decision to reverse the normal construction process was taken for two reasons. Firstly; the construction site and laying down areas were very compact as the building spanned most of the site. Secondly; constructing the building frame and roof first would provide shelter from the Scottish weather during construction meaning less days would be lost to bad weather and there was less chance of flooding or low temperatures affecting the concrete. Figures 5 to 7 show the progress of the construction from initial excavations through to the construction of the upper portion of the tank. It is also interesting to note that the strategy adopted by Graham enabled the facilities gantry crane to be used to manoeuvre the shuttering used to pour the tank walls.

Figure 5 shows the initial excavation for the tank in progress with the steel frame for the portal frame building in place. The excavation works included the removal almost $5000\mathrm{m}^3$ of clay, down to a depth of nearly $6\mathrm{m}$, just below this depth bedrock (basalt) starts. After the excavation had been completed rock anchors where fixed into the basalt and rebar was installed for the concrete floor (Figure 6), during the this time construction work on the portal frame building continued with the construction of the curtain walls and roof. Figure 7 shows the installation of the reinforcement for the step on which the wave makers are mounted. This step, located $2m$ below the still water level, marks the transition between the 25m diameter and 30m diameter sections of the tank. The wider sections is necessary to accommodate the maintenance and access gallery behind the dry-backed, flap-type, wave makers.

The civil construction began in late 2011 and was sufficiently complete by January 2013 that the E&M installation could begin. Handover of the building from the civil contractors took place in November 2013.

C. E&M Installation

The design and installation of the electrical and mechanical equipment for the 168 wave makers, 28 flow drives and the associated control was over seen by Edinburgh Designs Ltd (`www.edesign.co.uk`). EDL is a spin out company from the University of Edinburgh and have been specialists in the design, manufacture and installation of a wide range of wave and tidal generators since 1987. Installation began with the erection of the wave making flaps, followed by the $90°$ turning vanes (Figure 8). Each of the 28 flow drive units has it's own set of turning vanes and baffles are installed between them to prevent short-circuiting of the the flow path. Once the turning vanes had been erected the flow drive units were positioned (Figure 9) and then the floor was installed (Figure 10). The between the lower and upper skins the floor frame holds a large number of floatation tanks, sufficient to provide enough buoyancy to ensure the floor can support a load of 5 tonnes without significant movement, the cables which hold the floor down against the buoyancy force have been sized so this can be applied as a point load on the edge of the floor.

In addition to the mechanical equipment described above, control cables and power had to be installed for the 168 wave makers and 28 flow drives. The wave makers draw a maximum of $300\mathrm{kW}$ and the flow drives a maximum of $700\mathrm{kW}$, allowing for a diversity factor, making the total electrical demand $1\mathrm{MW}$. It is interesting to note that when the wave makers are in "absorbing" mode the energy is injected back into the electricity supply, this means that if the tank is instructed to stop making waves for a few minutes we have a grid connected $300\mathrm{kW}$ wave power machine!

Once the E&M Installation was complete the tank was filled with $2.5Ml$ of potable water and commissioning tests began. Figure 11 shows the floor in the raised position.

III. Commissioning

A. Current system

Simulations by Robinson et al [2] show that by individually controlling each of the 28 flow drive units, linear flow can be achieved across the test section of the basin at the desired velocity (Figure 12).

Once the flow drive system had been installed and the tank filled a series of measurements were conducted using a single-axis electromagnetic flow meter to check this and to derive a calibration curve relating motor speed (in RPM) to flow speed (in ms^{-1}. measurements were made using a Valeport Model 801 single-axis electromagnetic open channel flow meter.

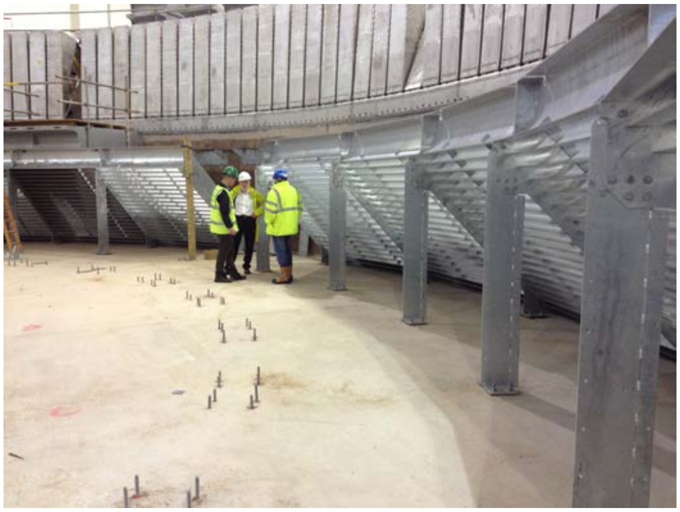

Fig. 8. Installation of the 90° turning vanes, with the wave-makers erected on the step, the bolts in the floor mark the locations of the flow drive units..

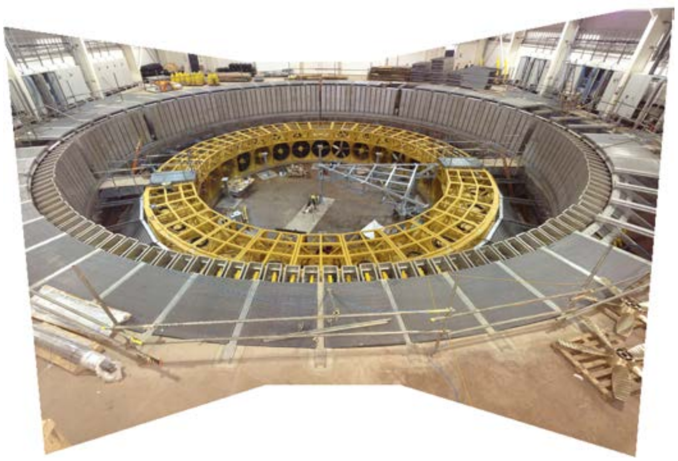

Fig. 9. Complete installation of the 28 flow drive units with the frame for one section of the raisable floor in place.

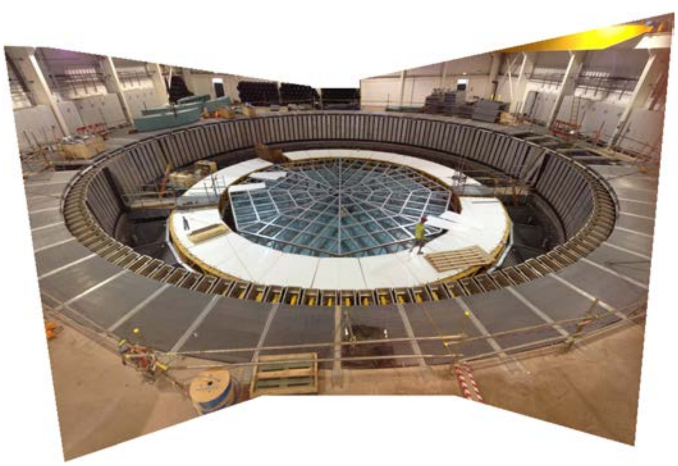

Fig. 10. Completed floor frame installation, prior to installation of the buoyancy tanks

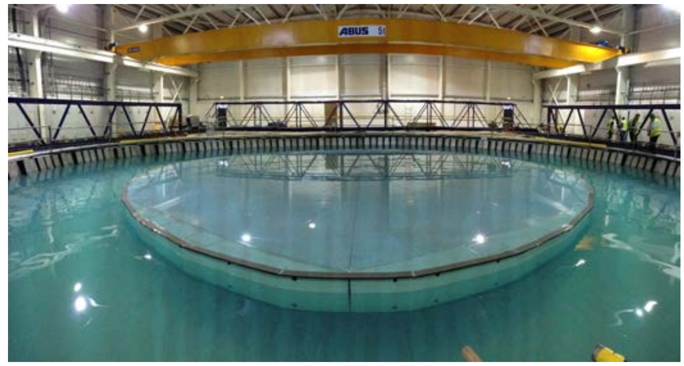

Fig. 11. Basin following completion of the O&M installation and the initial fill with the TLP floor in the raised position.

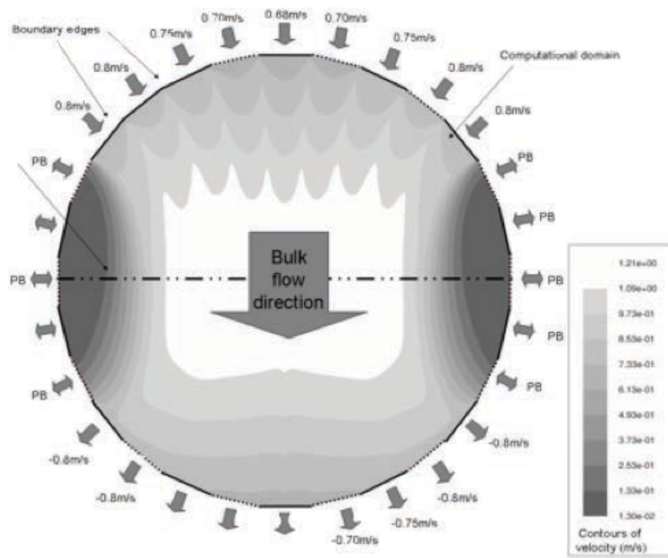

Fig. 12. Mosaic plot of depth averaged velocity across the basin from a CFD simulation: The plot shows that if the inflow- and outflow- velocities are properly specified linear flow can be achieved across the test section, after [2]

The Model 801 is a high precision instrument which gives accurate readings ($\pm 0.5\% + 0.005\text{ms}^{-1}$) over a flows with velocities of $\pm 5\text{ms}^{-1}$. In the calibration tests the "flat-type" probe was used which has a cylindrical sensing volume $20\text{mm}\varnothing \times 10\text{mm}$. It has a sampling frequency of 1Hz and can average data over a period of between 1 and 60 seconds, in accordance with the manufacturers recommendations sampling periods 30s were used to ensure stability of the measurements in a turbulent flow environment. The Model 801 also records the sample's standard deviation.

For these, current only, tests the wave makers were inactive and parked against their backstops. Thus the water level for these tests is approximately 90mm lower than the nominal 2m working depth. The probe was placed at a depth of 0.5m below the still water level (i.e. approximately 1.4m from the tank floor) and aligned with the flow direction. Velocity measurements were taken from the centre of the tank out to a radius of 9.5m in increments of 0.5m, by moving the gantry with the flow meter fixed in place. Throughout the tests the maximum flow drive speed was set to 100 rpm which corresponds to a flow velocity of 1ms^{-1} which is very close

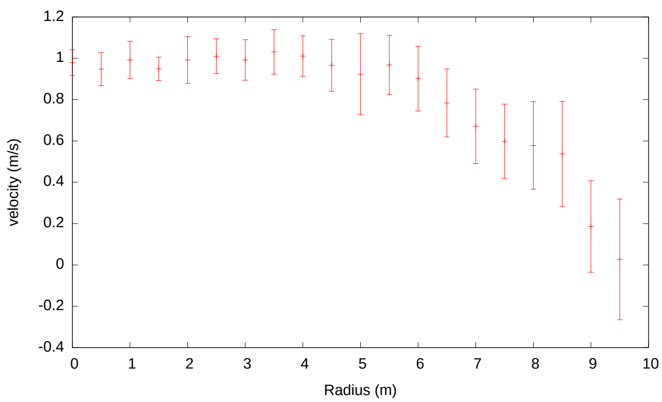

Fig. 13. Measured velocity with 95% confidence intervals (based on $\pm 1.96\sigma$) plotted against radius from the centre of the FloWave basin (measured in the cross flow direction) with the maximum flow drive rotation speed set to 100 rpm.

to the velocity of $0.8\mathrm{ms}^{-1}$ used to design the flow transition vanes.

Figure 13 shows the measured flow velocity profile across the basin together with the 95% confidence intervals, estimated as $\overline{u_i} \pm 1.96\sigma_i$ plotted against radial distance from the centre of the basin in the crossflow direction. The plot shows good agreement with the profile predicted using CFD (Figure 12). The results also show that uniform flow is achieved out to $r = 5.5$m, demonstrating that the central 11m of the tank have approximately uniform flow conditions.

Initial calibrations based on the central velocity (at $r = 0$) show that the flow velocity varies linearly with the maximum flow drive rpm up to the maximum speed of 200 rpm, which equates to a flow velocity of $2.0\mathrm{ms}^{-1}$. The final maximum flow velocity for the basin is expected to be around $1.6\mathrm{ms}^{-1}$ as additional flow conditioning membranes need to be installed underneath the flow transition vanes to further reduce the turbulence intensity (which is currently around 10%).

B. Wave system

Preliminary calibration of the wave system is done by generating long crested regular waves over a number of directions. Once the generation and absorption characteristics of the tank have been established. Figure 14 shows photographs taken from the centre of the truss on the north side of the tank during tests with long crested regular waves. In both cases the wave amplitude is the same (circa $400\mathrm{mm}$) but the directions of wave propagation are at $0°$ and $90°$ with respect to the E-W axis of the tank (we define $0°$ as being away from the control room window).

Figure 15 shows the a JONSWAP wave spectrum ($T_p = 2$s, $H_{m0} \approx 300\mathrm{mm}$, $\gamma = 3.3$) with a uniform propagation direction of $270°$ and a $30°$ cosine spreading function. Random waves are generated using an inverse Fourier transform method with randomised component phases and so are completely deterministic. Currently these tests are being repeated with a wave gauge array deployed from the gantry to calibrate the tank transfer function and to check the directionality of the waves.

Fig. 14. Regular, long crested, plain, waves with a 2s period and a wave propagation directions of $0°$ (top) and $90°$ (bottom).

Fig. 15. Psudo-random waves generated using a JONSWAP spectrum ($T_p = 2$s, $H_{m0} \approx 300\mathrm{mm}$, $\gamma = 3.3$) with a uniform propagation direction of $270°$ and a $30°$ cosine spreading function.

A final check on the quality of wave making in circular tanks can be performed by focussing concentric circular waves onto the centre of the basin. The idea is to generate a circular, breaking wave, in the centre of the tank which creates a circular jet. The jet is formed by creating waves of decreasing frequency at the wave-makers in such as way as they all arrive at the centre of the tank at the same instant. The process can be thought of as the "inverse stone throwing problem" where instead of watching the ripples spread out from the point of impact, we simply create the ripples at the edge of the tank and run time backwards!

The formation of the up rushing jet is a highly non-linear phenomena which is thought to be generated by a circular

Fig. 16. Focussed breaking wave in the centre of the basin. The top photograph shows phase-locking of the principal wave components approximately 2s before impact, while the lower photograph shows the rapidly up rushing column of water, shortly after impact.

version of the "flip-though" process described by Peregrine and Cooker (see [11]). Flip-through was described in relation to the impact of breaking waves on vertical walls and has been shows to cause extreme up rushing velocities, many times the inshore wave celerity. Indeed, experiments by Bruce et al [12], conducted on a vertical wall in the large wave flume in Barcelona, measured velocities in excess of 20 times the inshore wave celerity. In terms of testing the wave generation in the FloWave basin, the created jet should be a completely circular column of water show no obvious asymmetry.

Figure 16 shows the the "phase-locking" of the wave components approximately 2s before impact and the rapidly up-rushing jet just after impact. In these tests a maximum current of 1.2A was supplied to the wave maker motors (which are rated for 12A), and the resulting jet hits the ceiling of the tank hall (10m above the water surface). Provided the surface of the basin is quiescent prior to the start of the experiment, both the up rushing column of water and the incident wave crests show almost perfect circularity and there are no defects, or scars, observed in the uprushing column of water until the jet starts to fragment. This test shows the wave making process is well controlled and the waves of a very high quality.

C. Initial WEC deployment

As part of the calibration procedure for the FloWave basin two Scottish developers (one wave energy company and one tidal energy company) have been given the opportunity to conduct preliminary tests of their device in the basin. The

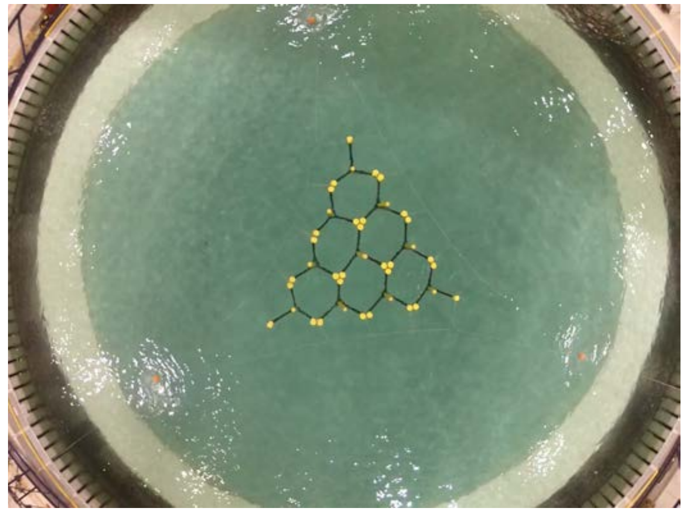

Fig. 17. AlbaTERN WaveNET array comprising 10 SQUID units deployed in the FloWavebasin and subjected to long-crested random waves. The photograph was taken using a GoPRO camera with a wide angle lens attached to the hook of the crane, which was positioned over there centre point of the basin.

wave company is AlbaTERN (`www.albatern.co.uk`). AlbaTERN's WaveNET wave energy converter is a modular array of their SQUID units, which can also function as a stand-alone wave energy device. SQUID devices are currently being developed at 7.5kW nameplate capacities. The SQUID device is road transportable and can be launched from a wide variety of locations. AlbaTERN are currently developing a 75kW SQUID unit. An WaveNET array of 10 SQUID units was deployed in the basin and tested under a range of long-crested regular and irregular wave conditions (Figure 17).

The primary purpose of the test was to demonstrate the installation process and to check the mooring arrangement used. Following these tests AlbaTERN are designing the mooring system to include force transducers on the moorings and to instrument the SQUID energy conversion units.

IV. Conclusion

The FloWave basin, constructed at the University of Edinburgh, is the worlds first completely multidirectional, combined current and wave basin. The 25m diameter basin is able to create, highly repeatable waves using 168 individually controlled force feedback wave makers. The wave makers are designed for waves with an amplitude of 700mm and a period of 2s. Preliminary tests on the wave making indicate that high quality, highly repeatable, waves can be generated in the basin. Further work is on-going to characterise the waves using an array of wave gauges to check both the quality and directionality of the waves.

In terms of current, calibration measurements have shown that the basin can exceed it's design velocity of $0.8\mathrm{ms}^{-1}$ and that uniform flow can be created across a circa $11\mathrm{m}$ diameter section in the centre of the basin. Calibration tests have also shown that the flow speed varies linearly with the motor speed, providing a high degree of control over the current velocity. Further measurements are presently being undertaken to characterise the boundary layer across the floor of the basin. The current measurements demonstrate that the CFD simulations and flume experiments used to design the turning vanes in the basin have been successful and that a quiescent region of water is created in front of the wave makers allowing the combination of waves and currents.

Preliminary tests with a wave energy device developer have shown that the basin provides a sufficiently large area for array tests to be performed and that models can quickly and easily be installed and removed.

FloWave thus represents the first time that realistic ocean conditions, typical of those found at marine energy deployment sites, can be created, under controlled conditions, in the laboratory. Over the next few months further calibration work will be conducted on both the wave and current systems and early experiments with combined conditions will be performed.

Acknowledgment

The authors would like to thank the UK Engineering and Physical Science Research Council for direct funding for FloWave (EP/I02932X/1) and for funding the research project "Design of Wave and Current Generators for Stable Wave Generation in Multidirectional Combined Wave Current tanks" (EP/H012745/1). We would also like to thank The University of Edinburgh and Scottish Enterprise for their financial support, and Edinburgh Designs Ltd for helping to turn our dream into reality.

The authors are extremely grateful to the staff of the FloWave facility especially, Dr Tom Davey and Mr Jeff Steynor, for providing the velocity calibration data from the basin.

References

[1] S. Salter, "Proposals for a combined wave and current tank with independent 360° capability," in *Proceedings Marec 2001*. London: Institution of Marine Engineers, 2001.

[2] A. Robinson, I. Bryden, D. Ingram, and T. Bruce, "The use of conditioned axial flow impellers to generate a current in test tanks," *Ocean Engineering*, vol. 75, no. 1, pp. 37–45, doi:10.1016/j.oceaneng.2013.10.016 2014.

[3] M. Richmond, J. Thomson, V. Durgesh, and B. Polagye, "Inflow characterization for marine and hydrokinetic energy devices FY-2010 annual progress report," Pacific Northwest National Laboratory, Richland, Washington 99352, USA, Tech. Rep. PNNL-19859, 2011.

[4] J. Spinneken and C. Swan, "Second-order wave maker theory using force-feedback control. Part I: A new theory for regular wave generation," *Ocean Engineering*, vol. 36, pp. 539–548, 2009.

[5] ——, "Second-order wave maker theory using force-feedback control. Part II: An experimental verification of regular wave generation," *Ocean Engineering*, vol. 36, pp. 549–555, 2009.

[6] A. Robinson, J.-B. Richon, I. Bryden, T. Bruce, and D. Ingram, "Vertical mixing layer development," *European Journal of Mechanics - B/Fluids*, vol. 43, no. Jan-Feb, pp. 76–84, doi:10.1016/j.euromechflu.2013.07.001 2014.

[7] S. Naito, "Wave generation and absorbtion – theory and applications," in *Proceedings of the sixteenth (2006) International Offshore and Polar Engineering Conference, San Francisco, California*, vol. 3, 2006, pp. 1–9.

[8] J. O'Dea and J. Newman, "Numerical studies of directional wavemaker performance," in 28^{th} *American Towing Tank Conference, Ann Arbor, Michigan 9–10 August*, 2007.

[9] M. Minoura, R. Takahashi, E. Okuyama, and S. Naito, "Generation of extreme wave composed of ring waves in a circular basin," in *Proceedings of the Nineteenth (2009) International Offshore and Polar Engineering Conference, Osaka, Japan, June 21–26*, 2009, pp. 389–396.

[10] M. Minoura, T. Muto, E. Okuyama, and S. Naito, "Generation of arbitrary wave field in arbitrary configured wave basin composed by element absorbing wave-makers," in *Proceedings of the Twentieth (2010) International Offshore and Polar Engineering Conference, Beijing, China, June 20–25*, 2010.

[11] D. Peregrine, "Water wave impact on walls," *Annual Reviews of Fluid Mechanics*, vol. 35, pp. 23–43, 2002.

[12] T. Bruce, J. Pearson, and N. Allsop, "Hazards at coast and harbour seawalls – velocities and trajectories of violent ovetopping jets," in *Coastal Engineering 2002: Solving Coastal Conundrums*, J. McKee Smith, Ed., vol. 2. World Scientific, 2003, pp. 2216–2226.