Infrastructure Access Report

*Infrastructure*: ECN Hydrodynamic and Ocean Engineering Tank

*User-Project*: HiWave

Tank testing of high-efficiency phase-controlled Wave Energy Converter

CorPower Ocean

Status: Final
Version: 1.0
Date: 18-Feb-2015
ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC’s Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The aim of the initiative is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

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Sustainable Energy Authority of Ireland (SEAI_OEDU)

Denmark
Aalborg Universitet (AAU)
Danmarks Tekniske Universitet (RISOE)

France
Ecole Centrale de Nantes (ECN)
Institut Français de Recherche Pour l’Exploitation de la Mer (IFREMER)

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National Renewable Energy Centre Ltd. (NAREC)
The University of Exeter (UNEXE)
European Marine Energy Centre Ltd. (EMEC)
University of Strathclyde (UNI_STRATH)
The University of Edinburgh (UEDIN)
Queen’s University Belfast (QUB)
Plymouth University (PU)

Spain
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Tecnalia Research & Innovation Foundation (TECNALIA)

Netherlands
Stichting Tidal Testing Centre (TTC)
Stichting Energieonderzoek Centrum Nederland (ECNeth)

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Universitaet Stuttgart (USTUTT)

Portugal
Wave Energy Centre – Centro de Energia das Ondas (WavEC)

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Università degli Studi di Firenze (UNIFI-PIN)
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Consiglio Nazionale delle Ricerche (CNR-INSEAN)

Brazil
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Sintef Energi AS (SINTEF)
Norges Teknisk-Naturvitenskapelige Universitet (NTNU)

Belgium
1-Tech (1_TECH)
**DOCUMENT INFORMATION**

<table>
<thead>
<tr>
<th>Title</th>
<th>Tank testing of high-efficiency phase-controlled Wave Energy Converter</th>
</tr>
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<tr>
<td>Distribution</td>
<td>Public</td>
</tr>
<tr>
<td>Document Reference</td>
<td>MARINET-TA1-HiWave</td>
</tr>
</tbody>
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**REVISION HISTORY**

<table>
<thead>
<tr>
<th>Rev.</th>
<th>Date</th>
<th>Description</th>
<th>Prepared by (Name)</th>
<th>Approved By Infrastructure Manager</th>
<th>Status (Draft/Final)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>30 Jan 2015</td>
<td>Full version for internal review</td>
<td>Jørgen Hals Todalshaug</td>
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<tr>
<td>0.9</td>
<td>18 Feb 2015</td>
<td>Full version – updated after comments</td>
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</tr>
<tr>
<td>1.0</td>
<td>21 Feb 2015</td>
<td>Cosmetic changes</td>
<td>Jørgen Hals Todalshaug</td>
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ABOUT THIS REPORT

One of the requirements of the EC in enabling a user group to benefit from free-of-charge access to an infrastructure is that the user group must be entitled to disseminate the foreground (information and results) that they have generated under the project in order to progress the state-of-the-art of the sector. Notwithstanding this, the EC also state that dissemination activities shall be compatible with the protection of intellectual property rights, confidentiality obligations and the legitimate interests of the owner(s) of the foreground.

The aim of this report is therefore to meet the first requirement of publicly disseminating the knowledge generated through this MARINET infrastructure access project in an accessible format in order to:

- progress the state-of-the-art
- publicise resulting progress made for the technology/industry
- provide evidence of progress made along the Structured Development Plan
- provide due diligence material for potential future investment and financing
- share lessons learned
- avoid potential future replication by others
- provide opportunities for future collaboration
- etc.

In some cases, the user group may wish to protect some of this information which they deem commercially sensitive, and so may choose to present results in a normalised (non-dimensional) format or withhold certain design data – this is acceptable and allowed for in the second requirement outlined above.

ACKNOWLEDGEMENT

The work described in this publication has received support from MARINET, a European Community - Research Infrastructure Action under the FP7 “Capacities” Specific Programme.

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EXECUTIVE SUMMARY

CorPower Ocean is developing a heaving-buoy type of Wave Energy Converter with a high energy density of more than 8 MWh annual delivered energy per tonne device. Its PTO system is placed inside the buoy and includes pneumatic pretension and a mechanical drive train and equipment for phase control. The system is currently at development stage 3.

In the current Marinet project a lab-scale version of the system has been tested at scale 1:16 in the ECN Hydrodynamic and Ocean Engineering Tank in Nantes, France. A hybrid experimental setup was used, where the machinery was represented by a force-controlled motor rig placed outside the water.

The tests were aimed at verifying technical solutions and comparing design alternatives and survival strategies. The results will be used for validation of mathematical models and refinement of design. A new type of phase control called WAVE SPRING was investigated. The results confirm resonant operation with less than half of the PTO loads compared to latching control, continuous motion and no need for real-time information on the surface elevation. The amplification of power absorption is similar to what has previously been demonstrated with latching, 3-5 times higher compared to resistive loading. Wave Spring control combines simplified and robust operation with high performance, and may provide a breakthrough for industrial adoption of phase controlled point absorbers.
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1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

CorPower Ocean has developed a new type of Wave Energy Converter with high energy density, with annual energy delivery exceeding 8 MWh/tonne device. The system includes a PTO having an oscillator with pneumatic pretension and a mechanical drive train with high natural frequency of oscillation. This is combined with phase control algorithms, making the WEC oscillate in resonance with incoming waves, giving high power output compared to the physical size and weight.

The technology has its origin in research on the pumping and control functions of the human heart conducted by inventor and M.D. Ph.D. Stig Lundbäck since the 1980s. During 2010 and 2011 two generations of scaled function demonstrators have been designed and built, showing the viability of the mechanical design concept. During 2012 and 2013 the technology has been verified through IEA-OES Stage 1 and 2, by bench testing PTO modules at KTH (Stockholm) and tank testing in scale 1:30 in Porto [1,2], together with WavEC (Lisbon) and MARINTEK (Trondheim). During the test campaign a new type of phase control called WaveSpring [3] has been benchmarked.

Scale 1:30 tank tests have previously verified (Porto, 2013):
1. >3 times increase in power absorption compared to the same buoys and optimized linear damping
2. Control algorithms working effectively in regular and irregular waves.
3. Survivability and mooring loads in extreme sea states (1:60 scale).

For this MARINET test tests have been performed in a larger-scale facility (1:16), aiming for improved reliability of measurements, using a new buoy and real-time controller.

1.2 DEVELOPMENT SO FAR

1.2.1 Stage Gate Progress

<table>
<thead>
<tr>
<th>STAGE GATE CRITERIA</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1 – Concept Validation</strong></td>
<td></td>
</tr>
<tr>
<td>• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)</td>
<td>✓</td>
</tr>
<tr>
<td>• Finite monochromatic waves to include higher order effects (25 –100 waves)</td>
<td>✓</td>
</tr>
<tr>
<td>• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)</td>
<td>✓</td>
</tr>
<tr>
<td>• Restricted degrees of freedom (DoF) if required by the early mathematical models</td>
<td></td>
</tr>
<tr>
<td>• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)</td>
<td>✓</td>
</tr>
<tr>
<td>• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable</td>
<td>✓</td>
</tr>
<tr>
<td>• Real seaway productivity (scaled duration at 20-30 minutes)</td>
<td>✓</td>
</tr>
<tr>
<td>• Initially 2-D (flume) test programme</td>
<td></td>
</tr>
<tr>
<td>• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them</td>
<td></td>
</tr>
<tr>
<td>• Evidence of the device seaworthiness</td>
<td></td>
</tr>
<tr>
<td>• Initial indication of the full system load regimes</td>
<td></td>
</tr>
</tbody>
</table>

| **Stage 2 – Design Validation** | |
| • Accurately simulated PTO characteristics | ❓ |
### STAGE GATE CRITERIA

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>- Performance in real seaways (long and short crested)</td>
<td></td>
</tr>
<tr>
<td>- Survival loading and extreme motion behaviour.</td>
<td></td>
</tr>
<tr>
<td>- Active damping control (may be deferred to Stage 3)</td>
<td></td>
</tr>
<tr>
<td>- Device design changes and modifications</td>
<td></td>
</tr>
<tr>
<td>- Mooring arrangements and effects on motion</td>
<td></td>
</tr>
<tr>
<td>- Data for proposed PTO design and bench testing (Stage 3)</td>
<td></td>
</tr>
<tr>
<td>- Engineering Design (Prototype), feasibility and costing</td>
<td></td>
</tr>
<tr>
<td>- Site Review for Stage 3 and Stage 4 deployments</td>
<td></td>
</tr>
<tr>
<td>- Over topping rates</td>
<td></td>
</tr>
</tbody>
</table>

#### Stage 3 – Sub-Systems Validation

- To investigate physical properties not well scaled & validate performance figures
- To employ a realistic/actual PTO and generating system & develop control strategies
- To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag
- To validate electrical supply quality and power electronic requirements.
- To quantify survival conditions, mooring behaviour and hull seaworthiness
- Manufacturing, deployment, recovery and O&M (component reliability)
- Project planning and management, including licensing, certification, insurance etc.

#### Stage 4 – Solo Device Validation

- Hull seaworthiness and survival strategies
- Mooring and cable connection issues, including failure modes
- PTO performance and reliability
- Component and assembly longevity
- Electricity supply quality (absorbed/pneumatic power-converted/electrical power)
- Application in local wave climate conditions
- Project management, manufacturing, deployment, recovery, etc
- Service, maintenance and operational experience [O&M]
- Accepted EIA

#### Stage 5 – Multi-Device Demonstration

- Economic Feasibility/Profitability
- Multiple units performance
- Device array interactions
- Power supply interaction & quality
- Environmental impact issues
- Full technical and economic due diligence
- Compliance of all operations with existing legal requirements

### 1.2.2 Plan For This Access

The product development plan has been aligned with the 5-stage structured verification program as suggested by IEA-OES and Equimar. In stage 1 and 2 bench-testing and lifetime investigations of the mechanical system has been performed with KTH in Stockholm. Extensive numerical modelling and 1:30 tank test has during 2013 been performed in Portugal in collaboration with WavEC and MARINTEK. These tests have generated data confirming the key performance numbers, with energy density of > 8 kWh/tonne device annually (scale 1:1) and expected CAPEX
supporting LCOE < 150 EUR/MWh in volume. The purpose with the proposed scale 1:16 tank tests was to provide an additional verification step before conducting ocean testing. This activity has been run in parallel with PTO bench testing (Scale 1:3, hardware-in-the-loop) starting Q4-2014, forming an integrated functional and performance verification of hydrodynamics, mechanics, electronics and control systems. Ocean testing with a scale 1:2 device will be performed during 2016 in collaboration with Iberdrola Engineering through the pilot project HiWave, with scale 1:1 testing planned for 2017. The high level objective of the tank tests is to acquire accurate data on hydrodynamics, motion paths, system dynamics and loads to further calibrate simulation models and provide design input. Reducing the uncertainty on key parameters and verifying performance in 1:16 will reduce overall project risk, providing significant commercial benefits.

The direct objectives for the testing were the following:
- Verify new phase control solution (WaveSpring)
- Compare two alternative buoy shapes
- Acquire data for calibration of mathematical models, i.e. measure motions and forces in decay tests, forced motion tests, regular wave and irregular wave tests.
- Test survival strategies

2 OUTLINE OF WORK CARRIED OUT

This section gives an overview of the experimental setup and the wave conditions chosen for the tests, as well as selected results from the analysis of the tests carried out as part of the project. Where not otherwise specified, the numbers presented are given at prototype scale.

2.1 SETUP

The experimental setup consisted of a pre-tensioned buoy connected to a motor rig as shown in Figure 2.2. The motor rig was used to induce motions for radiation tests, and to control the wire tension at the buoy connection point in the runs with incident waves. The controller was programmed to behave like PTO system of the wave energy converter, which for the full-scale system will sit inside the buoy. The pulleys were tailor made using polyethylene sheaves fixed on roller-bearings to give low inertia and low friction. The submerged pulley was set in a “tripod” configuration in order to keep the pulley centre in a fixed position, elevated from the tank floor.

Initially the plan was to design the experiment at model scale 1:10-15. However, due to the capacity limits of the equipment to be used in the lab, such as the motor rig and the wave maker, the experiment were designed at scale 1:16. The main buoy properties are listed in Table 1 for the two buoy alternatives B1 and B2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of buoy model, plates and load cell, measured</td>
<td>kg</td>
<td>19.75</td>
<td>20.35</td>
</tr>
<tr>
<td>Buoy height</td>
<td>m</td>
<td>1.125</td>
<td>1.09</td>
</tr>
<tr>
<td>Buoy diameter</td>
<td>m</td>
<td>0.525</td>
<td>0.58</td>
</tr>
<tr>
<td>Buoy displacement at equilibrium position</td>
<td>m^3</td>
<td>0.0708</td>
<td>0.0669</td>
</tr>
<tr>
<td>Total buoy displacement</td>
<td>m^3</td>
<td>0.1055</td>
<td>0.1030</td>
</tr>
<tr>
<td>Total wetted surface of buoy</td>
<td>m^2</td>
<td>1.30</td>
<td>1.35</td>
</tr>
<tr>
<td>Sheave mass</td>
<td>kg</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td>Rope mass, including end pieces</td>
<td>kg</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Motor slide mass</td>
<td>kg</td>
<td>47.70</td>
<td>47.70</td>
</tr>
<tr>
<td>Water depth</td>
<td>m</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Depth of mooring point</td>
<td>m</td>
<td>3.09</td>
<td>3.09</td>
</tr>
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</table>

Table 1. Main properties of the experimental setup. Numbers at lab scale, i.e. a model scale of 1:16. The buoys are illustrated in Figure 2.1.
The following measurements were made:
- Wave elevation at five positions
- Buoy position and attitude using optical position measurement system (Qualisys)
- Motor slide position (used also as measurement of mooring line travel) by optical position encoder
- Force (calibrated load cell) at motor end of mooring line
- Force (calibrated load cell) at buoy end of mooring line

Figure 2.3 shows the positions of the five wave probes used.

The motor rig was controlled through a Simulink interface using the xPC Target real time environment. Also the data acquisition was done through this interface.
Figure 2.2 Experimental setup with the following key components: Floating buoy, mooring line, pulley units and motor rig. See also Figure 2.4.

Wave probe positions as measured after installation

Figure 2.3 Positions of the wave five wave probes relative to the initial buoy position.
2.2 WAVE CONDITIONS

The input setting for runs with regular and irregular waves were as shown in Table 2 and Table 3, respectively. Only a subset of the regular waves were actually run: R3-R15, R18, R21, R24 and R28-36. A peak enhancement factor of 1.0 (i.e. a Bretschneider spectrum) was used for all the normal operation runs.

Table 2. Combinations of wave period $T$ and wave height $H$ used for the regular wave runs. Model scale 1:16.
Table 3. Combinations of peak wave period $T_p$ and significant wave height $H_s$ used for the irregular wave runs. Only the sea states labelled in black were run. Model scale 1:16.

<table>
<thead>
<tr>
<th>State no.</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
<th>Wave spec.</th>
<th>γ</th>
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<tr>
<td>S1</td>
<td>0,375</td>
<td>1,75</td>
<td>6,00</td>
<td>7,00</td>
<td>JONSWAP</td>
<td>5,00</td>
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<tr>
<td>S2</td>
<td>0,500</td>
<td>2,00</td>
<td>8,00</td>
<td>8,00</td>
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<td>5,00</td>
</tr>
<tr>
<td>S3</td>
<td>0,563</td>
<td>2,25</td>
<td>9,00</td>
<td>9,00</td>
<td>JONSWAP</td>
<td>5,00</td>
</tr>
<tr>
<td>S4</td>
<td>0,688</td>
<td>2,75</td>
<td>11,00</td>
<td>11,00</td>
<td>JONSWAP</td>
<td>5,00</td>
</tr>
<tr>
<td>S5</td>
<td>0,750</td>
<td>3,25</td>
<td>12,00</td>
<td>13,00</td>
<td>JONSWAP</td>
<td>4,20</td>
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<tr>
<td>S6</td>
<td>0,750</td>
<td>3,75</td>
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<td>S7</td>
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<tr>
<td>S8</td>
<td>14,00</td>
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<tr>
<td>S9</td>
<td>15,00</td>
<td>15,00</td>
<td>JONSWAP</td>
<td>3,65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.4 Sea states used for survival runs.

2.3 DECAY AND FORCED MOTION TESTS

Decay and forced motion tests were used to acquire data for calibration and validation of the hydrodynamic models of the system, including radiation and drag coefficients. An example of a decay test is shown in Figure 2.5, showing how the damping level could be derived through the fitting of a numerical oscillator model. The buoy were given an initial surge excursion and then let free with the motor rig blocked.
Radiation tests were carried out only for the heave mode as this was the only mode that could be forced with the experimental setup. Figure 2.6 shows how the derived results for radiation damping compare to corresponding numerical estimates computed by WAMIT for buoy B1.

**2.4 Controller performance**

The force imposed on the mooring line by the linear actuator is controlled to make the measured force under the buoy follow a computed reference signal. An example of reference following is shown in Figure 2.7. The measurement signals had to be extensively filtered in order to yield usable input for the controller. Both the bridge on which the motor rig was fixed and the mooring line compliance gave oscillations that had to be removed from the signal. In addition the pulley friction induced jumps in the line force, seen as peaks in the tracking error. We did not manage to get sufficient quality of online estimates of accelerations initially planned as input to the PTO model, so we had to introduce some simplifications.
With filtering, tuning and the mentioned simplifications of the PTO model, it was possible to make the hybrid buoy-PTO setup work satisfactorily.

![Graph showing control reference force and actual measured force for the motor rig controller](image)

**Figure 2.7** Control reference force and actual measured force for the motor rig controller (upper plot). The deviation between the two is shown in the lower plot. The wave input parameters were $T_p = 2.5 \text{ s}$ and $H_s = 0.156 \text{ m}$. All numbers are at model scale.

### 2.5 Motion responses in waves

The following results are derived from time-domain analysis of the recorded measurement signal.

#### 2.5.1 Regular waves

The surge and heave amplitude responses for the two boys are shown in Figure 2.8, Figure 2.9 and Figure 2.10. The shown results are based on time domain analysis of the measured signals. For the surge response, there is a non-linear increase with wave period towards the upper end of the investigated interval. See Figure 2.8. The heave response behaves more linearly. Except for at wave periods around 9 s, the surge response is similar for the system with and without the phase control unit in operation, as seen in Figure 2.9.
Figure 2.8 Response amplitude operators for surge and heave motion in regular waves of different wave periods. The wave amplitude was 0.25 m. Results for the B1 buoy to the left, and for B2 to the right. The phase control unit was in operation. Numbers are given at prototype scale.

Figure 2.9 Response amplitudes for surge motion in regular waves of different wave amplitudes and periods. Results for the B1 buoy to the left, and for B2 to the right. The fully drawn lines show results for operation with the phase control unit in operation, and the dashed lines without it. Numbers are given at prototype scale.

This is not the case for the heave response, Figure 2.10, where the effect of the WaveSpring phase control unit is clearly demonstrated. The phase control induces a wave-to-response amplitude amplification of up to 3.3. It may is also observed that the amplification decreases with increasing wave amplitude, which is interpreted as a combined effect of reduced phase control effort, reduced marginal excitation force and increased viscous losses as the wave and motion amplitudes increase.
In Figure 2.10 response amplitudes for heave motion in regular waves of different wave amplitudes and periods. Results for the B1 buoy to the left, and for B2 to the right. The fully drawn lines show results for operation with the phase control unit in operation, and the dashed lines without it. Numbers are given at prototype scale.

In Figure 2.11 the mean offset from the initial surge position has been plotted as function of wave amplitude for three different wave periods. It is increasing quite linearly, with a mean trend that is some 30 % steeper for the B2 buoy. There is an exception for the B1 buoy without phase control, where a sudden decrease in offset is observed above 1 m wave amplitude. The same is seen for the 6 s wave period with phase control. An explanation for this has yet not been found. The offset is considerably larger with the phase control unit in operation than without, especially for the B1 buoy.

2.5.2 Normal operation

The sea state parameter range for normal operation are roughly mapped by the sea states defined in Table 3. Each sea state was realised with at least 300 waves, counted based on the peak period $T_p$.

In Table 2.5 the surge offset is given for the B1 buoy. The numbers correspond well to those found for regular waves. An offset of 5 cm in model scale, or 0.8 m in prototype scale, which is the largest measured for the chosen sea states, correspond to only 10 % of the buoy diameter, and a mean mooring line angle of less than 1°. Tidal currents need to be taken into account for the full-scale system.

The yawing of the buoy governs the choice of cabling and cable connections. From Table 2.6 it is seen that the yawing is modest, staying within about 30°. The yawing may be much governed by the properties of the mooring line. In laboratory setup an anti-rotational rope was used.
Table 2.5 Surge offset in irregular waves: Mean position relative to the initial position for surge motion of the B1 buoy. Numbers are given at model scale.

Table 2.6 Maximum yaw angle observed through each run of about 300 waves, counted based on peak period $T_p$. Buoy B1. Numbers are given at model scale.

The relative angle between buoy axis and mooring line were derived from the position measurement data. It was found that under normal operating conditions the relative angle reach up to above 20° for the sea states investigated. The maximum relative angle tends to increase with wave height and decrease with wave period.

Table 2.7 Maximum relative angle between buoy axis and mooring line for each sea state investigated. Buoy B1. Numbers are given at model scale.
2.6 LOAD RESPONSES IN WAVES

The only loads measure were the tension at both ends of the mooring line. Also the axial and lateral components at the buoy connection were derived. In addition the experiments gave estimates of machinery forces as measured in the PTO simulator.

2.6.1 Regular waves

The dynamic mooring line tension per wave amplitude is shown in Figure 2.12. In addition the mooring line is tensioned by the difference between buoyancy at the mean position and gravity of the buoy. It is found that the dynamic tension increases with wave period, but that the relative increase is reduced as the wave amplitude increases.

![Figure 2.12 Dynamic tension at buoy end of mooring line divided by wave amplitude as function of wave amplitude for three different wave periods. Result shown for buoys B1 (left) and B2 (right) with phase control unit in operation.](image)

In the next diagram, Figure 2.13, the forces handled by the conversion machinery are shown. As for the mooring tension, it is found that for large periods, where the machinery forces are larger, the machinery forces increase weaker and weaker as the wave amplitude increases.

![Figure 2.13 Relative amplitude of the dynamic forces in the conversion machinery as function of wave amplitude for three different wave periods. Result shown for buoys B1 (left) and B2 (right) with phase control unit in operation.](image)

2.6.2 Normal operation

Maximum values for the mooring line tension in normal operation are estimated in Table 2.8. At model scale the mean tension of the line is about 500 N, which means that the ratio of maximum to mean tension for the investigated sea states is about 1.7. It should be noted that the sea states only counted about 300 waves, and that somewhat larger maxima would have been likely for longer runs.
2.6.3 Survival in extreme conditions

From the survival runs we only summarise by giving the peak to mean tension values measured. The survival sea states were chosen along the breaking limit up the generating capacity of the wave maker. This meant that for peak periods higher than about 3 s at model scale (12 s at prototype scale) the significant wave height was limited to about 0.5 m (8 m at prototype scale).

<table>
<thead>
<tr>
<th>Buoy</th>
<th>T_peak/T_mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>2.21</td>
</tr>
<tr>
<td>B2</td>
<td>2.33</td>
</tr>
</tbody>
</table>

Table 2.9 Peak-to-average values for the mooring line tension in survival conditions.

The Qualisys system gave poor representation of the buoy motion with frequent periods of out points and erroneous reading for sea states with large motions and occasional splashing. For later experiments of the same kind the installation of accelerometers should be considered.

2.7 Power conversion

The converted power is here taken as the measured absorbed power minus a rough estimate of mechanical losses in the machinery. Generator losses are not taken into account. Since the tests were run with a simplified PTO model (see Section 2.4) and not with the same damping characteristics as in the actual device, the values of delivered power are not fully representative for the performance of the CorPower Ocean WEC. The data can, however, be used for comparison of the relative performance of the two control methods.

Figure 2.14 presents results with and without the WaveSpring phase control unit in operation. In both cases the machinery damping has been set approximately to theoretically optimal values derived from a simple heaving-buoy model. It should be noted that the purpose of the tests have been to produce data for validation and calibration of simulation models, not to achieve maximum power conversion in each sea state. In any case, it was found the phase control method is able to provide an amplification of power absorption by 3-6 times compared to optimized resistive loading control of the same buoy. It should be noted that this is achieved without any need for real time information on surface elevation, reducing the need for on-board sensors, electronics and algorithm complexity compared to other control alternatives such as latching control or reactive control by the active use of machinery.

Also shown is in the same figure is a comparison between the converted power from the two buoys tested in the campaign. The 11% larger diameter of the B2 buoy is seen as the main reason for its superior performance in terms of power output.
2.8 CONCLUSION

The experimental setup was successfully mounted in the ECN test basin, with buoy system, data acquisition and motor rig operation working satisfactorily. Both decay tests, radiation tests, normal operation tests and survival tests were carried out as planned. Despite some unforeseen challenges with the force feedback control during the experimental campaign, the acquired data are of sufficient quality to support conclusions for further development of the system. The experiments confirmed the strong effect of the WaveSpring phase control unit. As compared to the latching control strategy earlier applied to the system, the WaveSpring solution requires less than half the level of PTO force for the same annual energy output compared to latching control. In addition, the response is characterised by a much smoother motion, offering a more beneficial load case for drive train components compared to the more transient loading occurring with latching control.

3 MAIN LEARNING OUTCOMES

3.1 PROGRESS MADE

3.1.1 Progress Made: For This User-Group or Technology

The completed experimental campaign has given valuable input both for calibration of mathematical models and for the further development and refinement of the system design. With results from a model about twice as large as the one previously tested, the confidence in and understanding of the system has increased considerably.

3.1.1.1 Next Steps for Research or Staged Development Plan – Exit/Change & Retest/Proceed?

The user group is now working to complete development stage 3 (TRL 5-6) through further component testing, and enter into development stage 4 (TRL 7-8).

3.1.2 Progress Made: For Marine Renewable Energy Industry

This was the first time the motor rig at ECN was used in closed-loop force feedback mode. Although we had some problems with oscillations, the wire compliance and pulley friction, the setup worked satisfactorily. It has great potential for further hybrid testing studies with PTO systems simulated by the controlled motor.

3.2 KEY LESSONS LEARNED

- Friction forces in the line/pulley system were still significant in our setup at scale 1:16
- Due to line compliance and pulley friction, we had to use the force transducer at the buoy end of the line as input to the controller. Contrary to our initial assumptions, may be the best way to do it in any case.
- It is important that the motor rig has a really stiff base. In the current setup it was fixed at a bridge that gave resonant oscillations below 10 Hz, which we only barely managed to escape from.
- Using the motor slide to partly supply the pretension force by connecting the mooring line at the top end made almost all of the motor capacity available for the dynamic force control.
- The setup could have been improved by introducing a decoder at the submerged pulley for position measurement.
- The PTO model to be used in the hybrid setup should not be made to depend on acceleration measurements. Reformulation of models should make it possible to get around this problem.
- For the mooring line we used a Dyneema polyethylene rope delivered by Lankhorst ropes. Its stiffness showed to be lower than specified by the manufacturer. In retrospect we should perhaps have chosen a steel wire, which was also initially considered, or redesigned the setup to work with shorter lines. The wire length in the experimental setup corresponds to about 250 m in full scale, which approximately 5 times longer than the design length at prototype scale.
- The optical position measurement system gave poor results in survival conditions due to splashing on markers. For later experiments of the same kind the installation of accelerometers or other measurement techniques should be considered.

4 FURTHER INFORMATION

4.1 SCIENTIFIC PUBLICATIONS

List of any scientific publications made (already or planned) as a result of this work:


4.2 WEBSITE & SOCIAL MEDIA

Website: http://www.corpowerocean.com/
YouTube Link(s): http://youtu.be/ffOHzO9Jkos
LinkedIn/Twitter/Facebook Links: https://www.linkedin.com/company/corpower-ocean-ab
Online Photographs Link: https://www.dropbox.com/sh/s7tvxi1gk2ef1lt/AADsPJBYjTS7mFeOseN5B4ZDa?dl=0

5 REFERENCES


6 APPENDICES

6.1 STAGE DEVELOPMENT SUMMARY TABLE

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.
### Development Protocol

<table>
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<tr>
<th>Objective/Investigation</th>
<th>Stage 1: Concept Validation</th>
<th>Stage 2: Design Validation</th>
<th>Stage 3: Systems Validation</th>
<th>Stage 4: Device Validation</th>
<th>Stage 5: Economics Validation</th>
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<td>Grid Connections</td>
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<td>Array Interaction</td>
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<td>Maintenance</td>
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<td>Service Schedules</td>
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<td>Component Life</td>
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<td>Economics</td>
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<td><strong>Active Control</strong></td>
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<td><strong>Mooring system</strong></td>
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<td><strong>Survival Options</strong></td>
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### Output/Measurement

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<th>λ = 1: 1. Full size</th>
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<td>3D Basin</td>
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<td>Sheltered Full Scale Site</td>
<td>Exposed Full Scale Site</td>
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### Device

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<td>Approach Angle</td>
<td>Monoharmonic Waves (very low)</td>
<td>Deployment Plan</td>
<td>Design</td>
<td>Mass Loading</td>
<td>Full Score</td>
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<td>Approach Angle</td>
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<td>Design</td>
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### Maths Methods (Computer)

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<th>Hydrodynamic, Numerical Frequency Domain</th>
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<th>Finite Waves</th>
<th>Time Domain Response Model &amp; Control Strategy</th>
<th>Economic &amp; Business Plan</th>
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<td>Damping Model Unaltered Linear Equations of Motion</td>
<td>Finite Waves</td>
<td>Time Domain Response Model &amp; Control Strategy</td>
<td>Economic &amp; Business Plan</td>
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### Evaluation

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<th>Manufacturing Cost [€]</th>
<th>Capture [kW/m²]</th>
<th>Production [kW]</th>
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