Infrastructure Access Report

*Infrastructure*: IFREMER Deep Seawater Wave Tank

*User-Project*: TETRAFLOT


TetraFloat Ltd.

Status: Draft  
Version: 1  
Date: 21-Dec-2014
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.

Partners

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<tr>
<td>University College Cork, HMRC (UCC_HMRC)</td>
<td>Stichting Tidal Testing Centre (TTC)</td>
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<tr>
<td>Coordinator</td>
<td>Stichting Energieonderzoek Centrum Nederland (ECNeth)</td>
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# DOCUMENT INFORMATION

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<thead>
<tr>
<th>Title</th>
<th>Performance of a Free-Yawing Tetrahedral Floating Platform for Offshore Wind Turbines in Wind and Wave Conditions.</th>
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<td>Document Reference</td>
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</tr>
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<td>Infrastructure Accessed:</td>
<td>IFREMER Deep Seawater Wave Tank</td>
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<tr>
<td>Infrastructure Manager (or Main Contact)</td>
<td>[Insert Infrastructure Manager name]</td>
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## REVISION HISTORY

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<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>
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<tr>
<td>01</td>
<td>21/12/2014</td>
<td>Version 1 of report</td>
<td>S. D. Garvey</td>
<td></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

TetraFloat is a specific design of semi-submersible floating wind turbine platform that yaws over the surface of the water about a single mooring point. Because the wind load always acts in the same direction relative to the structure, the structure can make very effective use of material and the only natural vibration modes of the structure that couple significantly to the wind turbine are the six rigid-body-modes. All of these modes have very low natural frequency compared with rated rotational speed of the turbine and all are highly damped.

Testing at IFREMER Deep Seawater Wave tank (October 26 - November 7, 2014) used a 1:30 scale model (3m axis-height). One aim was just to gain general experience of the dynamics of the platform when subjected to wind and wave loads. Specific concerns with the platform design are:

- Will it yaw passively in the wind so that the platform axis remains broadly aligned\(^1\) to the wind?
- Will it exhibit a satisfactory stability margin against capsize when excited by wind and waves?
- Will the nacelle motions in conditions of strong wind and wave excitation remain sufficiently low in angular velocity, angular acceleration and linear accelerations for the fatigue lives of the blades not to be compromised?

In short, the answers to all of these questions proved to be positive. In particular, the equivalent moment loading on the blades in all senses was found to be lower than 0.2g for all expected weather conditions.

Measurements were taken of the total platform response - particularly the motions at the apex where the wind turbine nacelle is fitted. These measurements will be made available to any party on request. These measurements have been processed to determine equivalent added mass and added damping arising from interaction between the buoys of the platform and the surrounding water. A concept for deploying anti-heave plates very much deeper than the individual buoys was tested and this proved to be extremely effective.

One very interesting piece of yaw-dynamics was observed: the rear buoy naturally tries to orient itself in the "down-wave" direction relative to one of the front buoys and this could lead to the platform yawing away from the wind direction unless corrected. The correction is simple, however. TetraFloat's deliberate use of low water-plane areas is vindicated by very smooth responses in the pitch, roll and heave motions but it does also demand "trimming" of net buoyancy force to restore platform base to the horizontal plane when wind forces change. At IFREMER, we used two pumps at each buoy for trimming control and found this extremely effective. The extent of trimming required was illustrated very powerfully by some of the tests at the IFREMER Deep Seawater tank.

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\(^1\) Note: in the full TetraFloat implementation, at least one other measure will be deployed to "sharpen up" the alignment response – changing the relative lengths of the mooring chains extending forwards from the front buoy. It is possible also that a limited-angle yaw bearing could be fitted at the nacelle. Both of these provide a limited range of yaw adjustment and both
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1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

TETRAFLOAT is a patented design for a semi-submersible floating platform for future large offshore wind turbines. TETRAFLOAT Ltd. won a grant from DECC Offshore Wind Components competition (announced September 2013) to explore the design further and in particular to demonstrate the design in real offshore conditions. A condition of the grant was that initial testing was completed at the Cranfield University wave tank (limited to ~ 1:120 scale by the width of the tank) and subsequently that larger-scale testing would be conducted at a suitable wave basin with the capability to explore the platform response to wind and wave subsequently. The testing at Cranfield University was budgeted as an integral part of the DECC programme. The larger scale tank-testing was reliant on securing some additional support.

TETRAFLOAT Ltd. applied to the MARINET scheme in early 2013 and was successful in securing two weeks of access to the wave basin at the IFREMER Deep Seawater tank, Brest. This slot was finally timed at October 27-November 7, 2014 inclusive. A representative of DECC visited IFREMER to witness some of the tests occurring on Tuesday November 4. Extensive video footage acquired during the testing is available to any interested party in the EU.

A test plan was set out which would cover the main aspects of transient decay testing to establish fundamental characteristics of the platform, testing with regular waves, testing with irregular waves and finally testing with wind.

A major concern of this testing is to examine the effect that platform motions might have on compromising turbine blade life. Horizontal axis wind turbine rotors already experience alternating loads in the spanwise direction equivalent to “±1g” as they rotate. The blade root bearings and the innermost parts of the blades themselves must be designed to withstand many cycles of this. Most horizontal axis wind turbine blades also experience a strong component of flapwise excitation associated with the blade passing into “tower shadow” and then experiencing maximum downwind force exactly one half-cycle later as the blade goes through top dead centre. For large wind turbines, the steady bending moment associated with the downwind force is generally several times greater than the gravity bending moment – typically by a factor between 5 and 10. Thus, an alternating downwind (flapwise direction) bending moment in the order of “±1g” is also present.

For the TETRAFLOAT platform to be satisfactory as a wind turbine support, the accelerations at the nacelle in all three directions due to platform motion must be substantially lower than 1g. Angular accelerations are also of concern (for pitch and yaw) and we require a way to equate angular accelerations to translational ones. This equivalence is associated with the radius-of-gyration of the blade about the hub centre. Typically this will be around 55% of the blade tip radius, \( R_b \), and we will generally find that because this radius of gyration is small compared with the main dimensions of the TETRAFLOAT platform, the direct effects of angular accelerations are small relative to their indirect effects of the angular accelerations causing linear accelerations of the nacelle relative to the buoys. Angular velocities are also of potential concern because of Coriolis coupling (the root cause of gyroscopic couples). A 10MW wind turbine with blade tip diameter of 200m might typically have a rated spin speed of ~1rad/s. If there is some sinusoidal angular motion in the pitch and/or yaw directions with total magnitude \( \alpha \) rads and at sinusoidal frequency \( \omega \), then the excitation of blade root moments due to angular acceleration will be expressed as \( 0.55 \times R_b \times a \times \omega^2 \times 1g \) whereas the excitation of blade root moments due to angular velocity will be expressed as \( 0.55 \times R_b \times a \times \omega \times 1g \). Evidently the angular velocities become significant compared with the angular accelerations when \( \omega \gg 1 \) rad/s. We see from the testing reported below that the TETRAFLOAT platform places all of the rigid-body-resonances at very low frequencies (much lower than \( \omega \gg 1 \) rad/s for the full-scale platform). The platform has other resonant modes, of course, but none of those couple rotations at the nacelle with any significant wave forcing.
1.2 DEVELOPMENT SO FAR

1.2.1 Stage Gate Progress

A table supplied in the standard MARINET template is truncated in this report. The original table includes multiple entries from 5 different stages of maturity of an offshore energy device. At present, TetraFloat is between the concept validation stage (Stage 1) and the Design Validation stage (Stage 2). Most elements of the Design Validation stage will have been completed by the end of the DECC-funded project which will see a 20m axis-height platform trialled in real sea conditions. All parts of the table relating to subsequent stages have been deleted.

The testing at the IFREMER Deep Seawater tank was intended to resolve some of the issues remaining in those two stages but not even all of those. The table template provides two possible descriptions for any one development stage but does not allow for the fact that some elements are not already complete and were not planned to be completed either by this project. In the cases of the 11 actions suggested by the table to be completed for Stage 1 and Stage 2, the first six and the final two actions are relevant and are broadly addressed by the testing at IFREMER. Similarly for the cases of the ten actions suggested for Stage 2, the TetraFloat expectation was to address the third, fifth and sixth of these actions and it did this.

Previously completed: ✓
Planned for this project: ☐

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<td>• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)</td>
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<td>• Finite monochromatic waves to include higher order effects (25 –100 waves)</td>
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<tr>
<td>• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)</td>
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<td>• Restricted degrees of freedom (DofF) if required by the early mathematical models</td>
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<tr>
<td>• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)</td>
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<tr>
<td>• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable</td>
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</tr>
<tr>
<td>• Real seaway productivity (scaled duration at 20-30 minutes)</td>
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<td>• Initially 2-D (flume) test programme</td>
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<td>• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them</td>
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<td>• Site Review for Stage 3 and Stage 4 deployments</td>
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1.2.2 Plan For This Access

The plan for the testing aimed to conduct tests on the TetraFloat model in 2 different configurations: (a) with original set of heave-plates fitted directly to the bases of the buoys and (b) with the extended heave-plates hanging far below the bases of the buoys. It aimed, in both cases, to observe the transient decay performance of the platform in roll motion, coupled pitch+heave motion and coupled yaw-sway motion (under a wind load only). It also set out to establish response of the platform to regular and irregular wave excitation and to observe the behaviour of the platform in response to wind. Two different mooring configurations were employed: (a) a purely-horizontal mooring such that the (horizontal components of) net wave forces acting on the platform could be measured directly and (b) a catenary mooring representative of what would pertain in a real application.

2 OUTLINE OF WORK CARRIED OUT

2.1 Setup

The core concept of TetraFloat is a floating platform exploiting the high structural efficiency of a tetrahedron to provide relatively low cost support for future offshore wind turbines. The model used during the testing at IFREMER was an approximate scaled version of the expected equivalent design for a 10MW horizontal axis wind turbine. Figures 1-8 here show physical images of the model in various locations at the test site. Total model mass was ~110kg including the turbine but excluding the mass of water ballast. The “base-triangle” of the model comprises the three “buoyant caissons” (henceforth referred to as “buoys”) joined by hollow aluminium “tube” (70mm OD and 1.6mm wall-thickness) and stiffened against angular motion by “struts” (12mm OD and 2.0mm wall-thickness).

The vertical centrelines of the front two buoys were ~3.4m apart and the vertical centreline of the rear buoy was behind these by a distance of ~4.2m. The turbine axis-height was ~2.8m above the water surface and the total mass at the nacelle was 35kg. The wind turbine fitted to this platform was relatively small in blade-tip diameter for the scale of the platform – having a blade-tip diameter of only 1.6m where ~2.8m would be more representative of the final intention. The buoys themselves each comprised a large-diameter cylindrical section of diameter 400mm and height 700mm and a smaller-diameter cylindrical section of height 600mm fitted above that. For each of the two front buoys, the diameter of the upper cylinders was 200mm and for the rear buoy, that upper cylinder had diameter 150mm.
The design intention for the TetraFloat platform is that the mean water level lies above the larger-diameter buoy so that the water-plane area cut by the platform is relatively low. This has the effect of reducing both the net horizontal and vertical excitations due to waves. During the tests performed at the IFREMER tank, the reference water level was set to lie 200mm above the interface between large diameter and smaller diameter cylinders at each buoy. Each individual buoy was fitted with two pumps – one for pumping water inwards and one for pumping water back out. The level was adjusted from the side of the tank by energising these pumps. Figures 9-10 show the pipes at each buoy for bringing water in or out.

The following measurements were made in all tests:
(a) Six degrees of freedom of rigid-body motion using reflective spheres mounted on the platform (see Figure #6).
(b) Wave height at a position in the tank the same distance from the wavemaker as the reference point (see Figure #11)
(c) Mooring line force
(d) Wind (when the wind maker was energised)
One feature that was not present in the model but is known to be very desirable for a full-scale implementation of TETRAFLOAT is the provision of additional reserve buoyancy at each buoyant caisson – above the level where normal wave-action would occur. This reserve buoyancy would play no part in the usual operation of the turbine. Its significance would be to act as a fall-back final stabilisation feature in case any one individual buoyant caisson became ruptured or loaded with some substantial additional downward force.

### 2.2 Tests

#### 2.2.1 Test Plan

Tests were focused in three main categories:

- (a) Transient decay tests
- (b) Response to regular waves
- (c) Response to irregular waves

Tests were conducted in each of these categories with different configurations of platform as reported below.

### 2.3 Results

The original TetraFloat platform configuration had a 3.0m axis-height above water, heave-plates fixed directly to the base of the individual buoys and a mooring configuration which was a horizontal line to a bridge across the tank (“upwind” of the wind-generator). A revised configuration used a lower axis-height (2.7m – in order that the turbine would sit within the main wind field of the wind generator at IFREMER Deep Seawater tank). The revised configuration had heave-plates fitted at the ends of legs which were in turn fitted to the lower extremes of the buoyant elements of the platform (with a distance of 2.5m between the heave-plates and the buoy bases). In the revised configuration, a catenary mooring was used.

#### 2.3.1 Transient decay tests.

In zero wind, the TetraFloat platform has three zero-frequency rigid-body-modes (yaw, sway and surge) and three other modes which involve vertical motions at one or more of the buoys (heave, pitch and roll). Heave and pitch are intrinsically coupled in the case of the TetraFloat platform because the centre of mass does not coincide with the vertical line through the centre of buoyancy stiffness. Thus, one invariably finds two coupled heave+pitch modes. In one of these, pitch is in phase with heave and in the other it is out of phase. A suite of tests was done for both the original and revised platforms in calm-water. Heave+pitch modes were excited by dropping the platform using the
crane and separately by pushing downward the rearmost buoy. The roll mode was excited by forcing down the front right-hand-side buoy using a pole from the side of the tank. All of the data was then fitted using the smallest number of independent decaying sinusoids possible. In the case of two decaying sinusoids, the quantity (or quantities) of interest obey

$$x(t) = (x_{1c} \cos(2\pi f_1 t) + x_{1s} \sin(2\pi f_1 t))e^{-\alpha_1 t} + (x_{2c} \cos(2\pi f_2 t) + x_{2s} \sin(2\pi f_2 t))e^{-\alpha_2 t}$$

where $x(t)$ is a measured vector or scalar function of time and where $\{x_{1c}, x_{1s}, x_{2c}, x_{2s}\}$ are constant vectors (or scalars). In the case of heave+pitch, for example, $x(t)$ would contain the heave signal in one location and the pitch signal in the other. Using an approach whereby a sensibly-weighted sum of squares of residuals is minimised, we can discover best-fit values for the parameters $\{f_1, \alpha_1, f_2, \alpha_2\}$ and thereafter it is a linear problem to determine the best values for $\{x_{1c}, x_{1s}, x_{2c}, x_{2s}\}$.

Table 1 below shows the period times and the decay rates observed from this fitting. Figures 13-18 shows some of the fitted data. Yaw-sway data were obtained for the revised configuration with two different wind speeds. We observed that non-linear effects caused some fits to be fairly poor. The fits could have focused only on the lower-amplitude motions but a more representative overall picture emerges by taking some account of larger motions of the platform relative to the water.

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<th>$f_2$ (Hz)</th>
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<td>0.191</td>
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<tr>
<td>Yaw-Sway (revised config 8ms$^{-1}$)</td>
<td>0.0093</td>
<td>0.0518</td>
<td>0.0469</td>
<td>0.0303</td>
</tr>
<tr>
<td>Yaw-Sway (revised config 9ms$^{-1}$)</td>
<td>0.0090</td>
<td>0.0538</td>
<td>0.0484</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

Table 1. Summary findings from transient decay tests.

Figure 13. Heave+pitch decay tests (orig. config.) Figure 14. Heave+pitch decay tests (revised config.)
2.3.2 Regular wave tests.

Regular wave tests were conducted on this platform configuration achieved steady behaviour in all cases. The following results are distilled from the findings.

<table>
<thead>
<tr>
<th>Period (s)</th>
<th>PK Wave Ampl. (mm)</th>
<th>Surge Magn. Ratio (mm)</th>
<th>Surge Phase (degrees)</th>
<th>Heave Magn. Ratio (mm)</th>
<th>Heave Phase (degrees)</th>
<th>Pitch Magn. Ratio (degrs/m)</th>
<th>Pitch Phase (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>29.51</td>
<td>0.59</td>
<td>0.020</td>
<td>122.1</td>
<td>0.21</td>
<td>0.007</td>
<td>86.2</td>
</tr>
<tr>
<td>0.8</td>
<td>47.40</td>
<td>2.07</td>
<td>0.044</td>
<td>-6.2</td>
<td>0.71</td>
<td>0.015</td>
<td>-99.9</td>
</tr>
<tr>
<td>1.2</td>
<td>23.09</td>
<td>7.90</td>
<td>0.342</td>
<td>160.3</td>
<td>3.18</td>
<td>0.138</td>
<td>82.7</td>
</tr>
<tr>
<td>1.2</td>
<td>47.98</td>
<td>14.33</td>
<td>0.299</td>
<td>142.4</td>
<td>5.52</td>
<td>0.115</td>
<td>63.1</td>
</tr>
<tr>
<td>1.2</td>
<td>91.52</td>
<td>20.88</td>
<td>0.228</td>
<td>4.8</td>
<td>6.95</td>
<td>0.076</td>
<td>-77.7</td>
</tr>
<tr>
<td>1.7</td>
<td>24.80</td>
<td>12.66</td>
<td>0.511</td>
<td>123.6</td>
<td>7.95</td>
<td>0.320</td>
<td>41.3</td>
</tr>
<tr>
<td>1.7</td>
<td>49.82</td>
<td>26.30</td>
<td>0.528</td>
<td>123.6</td>
<td>15.34</td>
<td>0.308</td>
<td>39.6</td>
</tr>
<tr>
<td>1.7</td>
<td>98.91</td>
<td>52.12</td>
<td>0.527</td>
<td>106.5</td>
<td>29.76</td>
<td>0.301</td>
<td>19.5</td>
</tr>
<tr>
<td>2.3</td>
<td>26.87</td>
<td>7.52</td>
<td>0.280</td>
<td>129.9</td>
<td>8.75</td>
<td>0.326</td>
<td>18.4</td>
</tr>
<tr>
<td>2.3</td>
<td>52.26</td>
<td>15.51</td>
<td>0.297</td>
<td>130.4</td>
<td>18.59</td>
<td>0.356</td>
<td>16.4</td>
</tr>
<tr>
<td>2.3</td>
<td>104.86</td>
<td>30.81</td>
<td>0.294</td>
<td>127.9</td>
<td>38.31</td>
<td>0.365</td>
<td>9.8</td>
</tr>
<tr>
<td>2.3</td>
<td>194.51</td>
<td>62.56</td>
<td>0.322</td>
<td>96.0</td>
<td>75.25</td>
<td>0.387</td>
<td>-22.1</td>
</tr>
<tr>
<td>2.3</td>
<td>238.47</td>
<td>59.05</td>
<td>0.248</td>
<td>71.3</td>
<td>92.79</td>
<td>0.389</td>
<td>-34.4</td>
</tr>
<tr>
<td>3.0</td>
<td>50.85</td>
<td>23.70</td>
<td>0.466</td>
<td>77.1</td>
<td>26.85</td>
<td>0.528</td>
<td>-5.0</td>
</tr>
<tr>
<td>3.0</td>
<td>104.48</td>
<td>46.43</td>
<td>0.444</td>
<td>76.0</td>
<td>57.13</td>
<td>0.547</td>
<td>-6.2</td>
</tr>
<tr>
<td>3.0</td>
<td>209.59</td>
<td>95.47</td>
<td>0.456</td>
<td>59.7</td>
<td>117.38</td>
<td>0.560</td>
<td>-16.9</td>
</tr>
</tbody>
</table>

Table 2. Summary findings from regular wave tests on the original platform configuration.

The wavelengths corresponding to the periodic times used in this testing are summarised in Table 2 below:
The heave motion achieves magnitude ratios of around 0.53 – 0.56 at the very low frequency end. To give this some calibration, at a scale of 30 times larger, the 3s period of the tank-tests would correspond to a period of 16.4s and a corresponding wavelength of 419m (swell). For each 10m of peak amplitude (i.e. for 20m peak-to-trough wave amplitude), the acceleration of the water would be ~2 m/s^2 (or 20% of 1g) and the platform heave accelerations would be significantly lower – around 1.2m/s^2. At lower periods around 1.7s for the tank tests (equivalent to 9.3s at full scale), the response ratio is lower but due to the higher frequency, the platform heave accelerations could be more like ~1.4m/s^2.

Accelerations in the surge direction are lower than those in the heave direction by a factor of roughly (3/4) at all frequencies so these appear less of a concern. In Table 2 above, the pitch accelerations are in units of degrees and pitch is defined about the reference point at the centre of the low cross-bar as shown in Figure 6. Since the vertical distance between the reference point and the nacelle is 2800 mm in the original configuration, the pitch values may each be multiplied by (2800/180) (=48.9) to determine equivalent surge values at the nacelle. Total surge motion at the nacelle comprises the sum of surge (mm) measured at the reference point plus 48.9 times the pitch measured. Table 2 shows that these two components are quite similar in magnitude at ~0.3Hz.

Regular wave tests were then conducted on a revised platform configuration having the extended heave-plates and a slightly lowered nacelle. This platform was also moored via a catenary mooring (much more flexible in the surge direction than the horizontal line originally used for the results in Table 2). The results from these tests are distilled in Table 4 below.

Comparison of Table 4 with Table 2 shows that the extension of the heave-plates to a lower depth has an extremely beneficial effect on heaving and pitching motions. There has been a slight increase in the responsiveness of the platform to surge excitation. There are two reasons why this slight increase might have occurred: (a) the heave-
plates would have some benefit in providing damping against surge motions until they were suspended far beneath
the platform on legs that were free to pivot at the base of each buoy and (b) the catenary mooring line now affords
substantially greater flexibility. The latter effect is thought to dominate.

With the revised configuration, heave motions are reduced to the point where they are no longer any conceivable
concern and attention focuses naturally on whether the surge motion may be problematic. Note that yaw, roll and
sway motions are not considered directly here because they are not excited to a first order by wave fronts that are
symmetric about the plane of symmetry of the platform. One test with irregular waves later in the test series does
examine these effects.

Surging motion measured at the reference point achieves magnitude ratios up to 72.9% in Table 3. The surge
accelerations associated with these tests are not negligible. Table 5 below summarises the largest accelerations.
Note that with Froude scaling, linear acceleration does not change with scale. At the lowest frequencies (with wave
periodic times >2.5s), the pitching angular accelerations are almost exactly in counterphase to these and there is
some cancellation of surge acceleration at the nacelle. At the most severe frequency here (periodic times of 1.7s)
the pitching acceleration is ~90° out of phase and this has the effect of adding ~4% of amplitude to the surging
acceleration measured at the reference point.

<table>
<thead>
<tr>
<th>Periodic Time (s) (Tank Scale)</th>
<th>Periodic Time (s) (Full Scale)</th>
<th>Wave Amplitude (Tank scale, (mm))</th>
<th>Wave Amplitude (Full scale, (m))</th>
<th>Surge Acceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>4.38</td>
<td>50.2</td>
<td>1.51</td>
<td>0.232</td>
</tr>
<tr>
<td>1.2</td>
<td>6.57</td>
<td>95.6</td>
<td>2.69</td>
<td>0.739</td>
</tr>
<tr>
<td>1.7</td>
<td>9.31</td>
<td>145.7</td>
<td>4.37</td>
<td>1.081</td>
</tr>
<tr>
<td>2.3</td>
<td>12.60</td>
<td>246.6</td>
<td>7.40</td>
<td>0.578</td>
</tr>
<tr>
<td>3.0</td>
<td>16.43</td>
<td>208.1</td>
<td>6.26</td>
<td>0.448</td>
</tr>
<tr>
<td>3.5</td>
<td>19.17</td>
<td>96.6</td>
<td>2.90</td>
<td>0.203</td>
</tr>
</tbody>
</table>

Table 5. Summary findings from regular wave tests on the platform configuration with extended heave plates.

From Table 5, if pk-pk wave magnitudes of 20m (10m “amplitude) were to be experienced occasionally with period
times of ~10s, nacelle surge accelerations in the order of 2.5 m/s² would be seen.

2.3.3 Irregular wave tests.

Irregular wave tests were conducted using waves generated to follow JONSWAP distributions. Each different wave
distribution was characterised by three parameters: the periodic time of the nominal frequency, $T_p$ (s), the reference
amplitude $A$ (mm) and the value of $\gamma$ (which determines how wide the distribution is).

Six different cases were captured as Table 6 below summarises:

<table>
<thead>
<tr>
<th>CASE</th>
<th>$T_p$ (s)</th>
<th>$A$ (mm)</th>
<th>$\gamma$ ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (original configuration)</td>
<td>1.5</td>
<td>100</td>
<td>3.3</td>
</tr>
<tr>
<td>2 (original configuration)</td>
<td>2.5</td>
<td>100</td>
<td>3.3</td>
</tr>
<tr>
<td>3 (original configuration)</td>
<td>1.5</td>
<td>200</td>
<td>3.3</td>
</tr>
<tr>
<td>4 (original configuration)</td>
<td>2.5</td>
<td>200</td>
<td>3.3</td>
</tr>
<tr>
<td>5 (revised configuration)</td>
<td>1.5</td>
<td>100</td>
<td>3.3</td>
</tr>
<tr>
<td>6 (revised configuration oriented 15° from wind)</td>
<td>2.5</td>
<td>200</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 6. Different cases for which response to irregular waves was observed.
In each case, all displacement responses of the platform were measured. The data was “windowed” following standard practice to ensure that no spectral leakage problems occurred and then Fourier transforms of the data were obtained and processed. Figures 19-28 below summarise the outcomes. Although data was being sampled at 100Hz and therefore it was theoretically possible to obtain spectral information up to 50Hz, in reality we find that the uncertainties on the platform position measurements appear to be such that above ~1.5Hz, the data is rather unreliable. This is observed mainly by looking at the phase information which shows no consistency above 1.5Hz. It is also to be expected from the fact (seen in the free-decay testing section) that the platform (rigid-body) natural frequencies are all <0.2Hz. The combination of the fact that the applied wave spectrum was already becoming low in magnitude at 1.5Hz and the fact that the platform responses were being “filtered” by the platform inertia resulted in the natural deflections of the platform being rather low so that noise on the measurements appeared to take over.

Case #1 (represented by Figures 19 and 20 above) indicate that ratios between platform surge and heave motions and the causal wave excitation can exceed unity but only at very low frequencies (around 0.4 Hz). The magnitude response data above 1.5Hz is not to be trusted because the amplitudes of motion at ~5Hz are in the order of 0.03mm (for surge) and 0.07mm (for heave) whereas the uncertainty on the measurements themselves is in the order of 1mm.

Case #2 (represented by Figures 21 and 22 above) agree quite well with case #1 above for frequencies up to 1Hz but since the magnitudes of the wave excitation now drop away more quickly than previously with frequency, the frequency limit of validity of the frequency response functions is now ~1Hz. (Observe that the wave excitation drops below 1mm at about 1Hz). Observe also that spikes in the frequency response data at frequencies above 1Hz are associated with drops in the magnitude spectrum of the applied wave – confirming the interpretation that the data at frequencies above 1Hz here are not reliable.
Case #3 (represented by Figures 23 and 24 above) again agrees well with case #1 and again we see the response becoming untrustworthy at frequencies > 1.5Hz. Below this frequency, however, the system response does appear to be slightly smoother than it had been before.

All of the above cases employ the original TetraFloat geometry – with heave-plates fitted directly to the bottom faces of the buoys. The revised arrangement produces a slightly different frequency response – shown in Figures 25 and 26 below. Here, we see magnitude responses for surge and heave going below unity by 0.5Hz where previously, this had not occurred until around 1Hz.

The spectral analysis of the irregular wave responses indicates that we would need to capture rather more data to obtain a smooth spectrum and a smooth frequency response. However, the relevant broad trends are obvious. The fact that magnitudes of the frequency response rise above unity where they did not do this for the pure sinusoidal wave tests demands some further thought. At the present time, the theory is that for very small amplitudes of motion, non-linearities associated with, for example, slightly clearance in the fixings joining the heave-plates to the bases of the buoys may be playing a strong role but that these non-linearities “lock-up” for larger amplitudes of motion.
2.4 ANALYSIS & CONCLUSIONS

Data has been analysed in the sections above.

3 MAIN LEARNING OUTCOMES

3.1 PROGRESS MADE

This period of testing at the IFREMER Deep Seawater testing tank has answered some major questions about stability and frequency response of the TetraFloat platform in yaw-sway motion. Although this report has not focused much on the experiences with the wind generator, we did operate in wind for quite a significant portion of the available time and the main observation from this was simply that the wind turbine operation was not impaired in any way by the small motions of the platform.

3.1.1 Progress Made: For This User-Group or Technology

TETRAFLOAT is one of a small number of floating platform concept supports for future offshore wind turbines which are designed to yaw bodily relative to the water surface such that in steady operation the wind always acts in the same direction relative to the platform. This obviously has strong benefits in terms of the optimal use of structural material and it is likely that several other competing platform designs in this nature will emerge. The existing DNV standard for floating wind turbine platforms demands that there should NOT be a single point of mooring (or attachment to the platform) and yet all of these platforms ultimately rely on the capability of the platform to swivel relative to some point.

This series of tests has shown that at least one of these bodily-yawing platforms has the capability to provide a very creditable support structure for future offshore wind turbines. It may well be highly useful in helping to make the case that a relaxation of the insistence on redundant mooring provisions is required.

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

A core capability of all bodily-yawing platforms, including TetraFloat, is the ability to transmit both a mechanical reaction force and electrical power through a single attachment point. A concept for such a rotatable joint has been developed by TetraFloat Ltd. with the ability to transfer the force and to pass the power (magnetically). Investigation of this joint is a separate activity.

The next significant step for the TetraFloat platform will be to construct a ~20m axis-height platform and trial that at sea with a dummy turbine on the top. A possible interim step is to place the existing ~3m axis-height model in a tank which can develop random waves. At present, it is not fully clear that this is needed.
3.2 **Key Lessons Learned**

- The concept of fitting heave-plates at the ends of long legs descending into deep water below the lower end of buoyant supports for floating wind turbine platforms (or other devices) appears to have strong merit.
- Interestingly, these “extended heave plates” appear to cause a more stiff and less heavily-damped set of transient responses. However, they are also much more effective in suppressing the all motions of a floating platform in response to large waves (swell) where the buoys of that platform move vertically relative to the water.
- With these extended heave-plates fitted, the platform capability to surge appears to have increased. However, the extent of this swell is still relatively small in acceleration terms.
- A floating platform with buoyancy widely-separated on the horizontal plane has strong advantages. The minimum required water plane areas for a given “Mh” product (where \( h \) is the height of the platform centre of gravity over the water and \( M \) is the platform mass) reduces with the square of this spread whereas the moments caused by wave excitation rise only with the first power of this spread.
- We have observed a tendency of the platform to tend to become slightly yaw-unstable as some buoys tend to move towards the “wave-shadow” of other buoys. In one testing case, the platform came out of alignment with the wind to sit in a different (and obviously more stable) orientation.
- It is obvious that a platform engineered to have relatively low water-plane area will tend to have relatively low moment stiffness also. Moments arising from the downwind force on a turbine rotor acting at a distance far above a platform base can be substantial and the requirement to trim the platform at the same time that this downwind force builds up is a strong one.
- Numerous very practical lessons were acquired during the conduct and consideration of these tests. One is that conical shapes are extremely effective in transmitting a force between an inner radius and an outer radius – but these conical shapes are rather hard to make in some cases. Also, the practical deployment of “extended heave-plates” will very likely require that they should be folded during the deployment, but ideally “locked down” during deployment and configured so that they can be folded-up again in the event of a requirement to remove the floating platform from the water.

4 **Further Information**

4.1 **Scientific Publications**

One journal paper on the application of extended heave plates is planned. It is not yet written (Dec. 2014).

4.2 **Website & Social Media**

A website for TetraFloat Ltd. is presently (Dec. 2014) in preparation and it is expected that this will launch in Feb. 2015 along with initiatives on Twitter and Facebook.

5 **References**

All of the content of this report has been based on standard mechanical and marine engineering concepts and practice. No external reference is required.
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.
### Infrastructure Access Report: TETRAFLOAT

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#### Development Protocol

<table>
<thead>
<tr>
<th>Stage</th>
<th>Concept Validation</th>
<th>Design Validation</th>
<th>Systems Validation</th>
<th>Device Validation</th>
<th>Economics Validation</th>
</tr>
</thead>
</table>
| TRL 1: Confirmation of Operation | Op. Verification  
Design Variables  
Physical Process  
Validate/Calibrate  
Maths Model  
Damping Effect  
Signal Phase | Real Generic Seas  
Design variables  
Damping PTO  
Natural Periods  
Power Absorption  
Wave to Device  
Response Phase | Hull Geometry  
Components  
Configurations  
Power  
Take-Off  
Characteristics  
Design Eng. (Naval Architects) | Final Design  
Accurate PTO  
[Active Control]  
Mooring system  
Survival Options  
Power Production  
Added mass | PTO Method Options & Control  
Inst Power  
Absorption  
Electricity  
Production & Quality | Scale effects of  
Overall Performance  
Characteristics  
Mooring & Anchorage Security  
Environmental Influences & Factors |

#### Objectives/Investigations

- Vessel Motion Response Amplitude Operators & Stability  
- Pressure / Force, Velocity EAOs with Phase Diagrams  
- Power Conversion Characteristic Time Histories  
- Hull Seaworthiness: Excessive Rotations or Submergence  
- Water Surface Elevation Averages of Devices

#### Output/Measurement

- Motion EAOs  
- Phase Diagrams  
- Power vs Time  
- Wave Climates @ head, beam, follow

#### Primary Scale (λ)

- λ = 1:25 - 100 (λ = 1:5 - 10)  
- λ = 1:10 - 25  
- λ = 1:2 - 10  
- λ = 1:1, Full size

#### Facility

- 3D Frame or 3D Basin  
- 3D Basin  
- Power Electronics Lab  
- Design Site  
- Sheltered Full Scale Site  
- Exposed Full Scale Site  
- Open Location

#### Duration -inc Analysis

- 1-3 months  
- 1-3 months  
- 13 months  
- 6 - 12 months  
- 6 - 18 months  
- 12 - 36 months  
- 1 - 5 years

#### Typical No. Tests

- 250 - 750  
- 250 - 500  
- 100 - 250  
- 100 - 250  
- 50 - 250  
- 1,000 - 2,500

#### Budget (€,000)

- 1 - 5  
- 5 - 75  
- 25 - 50  
- 50 - 250  
- 1,000 - 2,500  
- 10,000 - 20,000  
- 2,500 - 7,500

#### Device

- Idealised with Quick Simulated PTO - (50-150 waves)  
- Distributed Mass  
- Minimal Drag  
- Design Dynamics  
- Final design  
- (internal view)  
- Mooring Layout  
- Advanced PTO  
- Simulation Special Materials  
- Full Fabrication  
- True PTO & Elec Generator  
- Grid Control Electronics or Emulator  
- Emergency Response Strategies  
- Pre-Production  
- Pre-Commercial  
- Operational Multi Device

#### Excitation / Waves

- Monochromatic (10-25Hz)  
- Random Waves (30m scale)  
- Deployment One Site Sea Spectra  
- Long Short Crested Classical Sea  
- Select Mean wave Approach Angle  
- Full Scatter Diagram for initial Evaluation  
- Time Domain Response Modal & Control Strategy  
- Naval Architects Design Codes for Hull, Mooring & Anchorage  
- System, Economic & Business Plan

#### Specials

- Doff (heave only)  
- Short Crest Seas  
- Angled Waves  
- As Required  
- Storms Seas (3hr)  
- Finite Waves  
- Applied Damping  
- Multi Frep Inputs  
- Power Take-Off  
- Data Output  
- Marine Growth & Corrosion  
- Marine Permits  
- Environmental Impact  
- System, Economic & Business Plan  
- Arrangement Interaction  
- Grid Interaction  
- Small Array  
- Array Generation Station  
- Marked Interaction  
- Continuous Someone  
- EIA Reviews  
- Periodic With Geometry  
- Evaluation

#### Evaluation [Stage Gates]

- Absorbed  
- Power  
- Weight [tonnes]  
- Manufacturing Cost [€]  
- Capture [kW/m³] or [kW/tonne]  
- Production [kW]

- ≤ 15 €/kW  
- ≤ 10 €/kW  
- ≤ 5 €/kW
6.2 Any Other Appendices