Physical model tests on SPAR Buoy for Offshore Floating Wind Energy Conversion


1 Dipartimento di Ingegneria dell’Innovazione, Università del Salento, Via per Monteroni, Lecce, Italy, roberto.tomasicchio@unisalento.it; elisa.leone@unisalento.it; letizia.lusito@unisalento.it
2 Dipartimento di Ingegneria, Università degli studi della Campania, Viale Abramo Lincoln 5, Caserta, Italy, diego.vicinanza@unicampania.it; ing.ferrante@gmail.com; sara.russo@studenti.unicampania.it
3,10,15,16,17 Dipartimento di Ingegneria Meccanica, Politecnico di Milano, Via La Masa 1, Milano, Italy, marco.belloli@unimi.it; federico.taruffi@polimi.it; alessandro.fontanella@polimi.it; simone.dicarlo@mail.polimi.it; sara.muggiasca@polimi.it
4 CNR (National Research Council), Via di Vallerano 139, Roma, Italy, claudio.lugni@cnr.it
5,25,26 Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London, England, j.p.latham@imperial.ac.uk; l.via-estrem16@imperial.ac.uk; j.xiang@imperial.ac.uk
6 MaREI, Environmental Research Institute School of Engineering, University College Cork, Ringaskiddy, Cork, Ireland, gregorio.iglesias@ucc.ie; abel.martdiaz@gmail.com
7 DHI Water & Environment, Agern Alle 5, Horsholm, Denmark, bjj@dhi.group.com; bje@dhi.group.com
8 Department of Aerospace Engineering, Delft University of Technology, Mekelweg 5, Delft, Netherlands, A.C.Vire@tudelft.nl; i.rivera-areba@tudelft.nl
9 Department of Civil Engineering, Catholic University of Leuven, Kasteelpark Arenberg 40, Leuven, Belgium, jaak.monbaliu@kuleuven.be; griet.decorte@kuleuven.be
10 Dipartimento di Ingegneria, Università Roma Tre, Via della vasca navale, Roma, Italy, luca.pustina@uniroma3.it
11 Dipartimento di Ingegneria Civile DINCI, Università della Calabria, Via Pietro Bucci, Arcavacata di Rende, Italy, antonio.francone@unical.it
12 Offshore Engineering and Ocean Energy Group, University of Cantabria, Calle Isabel Torres 15, Parque Científico y Tecnológico de Cantabria, Santander, Spain, tommaso.battistella@unican.es; raul.guanche@unican.es
13 Departamento de Civil Engineering, Aalborg University, Thomans Mannaes Vej 23, Aalborg, Denmark mta@civil.aau.dk; jpk@civil.aau.dk; mmtk@civil.aau.dk
14 AGENIA S.r.l., Piazza Galileo 6, Bologna, Italy, elenamusci87@gmail.com

Abstract
The present paper describes the experiences gained from the design methodology and operation of a 3D physical model experiment aimed to investigate the dynamic behaviour of a spar buoy floating offshore wind turbine. The physical model consists in a Froude-scaled NREL 5MW reference wind turbine (RWT) supported on the OC3-Hywind floating platform. Experimental tests have been performed at Danish Hydraulic Institute (DHI) offshore wave basin within the European Union-Hydrabl+ Initiative, in April 2019. The floating wind turbine model has been subjected to a combination of regular and irregular wave attacks and different wind loads. Measurements of displacements, rotations, accelerations, forces response of the floating model and at the mooring lines have been carried out. First, free decay tests have been analysed to obtain the natural frequency and the modal damping ratios of each degree of freedom governing the offshore. Then, the results concerning regular waves, with orthogonal incidence to the structure, are presented. The results show that most of longitudinal dynamic response occurs at the wave frequency and most of lateral dynamic response occurs at rigid-body frequencies.

Keywords: Offshore structures, Floating wind turbine, Hydrodynamic behavior, Spar Buoy
Introduction
The vast majority of the development of offshore wind energy so far has involved substructures fixed to the seabed—monopiles, jacket frames, gravity-based foundations, etc. These seabed-fixed substructures are limited to water depths of up to 50 m. For this reason, offshore wind has developed in shallow areas, primarily in the North Sea. There remain many untapped marine regions close to the coast and with a significant resource, where seabed-fixed offshore wind turbines are not an option because of the large water depths: the Californian, Portuguese and Norwegian offshore regions are cases in point (Breton & Moe, 2009), as is most of the Mediterranean. Floating offshore wind turbines (FOWTs) are the solution to harvest this resource. Three main types of floating substructures are being considered: (1) the spar-buoy, stable thanks to the righting moment provided by ballast at the bottom of the spar; (2) the semi-submersible platform, which draws its stability from its large water-plane area; (3) and the tension-leg platform, stabilized by taut cables pre-tensioned by buoyancy. These concepts have been scaled down from their respective counterparts commonly used in the oil and gas industry. The aero-elastic effects, together with the slenderness of the structures and the smaller submerged volumes, which make drag predominant, are clear differences relative to previously built offshore structures (Roal et al., 2013). Therefore, new research is necessary, including laboratory testing, to improve the current understanding of these innovative structures as well as to provide reliable, high-quality data to validate numerical models able to assess this complex behaviour. During Phase IV of OC3, a reference model for the floating offshore wind turbine of the spar-buoy type with the NREL 5MW wind turbine mounted on top has been developed based on the currently installed Hywind spar-buoys along the Scottish East Coast. The goal of this model was to enable code comparison in order to better appraise the current array of offshore wind turbine codes and to arrive at conclusions concerning future design practices with these codes (Jonkman, 2010; Jonkman et al., 2010).
In addition, in 2012, Goupee et al. conducted wave basin tests for three floating offshore wind turbine concepts, one of them being the OC3 Hywind spar (Goupee et al., 2014). However, although the simultaneously working wind and wave generator correctly modelled wind and waves, wind-wave misalignment was not studied. In 2014, as part of Hydralab IV, a wide array of directional and unidirectional wave cases were run on the OC3 Hywind spar-buoy in the Ocean Basin at DHI, Denmark. At the time no wind generator was available, and therefore an approximate system was used to model the wind (Tomasicchio et al., 2018).
This paper presents the laboratory tests carried out at DHI in 2019 within Hydralab+ with the aim of addressing the above-mentioned knowledge and data gaps. The specific objectives of the tests were to correctly model the combined unidirectional and directional wave and wind loads in the presence of a wind generator (novelty compared to Hydralab IV), and to create a reliable and accurate database for calibration and validation of numerical models. Additionally, the coupling between a pitch-controlled rotor and the hydrodynamics of the FOWT system (regarded as a rigid body) was investigated.

Design of the model
Aerodynamics
The Hydralab+ wind turbine model is defined as a 1:40 model of the reference NREL 5MW, scaled according to Froude similarity rule, whose geometric and dynamic characteristics are listed in Table 1. The rotor is designed upscaling the PoliMi WTM, a 1:75 wind turbine model of the DTU 10MW RWT designed and currently utilized for wind tunnel tests on FOWT. The aerodynamic design procedure had to match the reference thrust and the reference torque. The Hydralab+ rotor is designed as a geometrical upscale of the PoliMi WTM and the entire blade is designed using the SD7032 airfoil.

Hydrodynamics
In order to adequately model the wave-structure interaction during the experiments, a 1/40 Froude scaled model OC3-Hywind spar buoy by Jonkman (Jonkman, 2010) was adopted. Tomasicchio et al. (Tomasicchio et al., 2018) have used this very same layout in the previous experiments undertaken as part of the Hydralab IV call. The spar buoy is of very simple geometry; it consists of a hollow cylinder with a taper on top allowing for a smooth transition between the large immersed diameter needed for stability and the small diameter at the wind turbine-spar buoy interface. It also reduces the hydrodynamic
loads at the water surface. No VIV suppressing devices were added, enabling us to take the vortex shedding effects along as well.

Table 1. Downscaled properties of NREL 5MW wind turbine with model scale ratio (1/λ) = 1:40

<table>
<thead>
<tr>
<th></th>
<th>Full-scale</th>
<th>Model scale</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor orientation</td>
<td>Clockwise rotation - Upwind</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Control</td>
<td>Variable speed - Collective Pitch</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
<td>3</td>
<td>λ</td>
</tr>
<tr>
<td>Rotor Diameter [m]</td>
<td>126</td>
<td>3.15</td>
<td>λ</td>
</tr>
<tr>
<td>Hub Diameter [m]</td>
<td>3</td>
<td>0.075</td>
<td>λ</td>
</tr>
<tr>
<td>Hub Height [m]</td>
<td>90</td>
<td>2.25</td>
<td>λ</td>
</tr>
<tr>
<td>Rated wind speed [m/s]</td>
<td>11.4</td>
<td>1.8</td>
<td>λ^{3/2}</td>
</tr>
<tr>
<td>Rotor speed (rated) [rpm]</td>
<td>12.1</td>
<td>76.5</td>
<td>λ^{1/2}</td>
</tr>
<tr>
<td>Ideal power [W]</td>
<td>5.0 × 10^6</td>
<td>12.35</td>
<td>λ^{7/2}</td>
</tr>
<tr>
<td>Rotor Mass [kg]</td>
<td>110000</td>
<td>1.6768</td>
<td>λ^3</td>
</tr>
<tr>
<td>Nacelle Mass [kg]</td>
<td>240000</td>
<td>3.6585</td>
<td>λ^3</td>
</tr>
</tbody>
</table>

To reach the correct draft and full system overall properties, i.e. the mass and center of gravity, the bottom of the cylinder has been partially filled by an assortment of small lead grains of several diameters. The downscaled properties of the spar buoy are listed in Table 2. For further details concerning the OC3-Hywind model, the reader is kindly referred to the work of Jonkman (Jonkman, 2010).

Table 2. Downscaled properties of OC3-Hywind spar-buoy (λ = 40).

<table>
<thead>
<tr>
<th></th>
<th>Full-scale</th>
<th>Model scale</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform diameter below taper [m]</td>
<td>9.4</td>
<td>0.23</td>
<td>λ</td>
</tr>
<tr>
<td>Depth to the platform base below SWL [m]</td>
<td>130</td>
<td>3.25</td>
<td>λ</td>
</tr>
<tr>
<td>Platform diameter above taper [m]</td>
<td>6.5</td>
<td>0.16</td>
<td>λ</td>
</tr>
<tr>
<td>Depth to top of taper below SWL [m]</td>
<td>4</td>
<td>0.10</td>
<td>λ</td>
</tr>
<tr>
<td>Depth to bottom of taper below SWL [m]</td>
<td>12</td>
<td>0.30</td>
<td>λ</td>
</tr>
<tr>
<td>CM location below SWL [m]</td>
<td>89.91</td>
<td>2.25</td>
<td>λ</td>
</tr>
<tr>
<td>Mass, including ballast [kg]</td>
<td>7466330</td>
<td>116.66</td>
<td>λ^3</td>
</tr>
<tr>
<td>Roll inertia about CM [kg·m²]</td>
<td>4229230000</td>
<td>41.30</td>
<td>λ^5</td>
</tr>
<tr>
<td>Pitch inertia about CM [kg·m²]</td>
<td>4229230000</td>
<td>41.30</td>
<td>λ^5</td>
</tr>
<tr>
<td>Yaw inertia about centerline [kg·m²]</td>
<td>164230000</td>
<td>1.60</td>
<td>λ^5</td>
</tr>
</tbody>
</table>

For the mooring system, the original crowfoot layout of catenary lines of the OC3-Hywind spar-buoy, was downscaled. However, due to the limited available water depth at DHI's Ocean Basin, the original catenary lines from the OC3-Hywind project, had to be simplified after scaling down. As a result, each line was reduced to a series of seven springs connected to a mass (a concrete block) placed on the basin floor. Each spring configuration was designed in order to closely mimic the originally downscaled surge and sway behavior.

Experimental campaign

Experimental layout

The deep-water basin at DHI is 20m long, 30m wide and 3m deep, with a 3m x 3m and 6m deep pit at the mid of the basin. Its wave maker is equipped with 60 individually controlled flaps, which are able to generate regular and irregular unidirectional and directional wave fields. To minimize reflection, a 6.5m long sloping wave absorber is located opposite the wave maker. The free surface elevation is captured by a row of three wave gauges at 1.5m before the spar-buoy and a row of six wave gauges placed at 1m behind the spar-buoy. Both sets of wave gauges are placed perpendicular to the wave direction. In addition, two more wave gauges are located at the back of the spar-buoy to allow for an array reflection
analysis to obtain the incident and reflected waves (Mansard et al., 1980). These wave gauges are placed parallel with respect to the wave propagation. The far-field layout of basin and the wave gauge locations in the near-field area close to the FOWT are shown in Figure 1 together with the mooring system.

Wave elevation was sampled at 100Hz for regular and irregular waves. The duration for regular wave cases is about 3 minutes and 20-30 minutes for the irregular wave cases. Furthermore, in case of large amplitude long waves, typically leading to Keulegan-Carpenter numbers larger than 7, vortex-shedding may occur in the small portion of the spar buoy just below the water level (Sumer & Mutlu, 2006). In order to detect such vortex shedding effects, two Vectrino Acoustic Doppler Velocimeters were located close to each other at the back of the spar buoy. They were placed at an angle of 20 degrees with respect to the wave propagation. To evaluate the vertical distribution of the dynamic pressures, three pressure transducers are located on the spar-buoy in the splash region. The wave impact forces are then obtained by spatially integrating these pressure measurements. A Qualisys Tracking System was used to track the six-degrees-of-freedom motion of the FOWT. In addition, the model is equipped with four accelerometers. Two inertial frames measuring the translational and angular accelerations along three axes were used; one located at the top of the spar buoy and another one at the nacelle. Two uniaxial accelerometers were placed on the tower to capture the acceleration along the global x- and y-axis. A load cell was placed at each mooring line connection to observe the tension force produced by the spar-buoy motion. An encoder placed in the wind turbine rotor allows measuring the angular velocity of the generator and, in addition, enables to track the reference for the blades’ pitch. All observed data were synchronized by the DHI Wave Synthesizer.

**Load Analysis overview**

All the tests have been performed using different conditions of wave and wind. For what concern wave conditions, the assigned parameters characterizing a sea state, are wave height, wave period and wave direction, which are orthogonal (0°) and yawed (20°) to the structure; a distinction between regular and irregular waves must be done. In Table 3 the characteristics of the generated waves are given, where H and T are the regular wave height and wave period, respectively, and H_s and T_p are the significant wave height and peak wave period, respectively. For the regular waves, each wave height has been coupled with each period, for both wave directions. For the irregular waves, each wave height has been characterized by its wave period, only wave direction changed.

Wind conditions are characterized by “no wind condition” and “rated condition” represented by value of wind speed of 1.85 m/s. In addition, some tests have been performed at different nominal wind speed values: 1.25m/s, 1.45m/s, 1.65m/s, 1.95m/s.

**Dynamic response under regular waves**

*Free decay tests*

Free decay tests have been carried out to evaluate the natural frequencies of each DoF. The damping ratio was calculated using the logarithmic decrement method, as a function of two response amplitudes X_i and X_{i+1}, according to the following expression:
\[ \xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \]  

Where \( \delta = \frac{1}{j} \ln \frac{x_1}{x_{j+1}} \) being the number of the cycles taken into account (Karimirad, 2014). To quantify the non-linear nature of damping, the damping ratios were calculated considering the average value of different number of cycles, as shown in Figure 2. In this case, the strong nonlinearity of damping in the first cycle could affect the average damping of the first five cycles. Then, the damping ratios stabilize and become almost constant. In particular, values of 14.7%, 11.1%, 4.3%, 3.4%, 6.0%, 3.3% and 8.5% were found for surge, sway, heave, pitch, roll and yaw respectively when the first 7 cycles of oscillation were considered. The sway tests in above rated conditions were not conducted due to technical reasons.

### Table 3. Physical model test program

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular</td>
</tr>
<tr>
<td>0 m/s (no wind)</td>
<td>2</td>
</tr>
<tr>
<td>1.85 m/s (rated)</td>
<td>5.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W</th>
<th>H or H(_s)</th>
<th>T or T(_p)</th>
<th>Dir</th>
<th>H or H(_s)</th>
<th>T or T(_p)</th>
<th>Dir</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[m]</td>
<td>[s]</td>
<td>[deg]</td>
<td>[m]</td>
<td>[s]</td>
<td>[deg]</td>
</tr>
<tr>
<td>5.1</td>
<td>7.0</td>
<td>0</td>
<td>5.1</td>
<td>0.8</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8.9</td>
<td>0.05</td>
<td>1.4</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>12.0</td>
<td>20</td>
<td>0.25</td>
<td>1.6</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>13.9</td>
<td>0.06</td>
<td>1.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>7.1</td>
<td>0.13</td>
<td>1.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>9.7</td>
<td>0.08</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.3</td>
<td>0</td>
<td>1.15</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>9.1</td>
<td>20</td>
<td>1.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10.7</td>
<td>0.20</td>
<td>1.69</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Damping ratio from free decay tests, obtained from the average logarithmic decrement considering the peaks \( X_i \) and \( X_{i+1} \): no wind conditions (left) and above condition (right)

### Time and frequency domain analysis results

Only part of the data set is analyzed in this manuscript. In particular, six tests with regular waves, defined by \( H \) and \( T \), respectively the wave height and the wave period, were selected for time and frequency domain analysis. In Table 4, the selected tests are listed together with the first, second and third wave harmonic and the natural frequencies for each DoF [Hz] obtained from analysis of the free decay tests. Three tests refer to “no wind conditions” and three tests refer to “above rated conditions”. For all selected tests, wave incidence was orthogonal to the structure.
As an example, sample time histories of surge, sway, roll and pitch of test #250 are shown in Figure 3. It is noted that the small quantities associated with a longitudinal motion are almost sinusoidal and the dominant wave frequency can be clearly seen. However, the small quantities associated with lateral motion, show different behavior, mainly dominated by their respective natural frequency, with the dominant wave frequency superimposed on it. These findings are consistent for all tests analyzed and are further confirmed by frequency domain analysis. The power spectrum of all selected tests was obtained for each parameter, as an example in Figure 4 the PSD of surge measured during test #250 is shown. The dominant wave frequency of 0.63 Hz is clearly identified. In addition, the second and third harmonics are found at 1.25 Hz and 1.87 Hz, although for the considered case the contribution of the third harmonic is relatively low. The reason for this lies in the fact that the wave is closer to second order than to third order. So, the influence of this third harmonic is small. Finally, the natural frequencies of each DoF are pretty visible. These five
frequencies are recognized in almost all measured signals, with different relative amplitudes, depending on wave height and wind condition.

Figure 4. PSD of Surge as measured in test #250

To quantify the contribution of the different frequencies to the total response, Tables 5.1 through 5.3 show the power corresponding to narrow ranges around the relevant frequencies, together with the total power to evaluate the expected maxima of the response parameters, knowing that some quantities of energy may be shared by more DoF with similar frequency. In the tests for the longitudinal motions, the response is dominated by the fundamental wave frequency, while for lateral motions, a large amount of the excitation can be found at the respective natural frequencies. For the longitudinal response, it is observed that the fundamental wave frequency contributes to the total surge from 54.9% to 99.6%, to the total pitch from 73.7% to 98.8% and to the total longitudinal acceleration from 98.3% to 99.9%. Different behavior is noted in lateral response; for sway and roll the fundamental wave frequency is not always dominant, ranging from 7.2% to 71.6% to the total sway and from 15.8% to 52.0% to the total roll. Only in the case of lateral acceleration the fundamental wave frequency contributes in a dominant way from 98.4% to 99.9%.

Table 5.1. Surge and Sway narrow-band and total power

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Surge narrow-band and total power [%]</th>
<th>Sway narrow-band and total power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Wind 0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>H [m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1X Wave Freq.</td>
<td>54.9 99.6 90.9 71.2 89.4 95.4 71.6 20.7 34.9 8.4 7.2 36.4</td>
<td></td>
</tr>
<tr>
<td>2X Wave Freq.</td>
<td>8.3 0.3 7.2 2.6 2.8 0.0 0.1 1.4 7.2 10.3 6.0 13.1</td>
<td></td>
</tr>
<tr>
<td>3X Wave Freq.</td>
<td>0.2 0.0 0.1 0.2 0.1 0.0 0.0 0.5 0.0 0.1 0.2 2.3</td>
<td></td>
</tr>
<tr>
<td>Surge Freq.</td>
<td>11.1 0.2 0.4 2.3 4.7 1.1 1.7 15.6 18.9 2.7 4.4 5.0</td>
<td></td>
</tr>
<tr>
<td>Sway Freq.</td>
<td>10.8 0.3 0.3 / / / 3.6 39.3 30.1 / / /</td>
<td></td>
</tr>
<tr>
<td>Heave Freq.</td>
<td>0.2 0.0 0.0 3.8 0.2 0.3 2.8 5.1 10.5 7.2 2.7 3.4</td>
<td></td>
</tr>
<tr>
<td>Pitch Freq.</td>
<td>0.2 0.0 0.0 4.7 1.2 0.2 2.8 16.1 11.5 30.1 27.9 8.7</td>
<td></td>
</tr>
<tr>
<td>Roll Freq.</td>
<td>0.5 0.0 0.0 5.1 2.2 0.3 1.0 23.0 21.2 34.1 31.9 11.7</td>
<td></td>
</tr>
<tr>
<td>Yaw Freq.</td>
<td>0.3 0.0 0.0 1.5 0.6 0.1 0.1 0.0 5.0 5.7 6.5 4.2</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.2. Pitch and Roll narrow-band and total power

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Pitch narrow-band and total power [%]</th>
<th>Roll narrow-band and total power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Wind</td>
<td>Rated Condition</td>
</tr>
<tr>
<td>H [m]</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>1X Wave Freq.</td>
<td>96.9</td>
<td>98.8</td>
</tr>
<tr>
<td>2X Wave Freq.</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>3X Wave Freq.</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Surge Freq.</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Sway Freq.</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Heave Freq.</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Pitch Freq.</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Roll Freq.</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Yaw Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 5.3. Acceleration $a_{x,\text{base}}$ and $a_{x,\text{top}}$ narrow-band and total power

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Acceleration $a_{x,\text{base}}$ narrow-band and total power [%]</th>
<th>Acceleration $a_{x,\text{top}}$ narrow-band and total power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Wind</td>
<td>Rated Condition</td>
</tr>
<tr>
<td>H [m]</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>1X Wave Freq.</td>
<td>98.3</td>
<td>99.7</td>
</tr>
<tr>
<td>2X Wave Freq.</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>3X Wave Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Surge Freq.</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Sway Freq.</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Heave Freq.</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Pitch Freq.</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Roll Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Yaw Freq.</td>
<td>0.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Finally, the histograms of the occurrence frequencies of surge, sway, roll and pitch as evaluated from test #250 are shown in Figure 5. Consistently with what previously observed, it is noticed that the quantities related to the longitudinal response feature a bimodal distribution, indicating an almost sinusoidal response. On the other hand, the histograms of the quantities related to the lateral response appear to be associated with the combination of the narrowband process and a broader band process, whose relative intensity depends on the particular quantity observed.

**Dynamic Forces**

With regard to the internal forces, in the same format, Table 6 shows the power corresponding to narrow ranges around the relevant frequencies for internal forces. The wave frequency is always dominant, with contributions ranging from 94.4% to 99.0% for the longitudinal forces, and from 32.0% to 82.5% for the lateral forces. Even in this case, the energy associated to the wave frequency in lateral response is lower than in longitudinal response, however the second harmonics are predominant.
Figure 5. Histograms of the occurrence frequencies of surge, sway, pitch and roll as measured in test #250

Table 6 Forces $F_{x,nacelle}$ and $F_{y,nacelle}$ narrow-band and total power

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Force $F_{x,nacelle}$ narrow-band and total power [%]</th>
<th>Force $F_{y,nacelle}$ narrow-band and total power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Wind</td>
<td>Rated Condition</td>
</tr>
<tr>
<td>$H$ [m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1X Wave Freq.</td>
<td>98.1</td>
<td>99.0</td>
</tr>
<tr>
<td>2X Wave Freq.</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>3X Wave Freq.</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Surge Freq.</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Sway Freq.</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Heave Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Pitch Freq.</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Roll Freq.</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Yaw Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Mooring lines forces

Analysis of the mooring line forces revealed a strong sensitivity of the measured data on the alignment of the lines with the oncoming waves. In the experimental setup, the mooring lines 2 and 3 are symmetric at an angle of 120° with mooring line 1 which was aligned with the oncoming waves behind the model. In Figure 6, a sample time history of the forces measured in test #250 at mooring lines 1 and 2 are shown, demonstrating that the dynamic force in the mooring line 2 located ahead of the model is larger than the dynamic force in the mooring line 1 located behind the model. In time histories it can be seen that the force in the mooring line 2 is dominated by first wave frequency and surge and sway frequencies while the force in mooring line 1 the greatest contribute comes from dominant wave frequency. As displacement and acceleration spectra, the surge, sway, pitch and roll oscillations frequencies are clearly visible, together with the oncoming wave frequency and first, second and third harmonics. Table 7 shows the power corresponding to narrow ranges around the relevant
frequencies, together with the total power of the force in mooring line 1 and 2, respectively. In this case, most of energy is concentrated at the wave frequency up to 97.0% of the total power, but not always it is the dominant one. In some tests, most of energy is concentrated at sway and surge frequency up to 58.5%. Also in this case the dynamic forces are proportional to the oncoming wave height, whereas the mean forces are very little affected by it.

Figure 6. Sample time histories of mooring line forces for test #250

Table 7. Mooring line 1 and Mooring line 2 forces narrowband and total power

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Mooring line 1 narrow-band and total power [%]</th>
<th>Mooring line 2 narrow-band and total power [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Wind</td>
<td>Rated Condition</td>
</tr>
<tr>
<td>H [m]</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>1X Wave Freq.</td>
<td>97.0</td>
<td>95.3</td>
</tr>
<tr>
<td>2X Wave Freq.</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>3X Wave Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Surge Freq.</td>
<td>0.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Sway Freq.</td>
<td>0.1</td>
<td>4.2</td>
</tr>
<tr>
<td>Heave Freq.</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Pitch Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Roll Freq.</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Yaw Freq.</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Conclusion
In the present paper, the behavior of a model-scaled Spar Buoy Wind Turbine has been observed in order to investigate the dynamic behavior for different wave and wind conditions. Regular waves with a given wave period and different wave heights have been considered, in absence of wind load and with a value of wind speed that lead the above rated condition of the wind turbine rotor. Displacements, accelerations, tower forces and mooring line forces have been measured and analysed. Free decay tests were carried out to detect the natural periods of each DoF and the damping ratios; natural frequencies of order of (10^-2) were found for the surge and sway motions and of order of (10^-4) for the roll and pitch motions. The damping coming from free decay test were also calculated. Besides reaching the coefficient representing the exponentially decaying sinusoid, damping ratios of 14.7%, 11.1%, 4.3%, 3.4%, 6.0%, 3.3% and 8.5% were found from free decay oscillations for surge, sway, roll and pitch, respectively when the first 7 cycles of oscillation were considered. Analysis of the dynamic response have been carried out in terms of displacements, accelerations and tower and mooring line forces. It reveals that for the displacements and rotations associated with the longitudinal response, the behavior is dominated by the wave frequency, but for the same parameters associated with the lateral response, the wave frequency is not always dominant and most of energy lies within its DoF. It is noticed that at higher frequencies the response increases with wave height both without and with the wind load;
this trend is most prominent in presence of wind, suggesting that the gyroscopic effects and the rotor dynamics can partially affect the dynamic response.

Acknowledgments
The coordinator, Roberto Tomasicchio, thanks Mark Klein Breteler from Deltares and Bjarne Jensen from Danish Hydraulics Institute for their advices and patience since the submission of the proposal. The Users Group thanks DHI for the warm hospitality and the technicians for their assistance. “This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 654110, HYDRALAB+.”

References
National Renewable Energy Lab (NREL), Golden, CO, USA.