International Wind Engineering Conference
IWEC 2014

IMPROVED TANK TEST PROCEDURES FOR SCALED FLOATING OFFSHORE WIND TURBINES

KOLJA MÜLLER[*], FRANK SANDNER[*], HENRIK BREDMOSE[†], JOSÉ AZCONA[‡],
ANDREAS MANJOCK[§], RICARDO PEREIRA[§]

[*] Stuttgart Wind Energy (SWE) - University of Stuttgart
Allmandring 5B, 70569 Stuttgart, Germany
e-mail: mueller@ifb.uni-stuttgart.de, sandner@ifb.uni-stuttgart.de

[†] DTU Wind Energy - Technical University of Denmark
Nils Koppels Alle - Building 403, 2800 Lyngby, Denmark
e-mail: hbre@dtu.dk, www.vindenergi.dtu.dk

[‡]Wind Energy Department - National Renewables Energy Centre (CENER)
Ciudad de la Innovación 7, 31621 Sarriguren (Navarra), Spain
e-mail: jazcona@cener.com, www.cener.com

[§]DNV GL Energy - Renewables Certification
Brooktorkai 18, 20457 Hamburg, Germany
e-mail: andreas.manjock@dnvgl.com, ricardo.pereira@dnvgl.com

Keywords: Floating Offshore Wind turbines, tank testing, scaled models, rotor model, representative aerodynamic forces, Software-in-the-Loop

Summary: This study collects issues from previous tank test campaigns of scaled Floating Offshore Wind Turbines (FOWT), compares the different scaling methodologies, points out critical aspects and shows possible alternatives and recommendations for future tests depending on the specific objective. Furthermore, it gives practical recommendations for the modeling and construction of scaled rotors. The presented scaling procedure will be applied in tank tests within the EU Seventh Framework Program **InnWind** (ENERGY.2012.2.3.1 “Innovative wind conversion systems (10-20MW) for offshore applications”).

1 INTRODUCTION

The numerical simulation tools for calculating motion and dynamics of FOWT are still under development. Many existing codes of the offshore and oil & gas industry provide approved and validated routines describing the dynamics and loading from waves and currents to floating structures. But they lack a sufficient consideration of the aerodynamic loads on the rotor caused by turbulent wind, complex rotor aerodynamics and an own control system on top of the structure. This introduces a fully non-linear loading source to the entire system. Additionally, the influence of second order hydrodynamics and mooring line behavior is not always modeled in sufficient detail.

Currently many research programs like OC3/OC4 [1] compare the results of different simulation codes together with measurement data from model tests. Today only a few full scale prototypes are in operation and measurements of existing floating concepts are rare. Therefore experiments with scaled floating models in wave tanks in combination with wind modelling are a cost effective approach to gather data for referencing and validating the dynamics and loads of FOWT. This might also be a necessary step for the certification of a prototype.

2 LITERATURE REVIEW

For more than twenty years the idea of installing wind power generators offshore on floating foundations is pursued in research and industry. Within many of the past and present projects the challenge of experimental tests with combined wind and wave loading has been addressed. Overviews of these projects can be found in [2], [3], [4] and [5]. Useful practical information on scale model building can be found in the theses of the University of Worcester, see [6] and [7] and [8].

Wave tank tests of FOWT can be conducted with two major purposes: Firstly for **validation of numerical models** and secondly in order to obtain the full system dynamics in all occurring load situations for **full-scale prototypes**, which are going to be built. There have been various commercial projects for the implementation of floating wind energy systems. The projects **Hywind** [9], [10] and **WindFloat** [11], [12], [13] and [14] were among the first to gain commercial experience in the years 2009 and 2011, respectively. **Gicon** [15], [16] and **GustoMSC** with their “Tri-Floater” [17], [18], [19], [20] followed in the years after with multiple test campaigns. In Japan the **Fukushima project** [21] with various phases includes model and prototype tests for a conventional spar concept, a “hybrid spar” and a semi-submersible. The wave tank tests for the spar concept are documented in [22]. Innovative large-scale offshore floating structures are investigated by **Kyushu University**, [23]. Ishihara has developed an innovative multi-turbine foundation and presented model tests in [24] and [25]. The “**Japan Marine United Advance Spar**” was scaled for wave tank tests, [4]. The large-scale prototype projects in Europe, of which tank tests are known, are **HiPRWind** with a semi-submersible [26], **BlueH** with a two-bladed rotor and semi-submersible foundation [27] and the Norwegian **Sway**, which is a tension-leg spar [28]. A comparable concept is the **Nautica** wind power layout, for which some information on testing can be found online in [29]. The multi-turbine concept **WindSea** offers some data on the wave tank tests online, see [30] and [31]. Tests were also conducted for the multi-purpose foundation **Poseidon**, see [32]. This concept was tested in various wave tanks with and without wind and also on site with different prototype scales. The **Pelastar** TLP by Glosten Associates [33] was tested but very little information is published. The **Vertiwind** concept by Technip with a vertical-axis wind turbine was tested in a scale of 1:2, see [34]. Recently, the **Nautilus** semi-submersible concept, which has also been tested in the Cork wave tank in Ireland, was published in [35]. **Iberdrola** is developing a TLP concept and has presented the wave tank test layout in [36] with a publication on the most recent test campaign, see [37]. The University of Maine is involved in a project building the first scaled FOWT prototype in the US called **VolturnUS**, see [38]. All of the described model tests have used a scale between 1:130 and 1:2.

Various publicly funded research projects have included FOWT wave tank tests. As part of the **Marinet** project [39], state of the art scaling routines were revised and the dynamic-elastic scaling proposed as adequate for scaled FOWT-tests. The **DeepWind** project aimed at an integrated research on vertical-axis floating wind turbine (VFOWT) systems including tests [40]. A numerical model development of VFOWT together with a wave tank validation is given by [41].

Within the **Winflo** project [42], scaled models were developed and tested in order to understand the dynamic behavior of the concept design and to validate the floater and mooring design. The models included an adapted rotor design.

The **DeepCwind** [43] project to this point delivers the most throughout insight available on the capabilities of numerical and experimental investigation of the three major FOWT systems: tension leg platform (TLP), semi-submersible and spar buoy. Major parts of the research were the assessment of a proper scaling methodology [44] and its numerical verification [45], the realization of a model wind turbine for wave basin testing [46] and the development of thrust scaled blades [47]. Also in the focus were the analysis of the interaction of the mooring dynamics with the global response of the FOWT [48] and the calibration and validation of a full scale simulation model within the simulation software FAST [49]. In 2013 a new test campaign with the same semi-submersible platform has been performed under improved testing conditions in the MARIN facility in the Netherlands, see [50]. The results together with a comparison to the previous DeepCwind campaign and a model of a smaller scale (1:130) for a reliability assessment can be found in [51]. A code validation of the MLTSIM hydrodynamics code coupled with the FAST software with the same test data can be found in [52]. A discussion on the differences of the behavior of the three different platform concepts is available in [53].

A detailed test session description aiming at the realization of a full scale turbine has been given by **Utsunomiya**. His tests cover simplified scale model tests for extreme condition dynamic analysis, see [54], and simulation validation, see [55]. They reach towards scaled prototype tests in full-scale at-sea-environment [56] and [57]. The derivation of the numerical model is given in [58]. A semi-submersible with a single-point mooring has been tested by **Osaka University** see [59]. **Shin et al.** published test results to study the motions of the OC3-Hywind spar [60] and a new spar-type FOWT model in 2D and 3D wave tanks, see [61], [62]. Another investigation of a “stepped spar”-model in a curved wave tank has been presented by **Sethuraman et al.** with a focus on the validation of the software OrcaFlex and nonlinear mooring line behavior comparing the RAOs for pitch, surge and heave motion in regular and irregular waves, see [63]. **Philippe et al**. [64] tested a model of the Dutch Trifloater in order to validate their numerical model. The influence of storm waves on a simplified TLP model was analyzed by **Wehmeyer et al.** [65] with varying tower stiffnesses, putting large effort in high wave modeling quality and showing that the inclusion of second order hydrodynamics is essential, especially regarding TLP-specific responses such as ringing and slack line events. Another validation of numerical results for a TLP has been done by **Ren et al.**, [66] and **Olinger et al**. [67], who collected information on the dynamic behavior in pitch, surge and heave direction using simplified models of TLP and spar type FOWT. They found that surge motion of the platform dominates over other motions for TLP & Spar and that varying tether pretension has little effect on RAO values. Within the **AFOSP** project a monolithic concrete spar design of a FOWT has been developed and wave basin tests presented in [68].

The impact of the rotor dynamics of the wind turbine rotor or the gyroscopic effect on the coupled system dynamics has been studied in [69]. In [70] an instability of floating wind turbines has been reported, yielding large amplitudes in yaw together with large amplitudes in pitch-motion coupled by the gyroscopic effect.

The presence of two different phases of the surrounding medium (air and water) poses a general problem to the geometrical scaling of the considered system. A description of the general loads acting on offshore structures within classical marine technology and the underlying physics can be found in [71] and [72]. For hydrodynamic similitude, Froude scaling needs to be applied, but inevitably leads to an error in the scaling of the Reynolds number for both hydro- and aerodynamics. While testing experience indicates that on the hydrodynamic side, the KC number is more significant [73], the aerodynamic Reynolds number is of high importance due to its influence on the flow condition around the airfoil. The geometric downsizing of the wind turbine effectively alters the aerodynamics of the scaled turbine, i.e. the Reynolds number and the associated forces on the turbine [74]. In order to keep a correct relationship of the forces, different solutions have been used in the past. Rotor models range from concentrated masses with added point forces [55], over drag disks with a rotating body [12] up to the redesign of the rotor blades in order to correctly scale the aerodynamics of the rotor, see [50], [75] and [76]. More optimization of this state-of-the-art scaled blade design through an alternative pitch angle distribution is possible [77]. In order to avoid the discussed scaling problem, a part of the environment can be imitated by real-time controlled actuators as has been done for hydrodynamics [78], [79] and [80] and for aerodynamics [81].

Building on the given experiences, two alternative procedures for rotor modeling are presented and evaluated below. The aims are to optimize the quality of experimental results when using an adjusted blade design and to reduce the costs of future experiments.

3 AERODYNAMIC FORCES FROM RE-DESIGNED MODEL SCALE ROTOR

The scaling of the aerodynamic forces is sketched in the following. Further the establishment of these loads through direct wind forcing is discussed and the requirement of a tailored model scale rotor design is detailed, following the work of [39], [44], [51], [77] and [76]. As the wind generation system may limit the range of wind speeds that can be generated, a free parameter is introduced, which modifies the scaled inflow speed at the expense of changing the tip speed ratio. This approach is denoted the Froude-β scaling, see [82]. The limitations of the redesigned rotor approach and the open questions subject to current research are outlined.

a. Froude scaling and the need for a redesigned rotor

As mentioned above, testing floating wind turbines in wave tanks leads to application of Froude scaling in order to fulfill the requirement of a true scaling of the wave force. This follows from the role of gravity as the governing restoring effect for the waves. Given a length scale ratio of

$$\lambda = \frac{L_p}{L_m} \tag{1}$$

the conservation of gravitational acceleration g between prototype and model scale locks the time scale ratio to be

$$\frac{T_p}{T_m} = \lambda^{\frac{1}{2}}. \tag{2}$$

Here (L, T) are representative length and time scales and subscripts (p, m) denote prototype and model respectively. Due to the requirement of a conserved ratio between structural mass and water mass, mass M scales according to

$$\frac{M_p}{M_m} = \frac{\rho_{wp}}{\rho_{wm}} \lambda^3, \tag{3}$$

where ρ_w is the density of water. The above scaling of length, time and mass leads to a scaling of water particle velocities as

$$\frac{u_{wp}}{u_{wm}} = \lambda^{\frac{1}{2}}. \tag{4}$$

Hence, if the ratio of air and water velocities is to be preserved from prototype to model scale, a similar relation for the air-velocities u_a follows

$$\frac{u_{ap}}{u_{am}} = \lambda^{\frac{1}{2}}. \tag{5}$$

Further, forces, F, scale as

$$\frac{F_p}{F_m} = \frac{\rho_{wp}}{\rho_{wm}} \lambda^3. \tag{6}$$

Rotor thrust is given as

$$F_T = 0.5 \rho_a C_T A u_{a.}^2 \tag{7}$$

where C_T is the thrust coefficient, A is the rotor area and ρ_a is the air density. Given that the rotor area scales as λ^2 and that the air velocities scale by $\lambda^{\frac{1}{2}}$, the requirement of force to scale as

$$\frac{\rho_{wp}}{\rho_{wm}} \lambda^3 \tag{8}$$

yields the desired scaling of the thrust coefficient as

$$\frac{C_{Tp}}{C_{Tm}} = \frac{\rho_{wp}}{\rho_{wm}}. \tag{9}$$

Although this result of a conserved thrust coefficient may suggest that the prototype rotor design can be geometrically down-scaled to lab scale, the lowered lab-scale Reynolds number which results from the scaling of air-velocity leads to insufficient thrust levels. At the smaller Reynolds number, the lift-to-drag ratio is reduced and an increased chord-length is therefore needed for the model-scale blade to deliver the same thrust-coefficient as at full scale [39], [44], [51], [77] and [76]. For this reason a re-design of the blades at model scale is needed. In this context it is natural to base the design on low-Reynolds number air foils. The redesigned model scale rotor will thus have blades with increased chord-length relative to the prototype scale blades, see e.g. [77].

b. Adjustment of air-velocity scaling

The changed Reynolds number and blade geometry implies that the similarity of the aerodynamic flow between prototype and model scale is broken. Further, for the above scaling, a large scale ratio leads to very small air-velocities at lab scale – in some cases so small that perturbations from heat convection and other motion in the lab can cause significant distortion. On the other hand, the wind generation system may also have limited capacity such that at larger scale ratios, certain wind speeds cannot be obtained. Note here that the wind generation is very different from the controlled conditions in a usual wind tunnel. The model scale rotor area may be 3m in diameter and the wind must be generated over water. For the above reasons, an adjustment of air-velocity scaling may be needed. This can be described through a free parameter β, such that

$$\frac{u_{ap}}{u_{am}} = \lambda^{\frac{1}{2}}\beta. \tag{10}$$

For β = 1, Froude scaling is obtained, while β < 1 implies larger air velocities than for Froude scaling. With this modified air-scaling, the thrust coefficient must scale as

$$\frac{C_{Tp}}{C_{Tm}} = \frac{\rho_{wp}}{\rho_{wm}}\beta^2. \tag{12}$$

Further, the tip speed ratio (TSR) will not be conserved since

$$\frac{TSR_p}{TSR_m} = \beta. \tag{13}$$

Although conservation of TSR is generally preferred, the lack of aerodynamic similarity is likely to justify such a change. Note that with the factor β, the Reynolds number scales as

$$\frac{Re_p}{Re_m} = \frac{\lambda^{\frac{3}{2}}\nu_m}{\beta\nu_p}, \tag{14}$$

where ν is the kinematic viscosity. The Froude-β scaling is detailed in [82].

c. Pros and cons of the scaled rotor approach

The approach of a re-designed rotor at model scale is able to deliver the correct thrust, see e.g. [51], [76]. Further, given that the mass distribution and rotational speed are scaled correctly, the correct gyroscopic forces and 1P, 3P forcing frequencies will be reproduced [39], [77]. If also the structural stiffness is scaled correctly, the structural frequencies and deflection to the loads will scale correctly [39], [77]. Further dimensionless numbers which will be conserved are the Keulegan-Carpenter number (KC) and the Lock number. This is conserved in the Froude-β scaling, both for the aerodynamic and hydrodynamic forces.

Other dimensionless numbers are not conserved. These are the Reynolds number in the air and in the water which leads to changed hydrodynamic force coefficients and the need for a re-designed rotor; the Weber number which measures the balance of hydrodynamic surface tension to inertial loads (not expected to have importance, except at very small scales); the Strouhal number in water and air - for preserved Strouhal number and strict Froude scaling $\beta = 1$, though, the vortex shedding frequency will scale as $\sqrt{\lambda}$ which is consistent with the time scaling; the Mach number in water and air (not considered to be important); and the tip speed ratio, which is only conserved for $\beta = 1$. Besides the dimensionless numbers, a couple of effects will also not scale automatically:

- the aerodynamic torque
- the aerodynamic power
- the generator torque and its contribution to roll-forcing
- the magnitude of the 3P forcing from the tower shadow

However, a careful rotor and nacelle design may help on this. An accurate reproduction of the above mentioned properties is part of current active research.

4 AERODYNAMIC FORCES FROM SOFTWARE-IN-THE-LOOP METHOD

Another method to include a realistic force to represent the aerodynamic thrust in combined wind and wave scaled tests is based on the use of a ducted fan substituting the wind turbine scaled rotor. The fan thrust is controlled by the fan rotational speed set by the controller, which again depends on a computer real time simulation of the full scale rotor in the wind field. The real time simulation considers the platform motions measured in real time in the wave tank test. Therefore, the aerodynamic damping is modelled by the fan force. We refer to the described method as Software-in-the-Loop (SIL).

The layout of the SIL system is shown in Figure 1. The left side describes the simulation part of the system, which works in full scale, and the right side represents the wave tank scaled test. The different magnitudes that are interchanged between both blocks are transformed by the appropriated scaling laws based on the factor scale λ .

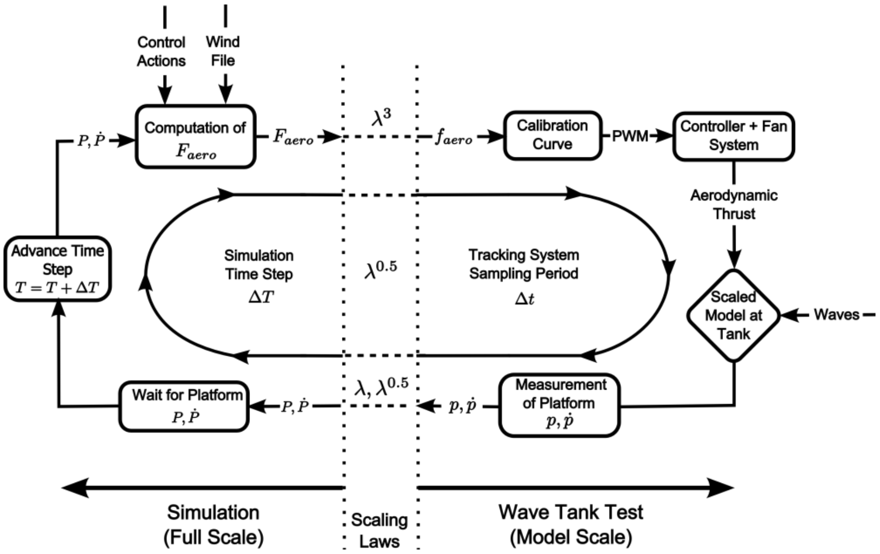

Figure 1: Software-in-the-Loop Method Diagram

The simulation tool provides the total aerodynamic force on the shaft F_{aero} from integration of all the aerodynamic loading at the blade elements. This force in full scale is transformed to the model scale (f_{aero}) and the pulse width of the PWM (Pulse-Width Modulation) signal needed to produce the force in the ducted fan is provided by a calibration curve previously obtained. The control system regulates the fan speed that introduces the desired force at the model's hub height. The waves produced by the wave maker are also acting over the platform and, together with the aerodynamic thrust, inducing motions. The acquisition system measures the positions and velocities for the 6 degrees of freedom of the platform at a certain sampling period. These measurements are sent to the simulation tool that is waiting for the data to advance one time step and calculate the new value of the aerodynamic thrust. For this

reason, the sampling period Δt and the simulation time step ΔT have to be set accordingly (with a factor $\lambda^{0.5}$).
The methodology is explained in more detail in [83], where some experimental results obtained in a test campaign of a 6 MW semi-submersible platform at the ECN (Ècole Centrale de Nantes) wave tank are also presented. These tests results using the SIL method are compared with computer simulations to show the performance and validate the method.

a. Pros and cons of the SIL approach

The SIL approach can provide a realistic aerodynamic thrust on the scaled model. As the computation of the force takes into consideration the motion of the platform, the effect of the aerodynamic damping is included. In addition, the control actions, the different types of wind (turbulent, constant, gusts) and the operating condition (idling, power production, etc.) are taken into account for the calculation of the thrust. Conditions where the waves and wind are misaligned are sometimes not easy to be reproduced in wave tanks with wind generation systems. With this method, they can be easily achieved by changing the fan orientation at the tower top. Furthermore, the SIL system allows performing test cases including wind at wave basins where the wind generation system is not available. In addition, the simplicity of the method makes it cost effective and flexible because the material is not specific for a certain wind turbine model and it could be used in different tests for different models.
Effects that are not scaled correctly with this procedure are:

- the aerodynamic torque
- the gyroscopic momentum.

Alternatively the use of a rotating scaled mass to represent the rotor inertia can be used to match the gyroscopic effects. Active research on the response of different fan units depending on the size of the wind turbine, scale factor, etc. is being conducted with the aim to explore the limits of the methodology.

5 CONCLUSIONS

To this point, numerous model scaled tests have been run and extensive experience on the dynamics of FOWT systems could thus be collected and have been summarized in this paper. The complex physics of the coupled wind-wave environment pose a strong challenge toward the scaling procedures. Past research projects have shown that various approaches with different levels of complexity for the combined Froude-scaled model test exist. As testing procedures are likely to become part of the certification process, two alternatives to the state-of-the-art procedure with blades modified according to Froude-scaling have been presented here in order to reduce the complexity of future test procedures. Whereas the SIL approach reduces the aerodynamics to a correctly reproduced thrust force by a fan the re-designed rotor aims at a match of power and thrust coefficients. Thus, the first solution will answer questions related to the full system dynamics whereas the latter allows also more detailed studies of the rotor aerodynamics and special effects therein. Eventually, the testing procedures for FOWT are significantly more complex than the common tests of naval architecture. It will be therefore essential to thoroughly select the adequate setup for each test and exclude features and effects where possible.

6 BIBLIOGRAPHY

[1] A. Robertson, J. Jonkman, M. Masciola, H. Song, A. Goupee, A. Coulling and C. Luan, "Definition of the Semisubmersible Floating System for Phase II of OC4".

[2] EWEA, "Deep water - The next step for offshore wind energy," 2013.

[3] A. R. Henderson and D. Witcher, "Floating Offshore Wind Energy - A Review of the Current Status and an Assessment of the Prospects," *Wind Engineering,* vol. 34, no. 1, pp. 1-16, 2010.

[4] L. Consulting Main(e) International, "Floating Offshore Wind Foundations: Industry Consortia and Projects in the United States, Europe and Japan - An Overview," Bremen ME 04551, USA, September 2012.

[5] C. M. Wang, T. Utsunomiya, S. C. Wee and Y. S. Choo, "Research on floating wind turbines: a literature survey," in *The IES Journal Part A: Civil & Structural Engineering*, 2010.

[6] J. Frye, N. Horvath and A. Ndegwa, "Design Of Scale-Model Floating Wind Turbine: Spar Buoy," 2011.

[7] D. Berlo, C. Gabrielson, S. Hanly, M. Parzych, M. Sacco and S. Ryan, "Design Of Scale-Model Floating Wind Turbine Platforms," 2010.

[8] S. K. Naqvi, "Scale model experiments on floating offshore wind turbines," 2012.

[9] F. Nielsen, T. Gunnar, D. Hanson and B. Skaare, "Integrated dynamic analysis of floating offshore wind turbines," *21st International Offshore and Polar Engineering Conference,* 2006.

[10] A. Myhr, K. J. Maus and T. A. Nygaard, "Experimental and Computational Comparisons of the OC3-HYWIND and Tension-Leg-Buoy (TLB) Floating Wind Turbine Conceptual Designs," in *Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference*, 2011.

[11] D. Roddier, "WindFloat: A Floating Foundation For Offshore Wind Turbines Part I: Design Basis And Qualification Process," in *Proceedings of the ASME 28th International Conference on Ocean, Offshore and Arctic Engineering*, 2009.

[12] C. Cermelli, D. Roddier and A. Aubault, "WindFloat: A Floating Foundation For Offshore Wind Turbines Part II: Hydrodynamics Analysis," in *Proceedings of the ASME 28th International Conference on Ocean, Offshore and Arctic Engineering*, 2009.

[13] A. Aubault, C. Cermelli and D. Roddier, "WindFloat: A Floating Foundation For Offshore Wind Turbines Part iii: Structural Analysis," 2009.

[14] D. Roddier, C. Cermelli, A. Aubault and A. Weinstein, "WindFloat: A floating foundation for offshore wind turbines," *Journal of Renewable and Sustainable Energy,* vol. 2, no. 3, p. 033104, 2010.

[15] J. Großmann and F. Dahlhaus, "Gicon-TLP For Floating Wind Turbines Experimental And Numerical Investigations," in *Proceedings of the EWEA Offshore*, 2013.

[16] F. Adam, T. Myland, F. Dahlhaus and J. Großmann, "Scale Tests of the Gicon-TLP for Wind Turbines," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, 2014.

[17] F. Huijs, J. Mikx, F. Savenije and E.-J. D. Ridder, "Integrated design of floater , mooring and control system for a semi-submersible floating wind turbine," in *Proceedings of the EWEA Offshore*, 2013.

[18] A. Courbois, "Étude expérimentale du comportement dynamique d ’ une éolienne offshore flottante soumise à l’action conjuguée de la houle et du vent," 2013.

[19] B. Bulder and A. Henderson, Studie Naar Haalbaarheid Van en Randvoorwaarden Voor Drijvende Offshore Windturbines, TNO-Bouw, 2002.

[20] F. Huijs, E.-J. D. Ridder and F. Savenije, "Comparison Of Model Tests And Coupled Simulations For A Semi-Submersible Floating Wind Turbine," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, 2014.

[21] "Fukushima Forward," The University of Tokyo, [Online]. Available: http://www.fukushima-forward.jp/pdf/pamphlet3.pdf.

[22] T. Chujo, Y. Minami, T. Nimura and S. Ishida, "Experimental Study For Spar Type Floating Offshore Wind Turbine With Blade-Pitch Control," in *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, 2013.

[23] Kyushu University, 2012. [Online]. Available: www.riam.kyushu-u.ac.jp/ship/indexe.html (30). [Accessed April 2014].

[24] T. Ishihara, P. V. Phuc, H. Sukegawa and K. Shimada, "A study on the dynamic response of a semi-submersible floating offshore wind turbine system Part 1 : A water tank test," in *Proceedings of the 12th International Conference on Wind Engineering*, Cairns, Australia, 2007.

[25] T. Ishihara, M. Waris Bilal and H. Sukegawa, "A Study On Influence Of Heave Plate On Dynamic Response Of Floating Offshore Wind Turbine System," in *The 3rd European Offshore Wind (EOW) Conference*, 2009.

[26] L. Quesnel, J. Bard and J. E. Hanssen, "Introducing Hiprwind high power, high reliability offshore wind technology," in *Proceedings of the EWEA*, 2011.

[27] Blue H Group, 2012. [Online]. Available: http://www.bluehgroup.com/. [Accessed 15 November 2012].

[28] Sway, 2012. [Online]. Available: http://www.sway.no/. [Accessed 16 April 2014].

[29] Nautica Windpower, 2012. [Online]. Available: http://www.nauticawindpower.com. [Accessed 16 May 2014].

[30] Windsea, 2012. [Online]. Available: www.windsea.no. [Accessed 19 April 2014].

[31] Scandinavian Oil-Gas Magazine, "Windsea - Next generation Floating Wind Farm," *Scandinavian Oil-Gas Magazine,* no. 7/8 2010, 2010.

[32] Floating Power Plant, 2012. [Online]. Available: http://www.floatingpowerplant.com/. [Accessed 20 April 2014].

[33] PelaStar Wind, 2012. [Online]. Available: www.pelastarwind.com/. [Accessed 3 May 2014].

[34] "Pole Mer Paca," 2012. [Online]. Available: http://www.polemerpaca.com/Ressources-energetiques-marines/Energies-marines-renouvelables/VERTIWIND. [Accessed 3 May 2014].

[35] G. Aguirre-Suso, G. Pérez-Morán, M. Sánchez-Lara, J. Lopez-Mendia, J. Fernández, A. Laidler, M. Guijón and M. Martin, "Nautilus: Design Considerations For A 5mw Wind Turbine Semisubmersible Platform," in *Proceedings of the EWEA*, 2014.

[36] J. Amate Lopez, V. d. D. Martín, L. Marugan García and P. Alonso, "Iberdrola Ingeniería TLPWind: "A smart way to drive costs down ”," in *Proceedings of the EWEA*, 2014.

[37] R. Zamora-Rodriguez, P. Gomez-Alonso, J. Amate-Lopez, V. De-Siego-Martin, P. Dinoi, A. Simos and A. Souto-Iglesias, "Model Scale Analysis Of A TLP Floating Offshore Wind Turbine," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, 2014.

[38] A. Viselli, A. Goupee and H. Dagher, "Model Test Of A 1:8 Scale Floating Wind Turbine Offshore In The Gulf Of Maine," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, 2014.

[39] H. Bredmose, S. E. Larsen, D. Matha, A. Rettenmeier, E. Marino and L. Saettran, "MARINET D2 .4: Collation of offshore wind-wave dynamics," 2012.

[40] U. S. Paulsen, T. F. Pedersen, H. A. Madsen, K. Enevoldsen, P. H. Nielsen, P. A. Berthelsen, S. Carstensen, E.-j. D. Ridder and G. V. Bussel, "Deepwind- An innovative wind turbine concept for offshore," in *Proceedings of the EWEA*, Brussels, Belgium, 2011.

[41] K. Wang, T. Moan and M. O. L. Hansen, "A Method For Modeling Of Floating Vertical Axis Wind Turbine," in *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, 2013.

[42] M. L. Boulluec, A. Martin and A. Houmard, "Tank Testing Of A New Concept Of Floating Offshore Wind Turbine," in *Proceedings of the 22nd International Conference on Offshore and Polar Engineering*, 2013.

[43] A. Robertson, A. Goupee, J. Jonkman, I. Prowell, P. Molta, A. Coulling and M. Masciola, "Summary Of Conclusions And Recommendations Drawn From The Deepcwind Scaled Floating Offshore Wind System Test Campaign," in *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, 2013.

[44] H. R. Martin, R. W. Kimball, A. M. Viselli and A. J. Goupee, "Methodology for Wind/Wave Basin Testing of Floating Offshore Wind Turbines," in *Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering OMAE2012*, 2012.

[45] A. N. Robertson, J. M. Jonkman, A. J. Goupee, R. W. Kimball and A. H. P. Swift, "FAST Code Verification of Scaling Laws for DeepCwind Floating Wind System Tests Preprint Anant Jain," in *Proceedings of the 22nd International Conference on Offshore and Polar Engineering*, Rhodes, Greece, 2012.

[46] H. R. Martin, "Development Of A Scale Model Wind Turbine For Testing Of Offshore Floating Wind Turbine Systems," 2011.

[47] M. Fowler, D. A. T. Iii, R. Kimball and A. Goupee, "Wave Basin Model Tests Of Floating Offshore Wind Turbines," in *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, 2013.

[48] M. Masciola, A. Robertson, J. Jonkman, A. Coulling and A. Goupee, "Assessment of the Importance of Mooring Dynamics on the Global Response of the DeepCwind Floating Semisubmersible Offshore Wind Turbine," in *Proceedings of the Twenty-third (2013) International Offshore and Polar Engineering*, Anchorage/Alaska, 2013.

[49] G. Stewart, M. Lackner and A. Goupee, "Calibration and Validation of a FAST Floating Wind Turbine Model of the DeepCwind Scaled Tension-Leg Platform," in *Proceedings of the 22nd International Conference on Offshore and Polar Engineering*, Rhodes, Greece, 2012.

[50] E.-J. D. Ridder, W. Otto, G.-J. Zondervan, F. Savenije and F. Huijs, "State of the art model testing techniques for floating wind turbines," in *Proceedings of the EWEA Offshore*, 2013.

[51] R. Kimball, A. J. Goupee, M. J. Fowler, E.-J. D. Ridder and J. Helder, "Wind/wave basin verification of a performance-matched scale-model wind turbine on a floating offshore wind turbine platform," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, 2014.

[52] B. Koo, A. J. Goupee, K. Lambrakos and H.-J. Lim, "Model Test Data Correlations with Fully Coupled Hull/Mooring Analysis For A Floating Wind Turbine On A Semi-Submersible Platform," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, 2014.

[53] A. J. Goupee, B. J. Koo, K. F. Lambrakos and R. W. Kimball, "Model Tests for Three Floating Wind Turbine Concepts," in *Offshore Technology Conference*, Houston, TX/USA, 2012.

[54] T. Utsunomiya, S. Yoshida, H. Ookubo, I. Sato and S. Ishida, "Dynamic Analysis of a Floating Offshore Wind Turbine Under Extreme Environmental Conditions," *Journal of Offshore Mechanics and Arctic Engineering,* vol. 136, no. 2, 2014.

[55] T. Utsunomiya, T. Sato, H. Matsukuma and K. Yago, "Experimental Validation for Motion of a SPAR-Type Floating Offshore Wind Turbine Using 1/22.5 Scale Model," *Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering,* pp. 951-959, 2009.

[56] T. Utsunomiya, H. Matsukuma, S. Minoura, K. Ko, H. Hamamura, O. Kobayashi, I. Sato, Y. Nomoto and K. Yasui, "At Sea Experiment of a Hybrid Spar for Floating Offshore Wind Turbine Using 1/10-Scale Model," *Journal of Offshore Mechanics and Arctic Engineering,* vol. 135, no. 3, p. 8, 2013.

[57] S. Ishida, K. Kokubun, T. Nimura, T. Utsunomiya, I. Sato and S. Yoshida, "At-sea experiment of a hybrid spar type offshore wind turbine," *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering,* 2013.

[58] H. Matsukuma and T. Utsunomiya, "Motion analysis of a floating offshore wind turbine considering rotor-rotation," *The IES Journal Part A: Civil & Structural Engineering,* vol. 1, no. 4, pp. 268-279, 2008.

[59] K. Iijima, M. Kawai, Y. Nihei, M. Murai and T. Ikoma, "Conceptual Design Of A Single-Point-Moored Fowt And Tank Test For Its Motion Characteristics," in *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, 2013.

[60] J. Jonkman, "Definition of the Floating System for Phase IV of OC3," 2010.

[61] H. Shin, "Model Test of the OC3-Hywind Floating Offshore Wind Turbine," in Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference, 2011.

[62] H. Shin and P. T. Dam, "Model Test of a Floating Offshore Wind Turbine Moored by a Spring-tensioned-leg," in *Proceedings of the Twenty-second (2012) International Offshore and Polar Engineering Conference*, 2012.

[63] L. Sethuraman and V. Venugopal, "Hydrodynamic response of a stepped-spar floating wind turbine: Numerical modelling and tank testing," *Renewable Energy,* vol. 52, pp. 160-174, 2013.

[64] M. Philippe, A. Courbois, A. Babarit, P. Ferrant, F. Bonnefoy and J.-M. Rousset, "Comparison of simulation and tank test results of a semi-submersible floating wind turbine under wind and wave loads," *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering,* 2014.

[65] C. Wehmeyer, F. Ferri and P. B. Frigaard, "Experimental Study of an Offshore Wind Turbine TLP in ULS Conditions," in *Proceedings of the Twenty-third (2013) International Offshore and Polar Engineering*, 2013.

[66] N. Ren, Y. Li and J. Ou, "The Wind-Wave Tunnel Test of a New Offshore Floating Wind Turbine with Combined Tension Leg-Mooring Line System," in *Proceedings of the Twenty-second (2012) International Offshore and Polar Engineering Conference*, 2012.

[67] D. J. Olinger, E. Destefano, E. Murphy, S. K. Naqvi and G. Tryggvason, "Scale-model experiments on floating wind turbine platforms," in *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2012.

[68] C. Molins, A. Campos, F. Sandner and D. Matha, "Monolithic Concrete Off-Shore Floating Structure For Wind Turbines," in *Proceedings of the EWEA*, 2014.

[69] H. Fujiwara, T. Tsubogo and Y. Nihei, "Gyro Effect of Rotating Blades on the Floating Wind Turbine Platform in Waves," in *Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference*, 2011.

[70] M. Karimirad, "Stochastic Dynamic Response Analysis of Spar-Type Wind Turbines with Catenary or Taut Mooring Systems," 2011.

[71] O. M. Faltinsen, Sea loads on ships and offshore structures, Cambridge [u.a.]: Cambridge University Press, 1993.

[72] T. Sarpkaya and M. Isaacson, Mechanics of wave forces on offshore structures, Van Nostrand Reinhold Co., 1981.

[73] S. Chakrabarti, "Physical Model Testing of Floating Offshore Structures," 1998.

[74] A. Jain, A. Robertson, J. Jonkman, A. Goupee, R. Kimball and A. H. Swift, "FAST Code Verification of Scaling Laws for DeepCwind Floating Wind System Tests," in *Proceedings of the Twenty-second (2012) International Offshore and Polar Engineering Conference*, 2012.

[75] M. Make, "Predicting scale effects on floating offshore wind turbines," 2014.

[76] E.-J. d. Ridder, W. Otto, G.-J. Zondervan, F. Huijs and G. Vaz, "Development of a Scaled-Down Floating Wind Turbine for Offshore Basin Testing," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, California, USA, 2014.

[77] A. M. Hansen, R. Laugesen, H. Bredmose, R. Mikkelsen and N. Psichogios, " Small scale experimental study of the dynamic response of a tension leg platform wind turbine," *Submitted for journal publication.,* 2014.

[78] C. Bottasso, F. Campagnolo and V. Petrovic, "Wind tunnel testing of scaled wind turbine models: Beyond aerodynamics," *Journal of Wind Engineering and Industrial Aerodynamics,* vol. 127, pp. 11-28, 2014.

[79] F. Campagnolo, C. L. Bottasso and P. Bettini, "Design, manufacturing and characterization of aero-elastically scaled wind turbine blades for testing active and passive load alleviation techniques within a ABL wind tunnel," *Journal of Physics: Conference Series,* 2014.

[80] I. Bayati, M. Belloli, D. Ferrari, F. Fossati and H. Giberti, "Wind Tunnel Tests On Floating Offshore Wind Turbines : Design Of A 6-DOD Robotic Platform For Floating Motion Simulation," in *Proceedings of the EWEA*, Barcelona, 2014.

[81] M. Hall, J. Moreno and K. Thiagarajan, "Performance Specifications For Real-Time Hybrid Testing Of 1:50-Scale Floating Wind Turbine Models," in *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, 2014.

[82] F. Sandner, H. Bredmose, A. Jose and K. Müller, "InnWind.EU design basis (4.22: Methods for performing scale-tests for method and model validation)," FP7 - InnWind.EU, 2014.

[83] J. Azcona, F. Bouchotrouch, M. González, J. Garciandía, X. Munduate, F. Kelberlau and T. A. Nygaard, "Aerodynamic Thrust Modelling in Wave Tank Tests of Offshore Floating Wind Turbines Using a Ducted Fan," *J. Phys.: Conf. Ser. 524 012089,* 2014.