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Hybrid and traditional scale model testing of floating offshore wind turbines

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Abstract

Floating offshore wind turbines (FOWTs) are nowadays designed and certified relying on numerical codes that must be calibrated and validated by means of experiments. Scale model testing represents a valuable source of low-cost and low-uncertainty experimental data. However, the inherent complexity of a FOWT requires to simultaneously reproduce phenomena with different physics making scale model tests a hard task. This paper presents two experimental methodologies that can fit the purpose. One is based on a physical scale model of the complete FOWT that is studied in a wave basin with suitable generation of wind and waves. The other exploits the hardware in the loop methodology and the real-time combination of a physical wind turbine scale model with a numerical model of the floating platform. The differences between the methodologies are highlighted, showing the most significative advantages of each of the two.

Keywords: Floating Offshore Wind Turbines, Scale Model Testing, Wind Turbine Control, Wind Tunnel Testing

1 Introduction

Floating offshore wind energy (FOWE) is nowadays a recognized technology representing the key to harvest the abundant wind energy resource of many coastal areas with water depths greater than 50 meters. Design and certification of floating offshore wind turbines (FOWTs) mostly relies on numerical simulation tools that must be calibrated and validated by a combination of computations and experiments [1, 2, 3].

Experimental data for validation can be collected either on a full-scale system or relying on scale model testing. Scale model experiments have been widely used to complement, or even replace, full-scale experiments in the development of new technologies. Making experiments at small scale inside a dedicated facility allows a greater control over the testing conditions and a better knowledge of disturbances and errors. Moreover, it is often possible to perform measurements that are not feasible at full-scale and, all of that, at reduced costs [4]. However, scale model testing presents some peculiar problems, the most notable that is not possible to match all the relevant properties of the full-scale system at small scale. This is even more true for FOWTs, that are complex system, interested by phenomena with very different physics that must be reproduced simultaneously.

Most of the experiments about FOWTs performed so far followed a traditional approach historically adopted by the oil and gas industry to qualify offshore structures. The complete floating system (i.e. floater, mooring lines and wind turbine) is reproduce by means of a physical scale model and tests are carried out in a wave/ocean basin with physical generation of wind and waves [5, 6, 7, 8]. The scale model is a scaled representation of the full-scale system that must be obtained imposing Froude similitude in order to preserve the reproduction of gravity-dependent loads, as weight and hydrodynamic forces. However, this is not ideal for FOWTs where also aerodynamic loads have to be reproduced. These strongly depends on the Reynolds number that cannot be preserved if Froude similitude is imposed [9].

To overcome this limitation hybrid methodologies were recently developed in some laboratories. The FOWT is divided in two complementary substructures, either reproduced by a physical scale model or through a real-time numerical model. The two subsystems are then coupled through suitable measurements and an actuation system. In ocean basin hardware in the loop (HIL) tests, a physical model of the floating platform and wind turbine tower is combined with an actuation system (tendons [10, 11], winches [12], ducted fans [13, 14] or multi-fan systems [15]) that is demanded to simulate rotor loads. A complementary methodology was developed at Politecnico di Milano (PoliMi), where aerodynamic and control-induced loads are generated by a physical scale model of the wind turbine operated inside a wind tunnel, whereas platform rigid-body dynamics and hydrodynamic loads are simulated in real-time from the integration of a numerical model [16, 17, 18, 19, 20].

The object of this work is to investigate the main differences, potentialities, drawbacks and consequences of the classical ocean basin testing opposed to wind tunnel hybrid HIL testing. The discussion is carried out on the base of the outcome of two test campaigns about FOWTs that were based on the above mentioned methodologies. The first one, was developed at PoliMi within the *LIFES50+ project* to study a FOWT based on the DTU 10MW reference wind turbine (RWT) [21]. A 6-degrees-of-freedom (DOFs) HIL system is used to reproduce the FOWT dynamics inside the PoliMi wind tunnel.The second one, was adopted within the *Hydralab+ SparBOFWEC* research framework. 1/40 Froude-scaled model of the OC3 spar-buoy floating wind turbine based on the 5MW NREL [22] was realized and used to investigate the overall structure dynamics under combined wind and wave loads at the DHI wave basin. The two methodologies are compared in terms of design requirements for the floating system scale model, fidelity of the reproduced aerodynamic and hydrodynamic loads, uncertainties in the experiment results, especially those concerning the rotor dynamics and platform motions.

2 Experimental setups

The setups discussed in this work are depicted in Figure 2 for comparison. The OO Star DTU 10MW was tested at the PoliMi wind tunnel adopting an HIL methodology, whereas the OC3 5MW NREL was studied at the DHI wave basin according to traditional practices. In both cases the wind turbine is simulated by a physical scale model with the same control capabilities of the full-scale machine. The model is exposed to a wind field and, in any case, it is demanded of reproducing the wind turbine rotor loads and the aerodynamic tower loads. It is evident that the main difference between the two setups, and then between the two experimental methodologies, is the simulation of the floating platform, in terms of rigid body motion of the FOWT, mooring system response and hydrodynamic excitation loads. While in wave basin experiments the reproduction of the floating platform also relies on a physical scale model, in the case of HIL wind tunnel tests the FOWT is split into complementary subdomains. The floater, and all the loads acting on it a part from those associated with the wind turbine, is the numerical subsystem of the experiment, that is combined to the wind turbine, or the physical subsystem, by real-time measurements and a 6-DOF robot (i.e. the actuation system).

The choice of splitting the problem into two complementary sub-problems and use a combination of a numerical model, measurements and actuation to reproduce one of the two, can be justified looking at Table 1. The main scale factors (defined as the ratio of a given quantity evaluated at full-scale and at model scale, $\lambda_x = x_p/x_m$) for the OOStar DTU 10MW, object of HIL wind tunnel tests, and of the OC3 5MW NREL, of wave basin tests, are shown. The scale factors effectively used in the experiments for both the systems are reported, indicated as real, together with those that would have been used adopting the complementary methodology, theoretical (i.e. "Wind tunnel (real)" are the scale factors that were effectively used to design wind tunnel HIL experiments about the OOStar DTU 10MW, whereas "Ocean basin (theoretical)" are the scale factors that would have been required to test the same system inside a wave basin according to the traditional methodology).

The length scale factor λ_L is fixed in any case by comparing the dimensions of the full-scale system with the space available in the test section of the adopted facility. The mass scale factor is in any case function of λ_L only (i.e. the mass depends only on the size of the object) being the density of the main fluids inside which the FOWT has to operate, air and water, the same at full-scale and model scale. The remaining independent dimension that complements length and mass is time. The time scale is fixed indirectly choosing a velocity scale factor λ_v, being time function of velocity and length only. The difference between the two methodologies ultimately lies in the velocity scale factor. In case of ocean

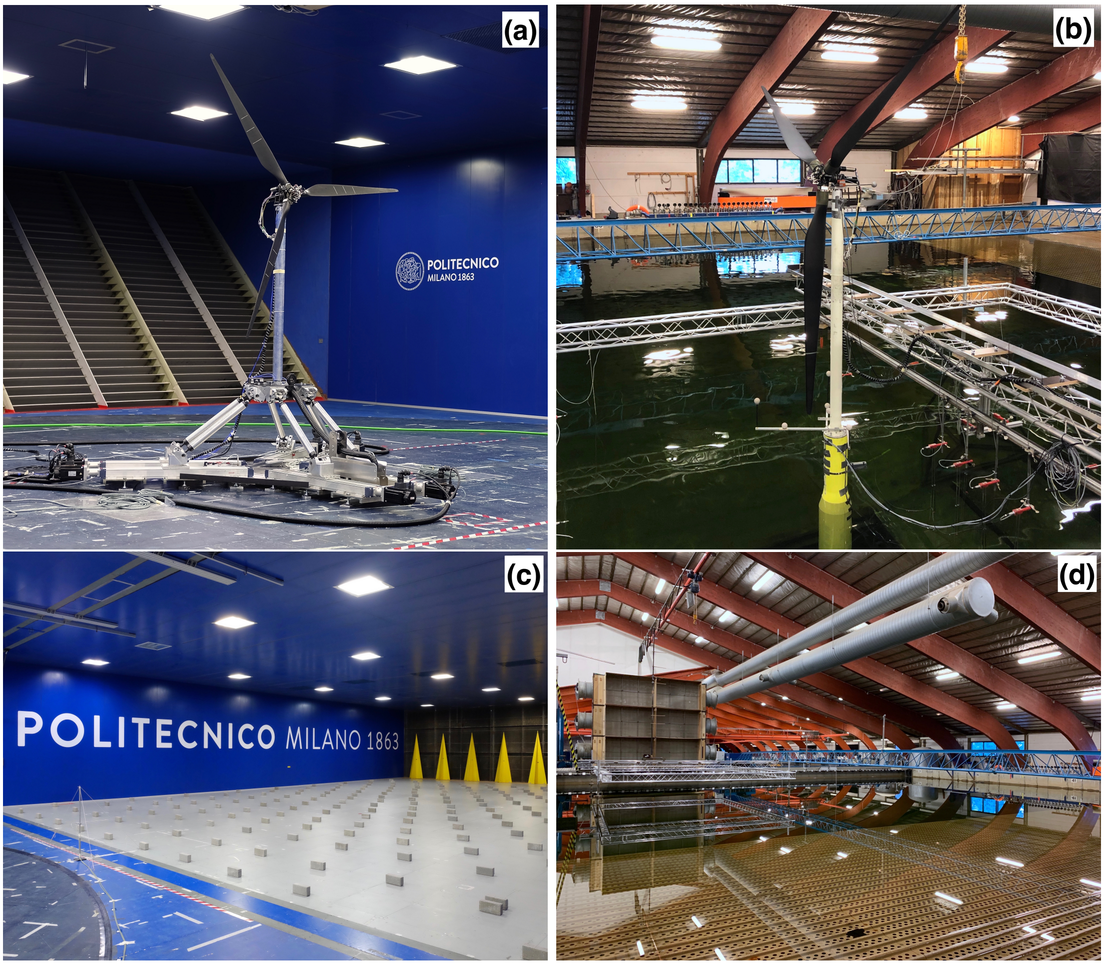

Figure 1: Experimental setup used for HIL wind tunnel tests about the OOStar DTU 10MW at the PoliMi wind tunnel (a, c) and for the wave basin tests about the OC3 5MW NREL at DHI (b, d).

basin tests, Froude scaling must be adopted to ensure the correct reproduction of gravity-dependent loads, and doing this, the velocity scale factor is function of the length scale factor according to $\lambda_v = \sqrt{\lambda_L}$. So if experiments are performed in an ocean basin with physical reproduction of the entire system, the only DOF for the scale model design is the length scale. In case of HIL tests, the reproduction of gravity-dependent loads relies on a numerical model thus λ_v can be fixed independently of λ_L, effectively becoming a second DOF for the design of the experiment. The length scale for modern multi-megawatt wind turbines is usually large and this implies an equally large velocity scale, or equivalently a great reduction of wind speed, in wave basin tests. This impacts the design of the model and of the experiment in different ways that are analyzed in the rest of this paper.

3 Wind turbine model

A physical wind turbine scale model is used in both the methodologies to reproduce the rotor loads, included those associated with control, and aerodynamic tower loads. The main dimensions (geometry and masses) for the full-scale wind turbines object of the experimental campaigns are reported together with those of the respective scale models in Table 2. Scale model values are reported at full-scale to ease the comparison.

The wind turbine scale models adopted for the experiments are featured by the same mechatronic design, which solutions were thought to realize the main control capabilities of the real wind turbine respecting as best as possible the mass and dimension constraints imposed by scaling laws [23, 24]. The

		OOStar - DTU 10MW		OC3 - 5MW NREL	
Factor	Expression	**Wind tunnel (real)**	Ocean basin (theoretical)	Wind tunnel (theoretical)	**Ocean basin (real)**
Length	λ_L	75	75	40	40
Velocity	λ_v	3	8.660	3	6.325
Mass	$\lambda_M = \lambda_L^3$	421875	421875	64000	64000
Time	$\lambda_T = \lambda_L/\lambda_v$	25	8.660	13.333	6.325
Frequency	$\lambda_\omega = \lambda_v/\lambda_L$	0.040	0.115	0.075	0.158
Acceleration	$\lambda_a = \lambda_v/\lambda_T$	0.120	1	0.225	1
Force	$\lambda_f = \lambda_a \lambda_M$	50625	421875	14400	64000
Reynolds	$\lambda_v \lambda_L$	225	650	120	253
Froude	$\lambda_v/\sqrt{\lambda_L}$	26	75	19	40

Table 1: Scale factors for the OOStar DTU 10MW and OC3 5MW NREL effectively used for the experiments (real) and as if tested with the complementary methodology (theoretical).

models have three independent actuators housed inside the hub for pitch control and an electrical motor that emulates the wind turbine generator.

The main difference between the scale models is found in the rotor and in the blades design. The adoption of the scale factors of Table 1 results both for wind tunnel and wave basin experiments in a Reynolds number noticeably lower for the scale model and this is due to the combination of reduced dimensions and velocities. As seen in Table 1, even for HIL tests where velocity scale factors are greater, the Reynolds number is in any case lower than for the full-scale system (i.e. $\lambda_{Re} > 1$). This represent the strongest constraint for the reproduction of aerodynamic loads. The possibility in HIL experiments of independently fixing λ_v alleviates the burden, allowing to achieve a Reynolds number reduction that is $\sqrt{\lambda_L}/\lambda_{v,HIL}$ lower than in corresponding ocean basin experiments. It is then easier to design the model rotor and have a generally better representation of aerodynamic loads.

For both the experiments it was required to re-design the wind turbine rotor to reproduce the correct aerodynamic loads. The aerodynamic design of the wind tunnel model is deeply discussed in [25] and it was focused on the minimization of the difference between the scale model and full-scale thrust coefficient. The SD7032 airfoil was used in place of the FFA-W3 series airfoils of the RWT since its lower thickness makes it less sensible to flow separation. The developed design procedure is based on the blade element approach and was aimed at defining the thickness-over-chord ratio (t/c) and twist angle distribution of the model blade. In common working conditions, the rotor thrust is mostly related to the blade lift force, thus the blade geometry was selected to match the lift force and the lift derivative with respect to flow angle for any blade section. The latter requirement is necessary to ensure that the unsteady behavior of the wind turbine is well reproduced by the model. The blade design for the wave basin model started from the same airfoil, thickness-over-chord ratio (t/c) and twist angle distribution of the wind tunnel

		DTU 10MW		5MW NREL	
Parameter	Unit	Full-scale	Scale model at full-scale	Full-scale	Scale model at full-scale
Rotor diameter	(m)	178.40	178.5	126	126
Blade length	(m)	86.40	86.25	61.50	58.4
Hub height	(m)	119	118.5	90	90
Blade mass	(kg)	42e3	105e3	18e3	38e3
Rotor mass	(kg)	228e3	915e3	110e3	206e3
Nacelle mass	(kg)	442e3	725e3	240e3	110e3
Rated wind speed	(m/s)	11.40	11.40	11.40	11.4
Rated rotor speed	(rpm)	9.60	9.60	12.10	12.10
Rated power	(W)	10e6	10e6	5e6	5e6

Table 2: Main dimensions of the DTU 10MW and 5MW NREL wind turbines and of the respective scale models used for the experiments.

model extended on the longer blade. Subsequently the aerodynamics of the rotor was assessed through FAST v8 simulations and the first tentative solution was adjusted increasing the chord by 10% (keeping constant the aspect ratio of the profile) in order to achieve a closer match of the target aerodynamic performances in terms of thrust and power.

Another important aspect and reason of difference between the two methodologies is the generation of wind. At the DHI ocean basin this was enabled by an array of fans on the edge of the basin (see Figure 2-d). Screens are placed in front of the fans outlet to improve the flow quality. Even with this expedient, the achieved flow quality is much lower than in a dedicated facility such as the wind tunnel, with a greater uncertainty for the wind speed time and spatial distribution over the test section.

4 Floating platform model

A different approach is used to reproduce the floating platform and all the loads acting on it in the two methodologies. In wind tunnel HIL test the floater dynamics, hydrodynamic loads and mooring system are introduced though a numerical model, whereas wave basin tests are relying on a physical model of the floating platform. The main dimensions for the full-scale platforms are reported together with those of the respective scale models in Table 3. In HIL wind tunnel tests, by simulating the floating platform with a numerical model, it is possible to have its dimensions perfectly matching the full-scale target. This is hardly achieved in wave basin experiments, where a physical platform model has to be realized respecting all the constraints imposed by manufacturing. Moreover, some simplification must be introduced when it is not possible to reproduce any of the platform subcomponents at small scale. This is usually a problem for moorings, since it is not possible to have a scaled reproduction of the real system both in terms of mechanical properties of the single line and footprint of the anchoring, that is constrained by the basin size.

In HIL wind tunnel tests, hydrodynamic loads are introduced in the experiment by means of a mathematical model that can be calibrated to match experimental data. However, it is still difficult to accurately represent all the phenomena involved in hydrodynamic loading, that are the result of the complex platform geometry and flow around the structure. The model is still affected by a great level of uncertainty for what concerns nonlinear phenomena like second-order wave loads [26].

5 Experimental tests

Similar tests can be run in the two facilities, wind tunnel and wave basin, especially when addressing the study of the floating wind turbine global response to combined wind and waves. Differences are obviously present in the procedures required to carry out the experiments, to respect the constraints and the peculiarities of each methodology. The accuracy level of the outcome of the same test is greatly affected by all the issues analyzed in the previous sections with different sources of uncertainty characterizing the experiments.

More specific tests are carried out taking advantage of the peculiarities of the facilities and different modeling of the floating system. Wind tunnel tests may be focused on the investigation of advanced control algorithms for the wind turbine, the unsteady aerodynamic loads developed by the rotor when interacting with its own wake due to platform motions, and the effects of in-array configurations typical

		OOStar semisub		OC3 spar	
Parameter	Unit	Full-scale	Scale model	Full-scale	Scale model
Water depth	(m)	130	130	320	120 (480)
Mass	(kg)	2.108e7	2.108e7	7.466e6	7.110e6
CM vertical distance below SWL	(m)	15.848	15.848	89.916	90.000
Displaced water volume	(m^3)	23509	23509	8029	8032

Table 3: Main dimensions of the OOStar semisub and OC3 spar floating platforms and of the respective scale models used for the experiments. Note: the DHI wave basin has a pit of 12m depth (480m at full-scale) in correspondence of the scale model position.

of wind farms. Wave basin tests may instead study with a greater precision viscous hydrodynamic loads and second order wave forces that are still difficulty reproduced by numerical models.

6 Conclusions

High-fidelity model testing is currently used only in the final design phases of FOWTs for the verification and optimization of the complete system. The scientific community still lacks of a common strategy to systematically investigate the different challenges related to FOWE. The accuracy levels of the different methodologies in relation to their capabilities still have to be assessed in order to provide more reliable best practices and guidelines for the design. What is certain is the complementarity of the methodologies developed so far and that results from experiments from different facilities can be combined to obtain more accurate results.

References

[1] van Kuik G A M, Peinke J, Nijssen R, Lekou D, Mann J, Sørensen J N, Ferreira C, van Wingerden J W, Schlipf D, Gebraad P, Polinder H, Abrahamsen A, van Bussel G J W, Sørensen J D, Tavner P, Bottasso C L, Muskulus M, Matha D, Lindemboom H J, Degraer S, Kramer O, Lenhoff S, Sonneschein M, Sørensen P E, Kunneke R W, Morthorst P E and Skytte K 2016 *Wind energy science* 26 – 27

[2] Robertson A N, Wendt F, Jonkman J M, Popko W, Dagher H, Gueydon S, Qvist J, Vittori F, Azcona J, Uzunoglu E, Soares C G, Harries R, Yde A, Galinos C, Hermans K, de Vaal J B, Bozonnet P, Bouy L, Bayati I, Bergua R, Galvan J, Mendikoa I, Sanchez C B, Shin H, Oh S, Molins C and Debruyne Y 2017 *Energy Procedia* **137** 38 – 57

[3] Popko W, Huhn L M, Robertson A, Jonkman J, Wendt F, Muller K, Kretschmer M, Vorpahl F, Hagen T R, Galinos C, Dreff J L, Gilbert P, Auriac B, Villora F N, Schunemann P, Bayati I, Belloli M, Oh S, Totsuka Y, Qvist J, Bachynski E, Sorum S H, Thomassen P E, Shin H, Vittori F, Galvan J, Molins C, Bonnet P, van der Zee T, Bergua R, Wang K, Fu P and Cai J 2018 *37th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Madrid, Spain*

[4] Bottasso C L, Campagnolo F and Petrovic V 2014 *Journal of Wind Engineering and Industrial Aerodynamics* **127** 11 – 28

[5] Koo B, Goupee A, Lambrakos K and Lim H J 2014 *33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE) - San Francisco, CA, USA* **9B**

[6] Goupee A, Fowler M, Kimball R, Helder J and Ridder E J 2014 *33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE) - San Francisco, CA, USA* **9B**

[7] Kimball R, Goupee A J, Fowler M J, Ridder E J and Helder J 2014 *33rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE) - San Francisco, CA, USA* **9B**

[8] Robertson A N, Jonkman J M, nad P Molta M D M, Goupee A J, Prowell I and Browning J 2013 *32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE) - Nantes, France* **8**

[9] Bayati I, Facchinetti A, Fontanella A, Giberti H and Belloli M 2018 *Journal of Physics: Conference Series*

[10] Sauder T, Chabaud V, Thys M, Bachynski E E and Sæther L O 2016 *35th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Busan, Korea* **6**

[11] Bachynski E E, Thys M, Sauder T, Chabaud V and Sæther L O 2016 *35th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Busan, Korea* **6**

[12] Gueydon S, Lindeboom R, van Kampen W and de Ridder E J 2018 *ASME 2018 1st International Offshore Wind Technical Conference (IOWTC) - San Francisco, CA.*

[13] Azcona J, Bouchotrouch F, Gonzalez M, Garciandia J, Munduate X, Kelberlau F and Nygaard T A 2014 *Journal of Physics: Conference Series* **524**

[14] Vittori F, Bouchotrouch F, Lemmer F and Azcona J 2018 *37th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Madrid, Spain* **10**

[15] Battistella T, Paradinas D D L D, Urban A M and Garcia R G 2018 *37th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Madrid, Spain* **10**

[16] Bayati I, Facchinetti A and Belloli M 2017 *36th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Trondheim, Norway* **10**

[17] Bayati I, Facchinetti A, Fontanella A and Belloli M 2017 *37th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Madrid, Spain* **10**

[18] Fontanella A, Bayati I, Taruffi F, Facchinetti A and Belloli M 2019 *38th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Glasgow, Scotland*

[19] Fontanella A, Bayati I, Taruffi F, Mura F L, Facchinetti A and Belloli M 2019 *38th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Glasgow, Scotland*

[20] Fontanella A, Bayati I, Taruffi F, Mura F L, Facchinetti A and Belloli M forthcoming *Ocean Engineering*

[21] Bak C, Zahle F, Bitsche R, Taeseong K, Yde A, Henriksen L C, Hansen M H, Jose J P A A, Gaunaa M and Natarajan A 2013 *DTU Wind Energy Report*

[22] Jonkman J, Butterfield S, Musial W and Scott G 2009 *Technical Report NREL/TP-500-38060*

[23] Bayati I, Belloli M, Bernini L and Zasso A 2017 *IET Renewable Power Generation* **11**

[24] Bayati I, Belloli M, Bernini L, Fiore E, Giberti H and Zasso A 2017 *Journal of Physics: Conference Series* **753** 217 – 227

[25] Bayati I, Belloli M, Bernini L and Zasso A 2017 *Journal of Wind Engineering and Industrial Aerodynamics* **167** 217 – 227

[26] Robertson A N, Bachynski E E, Gueydon S, Wendt F, Schunemann P and Jonkman J 2018 *37th International Conference on Offshore Mechanics and Arctic Engineering (OMAE) - Madrid, Spain*