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PERFORMANCE AND MOORING QUALIFICATION IN FLOATGEN : THE FIRST FRENCH OFFSHORE WIND TURBINE PROJECT

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Summary

The first multi-megawatt offshore wind turbine in France is a floating wind turbine. It was deployed at sea during the summer 2018 and the motion measurements and tests enable to confirm the adequacy of modelling techniques. Due to the fundamentally innovative nature of the project, several new concepts were introduced and tested. This paper describes how the seakeeping performance of the floater and the mooring system material are validated step by step to mitigate risks and increase the learning effect of the project.

The floating wind turbine includes a 2MW Vestas V80 turbine installed on top of a concrete hull, moored by means of polyamide mooring lines. We will focus here on the validation of the hydrodynamic concept, wind turbine coupling, mooring system and concrete material used.

I – Introduction

I – 1 Technology

The floater is essentially a barge fitted with a large central opening. The oscillations of the water mass entrapped in the central opening enable to damp wave frequency motion. The unit was deployed in shallow waters (around 35m water depth) in a severe environment: the North of the Gulf of Biscay. The combination of severe environment and shallow water guided the choice of nylon as a mooring material.

The principles of the damping pool is that the water entrapped within the hull can oscillate under the effects of the floater motion, but also of incoming waves. The water mass behaves as a mass-spring system. The phenomenon can well be described by perfect fluid models [3], but it could be argued that the sharp edges of the hull create vortex shedding that is not well represented by simulations.

The main dimensions of the demonstrator are reminded in Figure 1. They are in turn not much smaller than those of a 6 to 8MW unit [2]. The floater was designed by Ideol and built by Bouygues.

Hull width	36.0m
Breadth overall	40.2m
Hull depth	9.5m
Draft in place	7.0m
Turbine power	2MWe

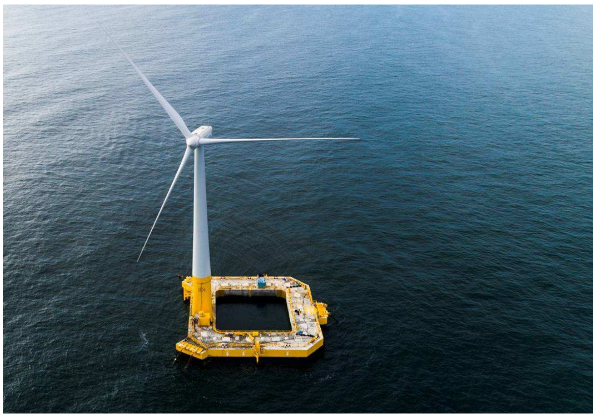


Figure 1. Dimensions of the demonstrator (left), photograph of the demonstrator at sea (right)

The mooring system comprises 3 groups of 2 mooring lines. The mooring lines are made out, from anchor to the platform, of drag embedment anchors, studless chain, a length of polyamide rope and a top chain segment. There are also buoyancy elements distributed along the lines that prevent chafing damage of the ropes on the seabed, and counter weights in the lines to keep the line under tensions. In the frame of the project, the mooring system was designed by Ideol and ECN procured the mooring lines and their offshore installation.

I – 2 The test site

SEM-REV is part of the experimental facilities of Ecole Centrale Nantes and Was developed, to validate and optimise Wave Energy Converters and Floating Wind Turbine in real open sea conditions. Using the well-known expertise of ECN in the scope of marine renewable energy, the strategy consists in building up a continuous and step-wise approach to testing of technologies, and offers the corresponding facilities and services from the initial proof of concept to the large scale verification of prototypes at sea.

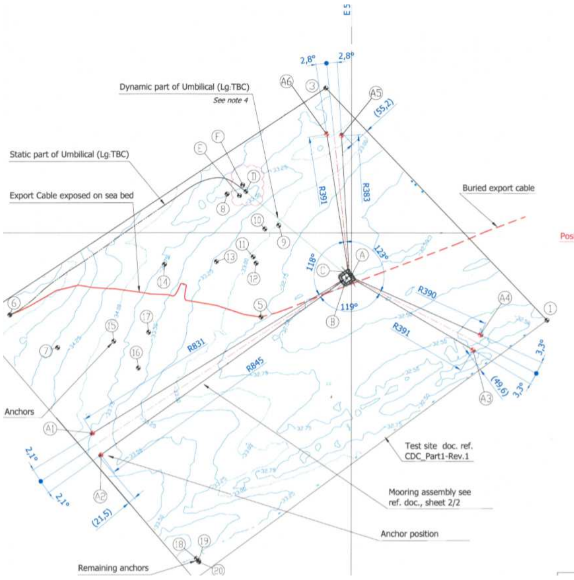


Figure 2: site layout

The SEMREV restricted area (1km2) is located 12 nautical miles offshore in about 35 meters L.A.T of water depth and opened to Atlantic Ocean's conditions. A 8MVA cable connects the test site to an electrical substation nearby the onshore base, which grants access to the local grid. Environmental and system operation control data are transmitted in real time from the offshore test site to the land base through optical fibers. The site is now 100% operational with all the required equipment to ensure operability, security and safety of data acquisition, energy production control and survey.

The SEM-REV test site has been equipped with a set of sensors monitoring the environmental conditions since 2009. Wave conditions in the SEM-REV test site are continuously monitored thanks to two directional Datawell MkIII buoys located inside SEMREV and DWR Belle-île is located some 40km westward from the site, offshore of the south coast of “Belle-Ile-en-Mer”. The data are both stored on the memory card on board and sent via VHF to the inshore station. The data consist in buoy motions time-series (heave and horizontal motions) sampled at 1.28Hz, from which averaged wave parameters (Hs, Tp…) or elevation spectral densities S(f) can be derived. Real-time data has been in use for the validation since the deployment of the wind turbine on site in April 2018.

II Damping Pool validation

The most critical innovation in this floating wind turbine are the principles of the wave frequency motion damping. Its step-by step validation consisted in combining perfect fluid simulations and wave tank testing, then verifying the upscaling by means of Computational Fluid Dynamics simulations and eventually performing measurements at sea. Being located on a test site with accurate wave measurement is instrumental to drawing clear conclusions from the motion measurements.

II – 1 Model testing

As in any new type of floating structure wave tank tests are necessary to confirm its behaviour. In the case of the Floatgen project, model tests were done at a scale of 1/30th. This enabled to adjust simulation models by the model-of-the-model method, and safely design all components. The water depth was scaled down to account for shallow water effects. The tests were performed in La Seyne sur Mer at Oceanide wave tank.

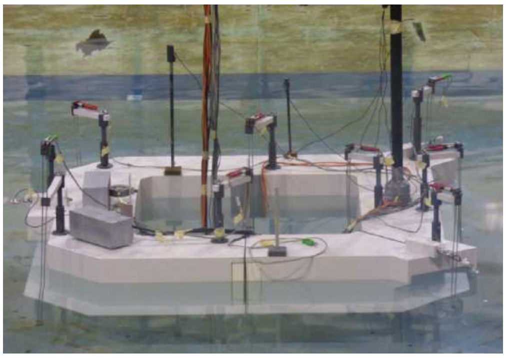


Figure 3. Model tests set-up

The environmental conditions were representative of SEM-REV offshore test site. Only three headings were considered because of the symmetries of the system. Regular waves were used in order to measure wave drift loads and compare them to numerical calculations. Current cases only were done to verify drag loads on the hull and also for towing loads evaluation. Finally, irregular waves with and without currents were run in order to better represent real-life storm conditions.

Another goal of this campaign was to choose between a semi-taut synthetic moorign system and a catenary one with steel cable. The choice was to consider the synthetic mooring because both maximum tensions and floater motions were smaller. Despite the shallow water depth, relatively low floater motions were a requirement, mainly for the umbilical design. Low tensions were also required to ease mooring components fabrication and offshore installation.

The hull was built in two parts to get access to the bending moments at mid ship. Floater accelerations were also calculated from motions measurements. They could be correlated to the tower base bending moment measurement. Sensors to derive green water and a number of wave elevation gauges were also installed. These measurements are not discussed here asthey would deserve additional publications.

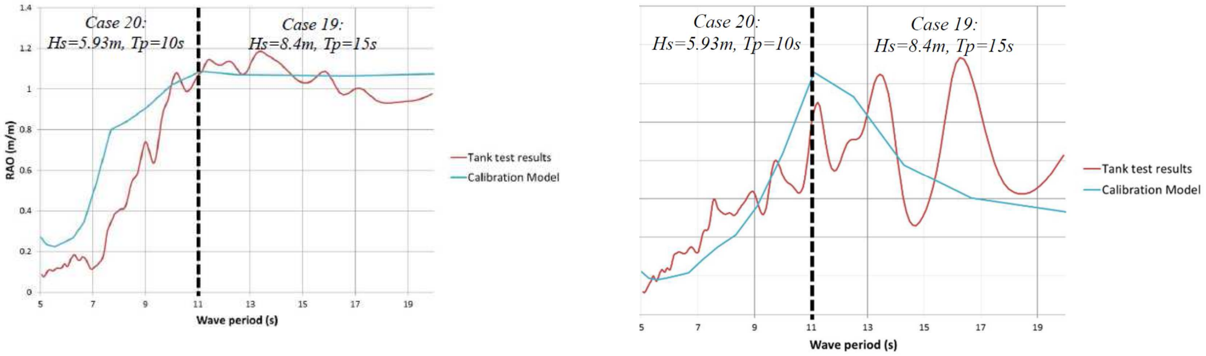


Figure 4. Comparison of motion RAO amplitude between simulations (in blue) and tests (in red) Heave (left) Pitch (right)

The models show good agreement with the model tests. The wriggles at large periods are caused by processing artefacts and wave tank reflections. It will be shown in the next subsections that the RAOs measured on site are actually closer to those simulated.

II – 3 Upscaling

Then, to make sure that the scale effect of the floater was done accurately, CFD simulations were performed by the University of Stuttgart [4]. They confirmed that the effect of the upscaling was negligible.

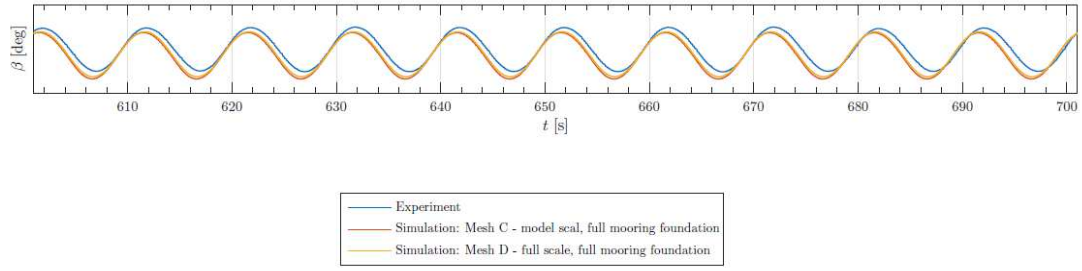


Figure 5. Comparison of pitch motion, model scale and full scale from CFD simulations

After construction, we performed tests in the same way as in model tests: inclining test to check the metacentric height, free-decay test by loading / unloading the wind turbine to identify the natural frequencies of the floating foundation and confirm its added inertia.

As the floater dimensions are reasonably small, the complete floating wind turbine can be assembled in the port, and put to its operating draught when moored alongside. The wind turbine could be tested up to 25% of its power production capacity. Figure 6 shows the wind turbine moored in the port of St Nazaire in the same condition as during tests and compares simulated to measured natural frequencies of the dynamically prevailing natural frequencies.

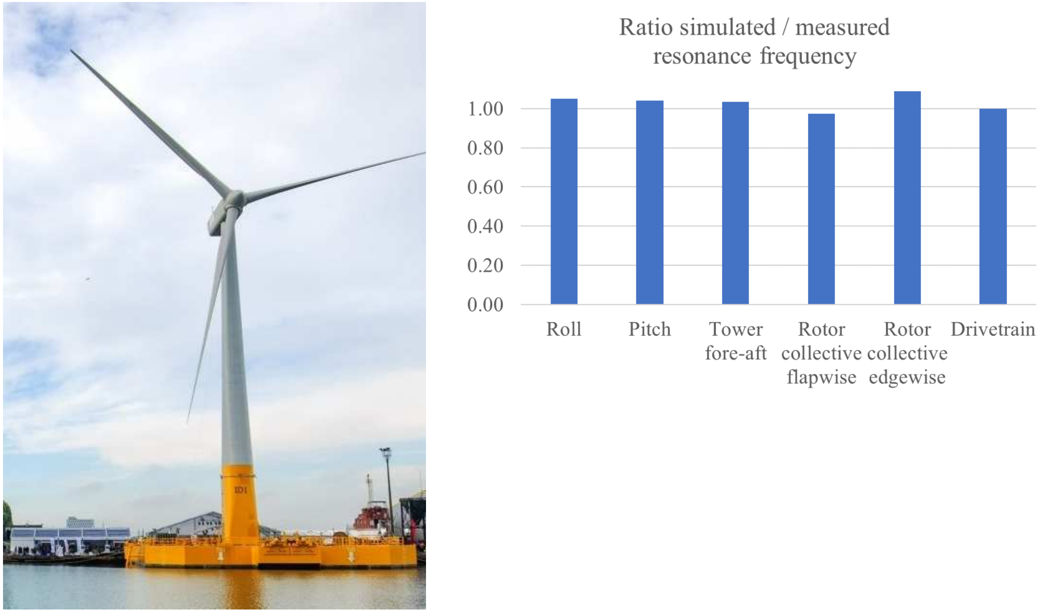


Figure 6. View of floating wind turbine in port (left) - Comparison of ratio of natural frequencies as measured during power tests in port to estimated in simulations (right)

II – 4 At sea experience

During first months of operation, the structure encountered large waves (3m significant wave height and peak period of 9s). This enabled to qualify the seakeeping performance of the floater. Motions of the floating wind turbine are obtained from an inertial measurement unit located in the transition piece. Wave elevation is taken from the SEMREV wave buoy located around 800m from the floating wind turbine.

The wave buoy provides information on the total wave elevation as well as directional and frequency spectra, but these cannot directly be used in simulations. Moreover, the wave elevation measurement is not synchronized with the motion measurement which makes it impossible to compare directly time-histories of motions. Therefore, the hydrodynamic modelling of the FWT has been verified throughout the motion comparison between measurements and numerical simulations in terms of RAO's and statistical values.

The calculation of RAOs and statistical values considered 1 hour of wave elevation and motion recording. This time duration is sufficiently long to neglect the effect of the distance between the buoy and the FWT and the lack of synchronization (order of magnitude of some seconds).

The same wave time history measured with the buoy has been used as input in the Orcaflex model. The wave heading is approximated by the:

$$\theta = Atan(\sigma_{roll}/\sigma_{pitch})$$

where σ_{roll} and σ_{pitch} are the roll and pitch motion standard deviations, respectively.

This approximation is valid under the conditions that the wave directional spreading is small, and that wind loads are moderate during the event of interest. This limits the number of candidate sea-states for validation but provides a quick way of estimating directions for the purpose of deriving motion transfer functions. The validity of this simplified formulation was verified using time domain simulations with Orcaflex model for several load cases (see figure 7 below).

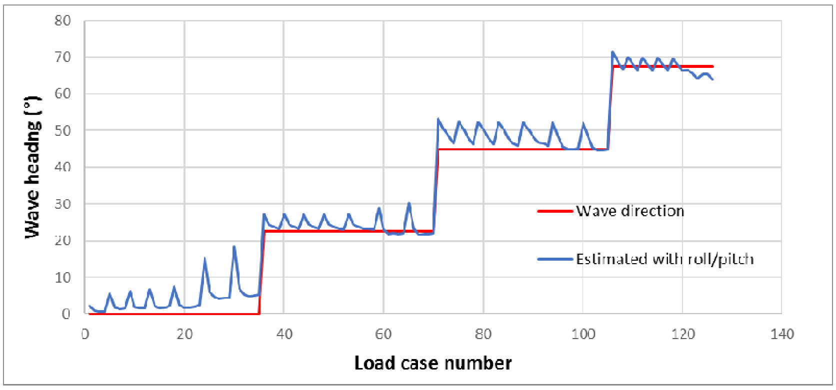
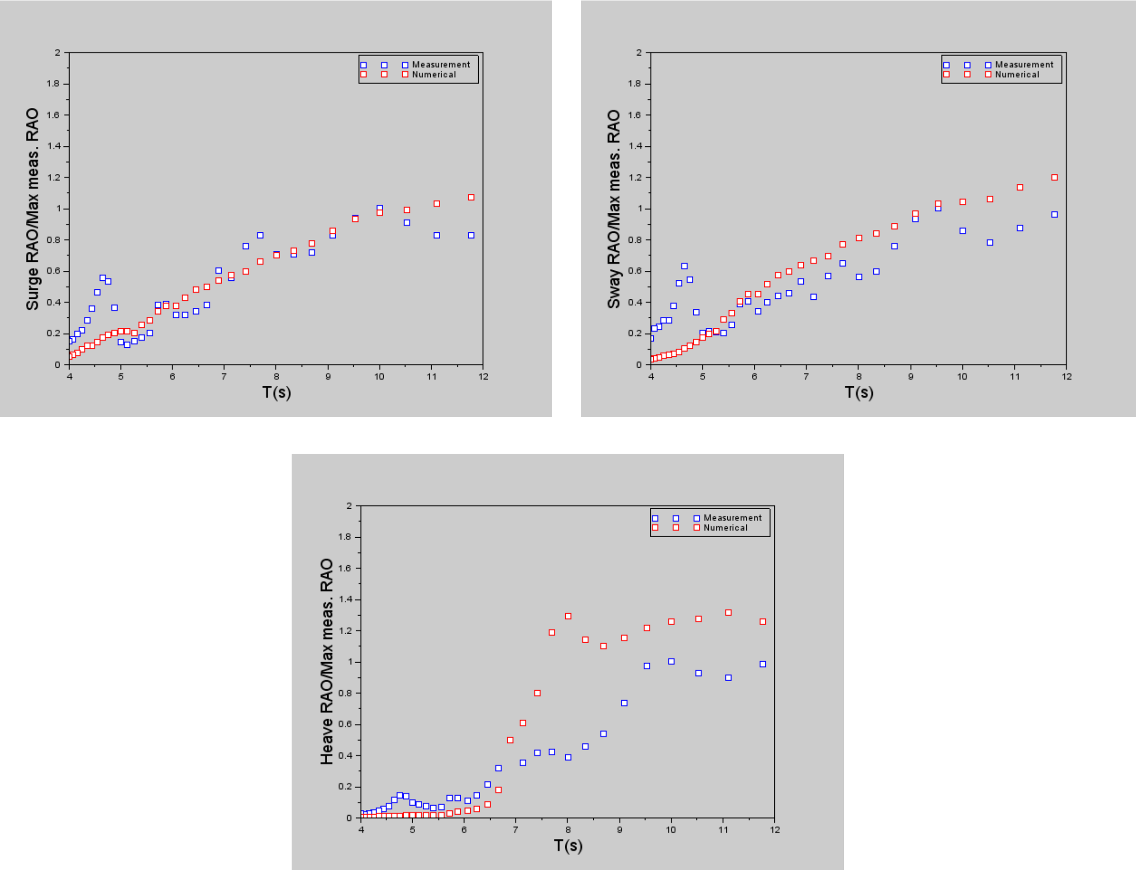


Figure 7: Input vs. estimated wave heading

Motion RAOs were derived from measurements and simulations. They are shown in figure 8 below. Wind and current were not taken into account in the numerical model as they do not excite the motions in the wave frequency range.

The records show a very good match for surge and sway motions. Roll and pitch motions give similar results with a good agreement at low period and Orcaflex being conservative at roll/pitch natural period. For heave motion, the effect of piston mode is clearly illustrated in the measured data. Numerical results are also conservative for that degree of freedom. Conservativeness for vertical degrees of freedom was also a feature of the simulations when compared to model tests. This was a choice in the design to mitigate risks in case of the floater underperforming.



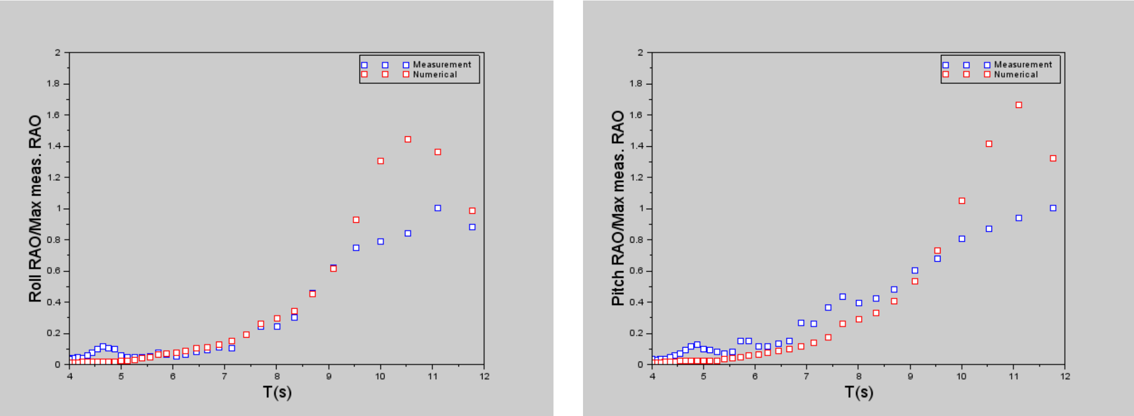


Figure 8: Comparison of measured (blue) and calculated RAO (red).
RAO Amplitudes are scaled to the maximum of the measured value.

III – Mooring line material

III – 1 Description and specification

The mooring system was designed to have the shortest length of line on the seabed to minimize chafing degradation of the seabed, and to be soft enough for the mooring radius to be as compact as possible. This was made possible by using polyamide mooring lines suspended to buoys to keep the lines off the seabed, and kept under tension between chains and weights.

Pre-existing research had already quantified the good fatigue performance of nylon ropes [5]. The mooring system was in addition validated by an independent analysis done by Lloyd's Register.

The validation steps included laboratory tests to assess the stiffness and stretching force needed to avoid retensioning the lines during the life of the floating wind turbine. Tests also enabled to quantify accurately the stiffness of the lines and its evolution over time in the specific loading context of the project.

III – 2 Behaviour at higher loads

During offshore installation, the lines were stretched up to the maximum storm force which enables to embed the anchors and in the same time stretch the ropes so that their length remains constant over the life of the floating wind turbine.

By definition, the load is representative of the storm conditions, and enables to validate onsite the behaviour of individual lines. This is a necessary step toward the confirmation of the behaviour of the moored floating wind turbine.

Figure 9 is an example of a stretching cycle compared to tests, which shows that the measurements are within 10% of the predictions, which is within design margins.

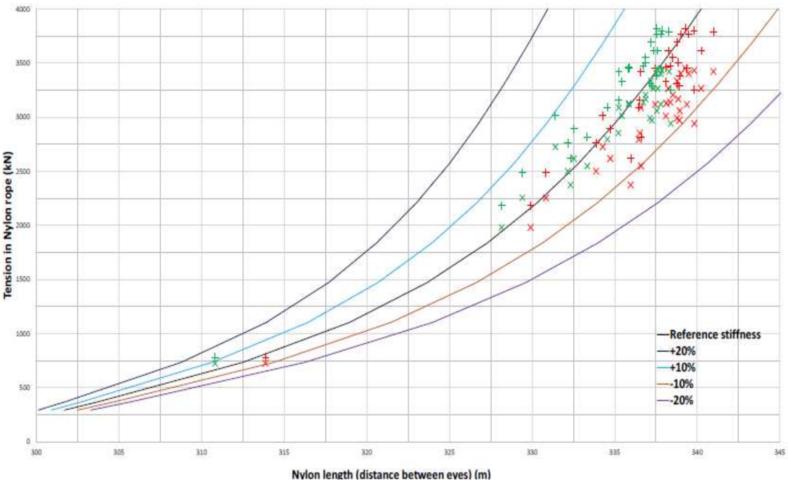


Figure 9. Pull-in test load/extension curve during installation

III – 2 Behaviour at lower loads

In addition to the stiffness of ropes at high loads, the applicability of the rope creep measured in laboratory and the stiffness at low loads can also be ascertained during the mooring lines installation.

During the mooring lines connection phase, load / extension tests were performed under tension around the hook-up tension. This enables to confirm the stiffness of the rope and the length at low load. After these tests, the ropes could safely be cut at the required length and connected to the wind turbine.

The tests revealed that the stiffness at low load was within 5% of the expectations, as derived from laboratory tests. The length of the lines is within 0.2% of predictions, which corresponds to the positions measurement accuracy of the anchor. It was then decided to use the theoretical values.

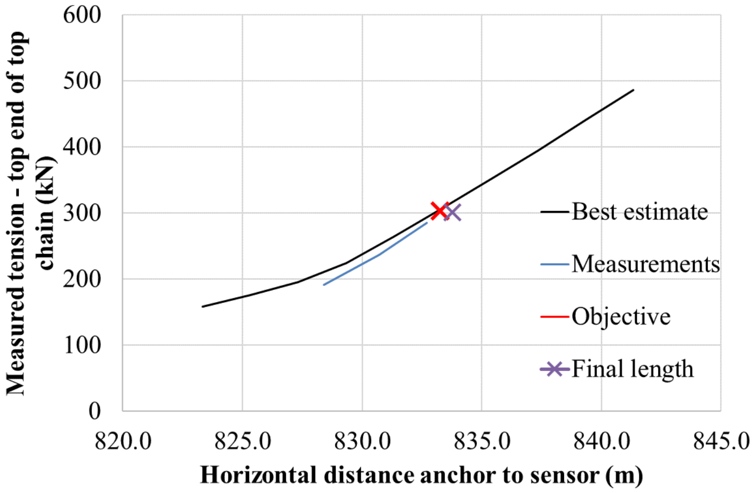


Figure 10. Load/extension curve during hook-up

The next steps in the validation will be to confirm the loads in the mooring lines in operation. Tension measurement sensors are planned to be installed later. Larger sea-states will be required as the mooring line tensions are mostly driven by second-order wave loads which are low 4m significant wave height.

IV – Wind turbine loads validation

A specificity of the project was to adapt the 2MW wind turbine to the marine environment and the floating application. A coupled aero-hydro analysis of the full system has been carried out for the design of the tower and transition piece, the update of the controller and the turbine loads verification.

A series of tests done in harbour and on-site during commissioning in order to validate the behaviour of the turbine in its floating configuration. Turbine components include a number of sensors that enable to compare measurements to coupled calculations done with FAST-Orcaflex.

Figures 11 compare of measured and calculated turbine loads during production at 500kW on the SEMREV site after complete hook-up of the mooring system. Nacelle acceleration is measured by means of an accelerometer, is a driving load for the tower and its statistics remain within 10% of the coupled calculations. As the floater response amplitude operators have been previously confirmed, these results indicate the correct modelling of the tower bending modes.

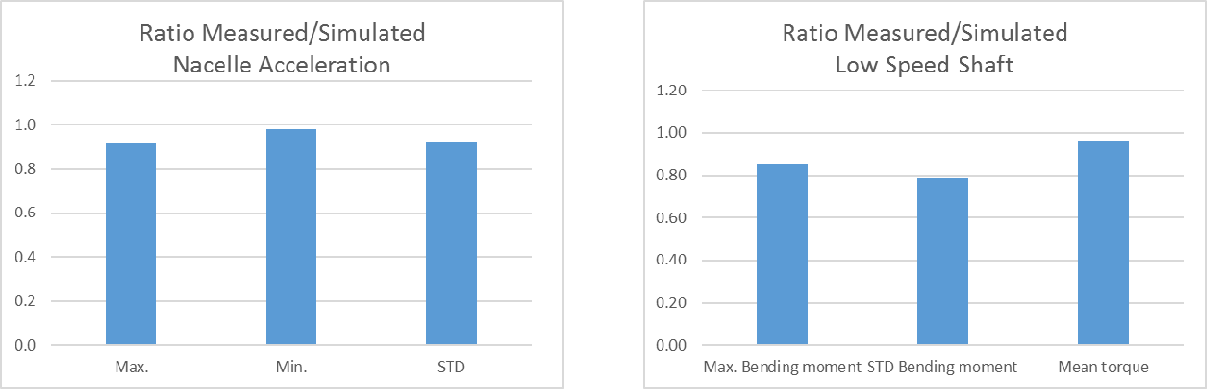


Figure 11. Nacelle acceleration (left) and low speed shaft moment (right) during 500kW production test – Significant wave height of 1.5m

Strain gauges are installed on the low speed shaft. They measured 20% lower bending moments than predicted and a 3% different torque. Results validate the drivetrain loads at the power of 500kW as they remain within the coupled values. Given the good match in tower top accelerations, it is likely that the difference in low speed shaft bending moment can either be caused by a difference in turbulence, wind speed and direction vertical gradient.

As this paper is being written, the turbine is still in the ramp-up phase during which the power is being increased to the rated power of 2000kW, at reduced wave height first and thereafter up to the maximum significant operating wave height of 5.8m.

Further validation will be made possible with the turbine producing in more severe sea-states and higher wind speeds.

V – Conclusions

The Floatgen project constituted a unique opportunity offered to test innovative systems as well as develop methods before commercial scale projects development. Academic and industrial collaboration was instrumental to reaching the ambitious objectives of the project.

The elementary verifications made in laboratory, during installation and construction enabled to validate the behaviour of the mooring lines, floater behaviour and floating wind turbine dynamics. This consequently limits the risks during power production at sea, to the combination of wind and wave events.

The approach of risk mitigation and narrowing during development also enables the project execution teams to focus primarily on their own performance, without being disturbed by lengthy validation steps.

We would like to thank the partners of the Floatgen project : Ecole Centrale de Nantes, University of Stuttgart, RSK, Zabala, Fraunhofer IWES, Bouygues TP for their contribution to the success of the projet. We would also like to thank TTI and Bridon for the work on the polyamide ropes. Lloyd's Register for the independent analysis work, Oceanide for model tests performance. We would eventually like to thank Prof. B. Molin whose work on the hydrodynamics of the moonpools was essential for imagining the damping pool system.

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