GRAND RENEWABLE ENERGY 2014 Proceedings
27 July - 1 August, 2014
Tokyo Big Sight, Tokyo Japan

O-WdOc-2-7

A ROBUST CONCRETE FLOATING WIND TURBINE FOUNDATION FOR WORLDWIDE APPLICATIONS

Thomas. Choisnet[1], Mathieu. Favré[1], Maria Lyubimova[1] and Etienne. Rogier[1]
[1]Ideol SA, La Ciotat, France

SUMMARY: Offshore wind now constitutes a significant part of the energy mix of several countries and larger capacities are in the construction and planning phases. It is now acknowledged that floating offshore wind turbine foundations can help unlock areas technically or economically inaccessible to bottom fixed foundations. Although technical feasibility of floating foundations is now proven with several units operating, the search for cost-effective floating foundations is still being pursued. This paper presents an original floating foundation concept which provides a cost effective yet robust support to wind turbine which features a shallow draft, concrete ring-shaped hull designed for harsh environmental conditions.

Keywords: wind power, floating foundation, concrete, wave tank testing, loads analysis

INTRODUCTION

Although it is now acknowledged that floating offshore wind turbines can contribute to open new areas to the development of offshore wind power, the search for cost-effective floating foundations is still going on as economic aspects are not all solved yet.

A few projects in Japan and in Europe have demonstrated the technical feasibility of floating offshore wind turbines, and have paved the way toward the production of floating-wind-generated electricity at an affordable price.

The floating foundation concept introduced in this paper is designed and optimized to suit existing wind turbines while minimizing construction cost. It is essentially a floating ring-shaped concrete hollow caisson. This paper details the features of a 5MW generic design. A view of the floating wind turbine is shown on figure 1 and the dimensions of the floater are reminded in table 1 below.

The water mass entrapped in the moonpool acts as a damper to wave excitation, which guarantees the good performance of the floater. Additional motion pitch performance improvement is made possible by adding a horizontal skirt around the hull.

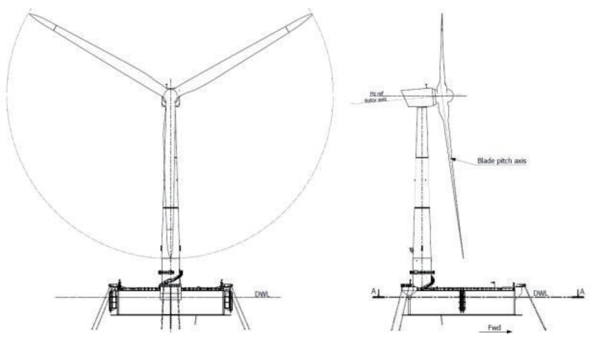

Figure 1. Overview of floating foundation.

Table 1. Summary of 5MW floater dimensions.

Hull width	Breadth overall	Depth	Draft	Displacement
41m	46.5m	9.6m	7m	8220t

We will review in a first step the basis of design in terms of wind energy converter, environment and design standards. We will outline the validation of the floater hydrodynamic performance, detail the loads exerted on the wind turbine and the mooring system. We will eventually address the structural integrity of the hull as a whole and conclude on construction, offshore installation and operation considerations.

BASIS OF DESIGN

Wind energy converter

The wind energy converter selected for the purpose of the generic basic design is the 5MW Baseline turbine proposed by the National Renewable Energy Laboratory. The wind turbine features a rotor diameter of 126m.

Modifications to its control system as described in [1] were implemented so as to adapt the wind energy converter to its floating condition. This essentially consisted in reducing the gains of the proportional-integral controller so as to reduce its bandwidth.

The operational target in terms of wind speed was to impose no reduction to the wind speeds range, and to allow safe operation of the turbine until the 1-year return period in severe environments. This guarantees that the down-time due to waves is limited to 3 hours per year. The operability of the turbine was considered satisfactory when the loads in the drive-train remained equivalent to those of the wind turbine onshore.

It was acknowledged that the tower would need to be reinforced to adapt to its floating condition.

Offshore sites

The design of the floater was verified for three offshore sites representing a wide range of water depth and weather conditions as presented in table 2. Wind turbulence levels and gradient were taken as per the class 1A for offshore sites.

Table 2. Summary of 50-year return period conditions at sites.

Site	North'n North Sea	East of UK Coast	West Medit. Sea
Water depth	220m	45m	70m
Wave height	H_s=12.9m	H_s=8.6m	H_s=6.2m
Wave peak period	14.1s to 18.2s	12.3s to 15.8s	10.5s to 13.7s
Current speed	1.7m/s	1.28m/s	1.15m/s
10-min wind at hub	46m/s	46m/s	41m/s

In addition, a sensitivity study was conducted in order to assess the impact of a cyclone attack. The environment in this case were a significant wave height of 14.6m associated to a peak period of 15s and a 1-hour averaged wind speed at hub in excess of 52m/s. This case was aimed at testing the survivability of the foundation in extreme conditions and its potential for deployment in areas exposed to cyclones.

Regulatory frame

When the design was initiated, the only standard available for floating wind turbine was Bureau Veritas guidance note [2] which was complemented by Det Norske Veritas offshore standard for concrete structures [3]. Hence this set of standards was used.

In practice, this set of standard proved to be very similar to the ClassNK rules and other floating structures rules which were subsequently published. In general, the stability needs to be verified as for any offshore structure according to the MODU code. It was voluntarily considered in our design that damaged cases as per oil and gas industry standards would be followed in order to provide a safe foundation: survival is required in case of compartment and mooring line damages.

The mooring system and structural design rules are in practice similar to any offshore structure but the load cases to be considered are specific to offshore wind turbines.

HYDRODYNAMIC PERFORMANCE AND MOORING SYSTEM DESIGN

Model testing

Model testing was carried out with the objectives of confirming the hydrodynamic behavior of the floater, providing sufficient validation data to calibrate hydrodynamic moonpool models and validate coupled wind turbine / floater behaviour. The test set-up is shown on figure 2.

Figure 2. Model tests of floating wind turbine.

The tests covered a range of wave heights up to 12m and the full range of wind turbine operating wind speeds.

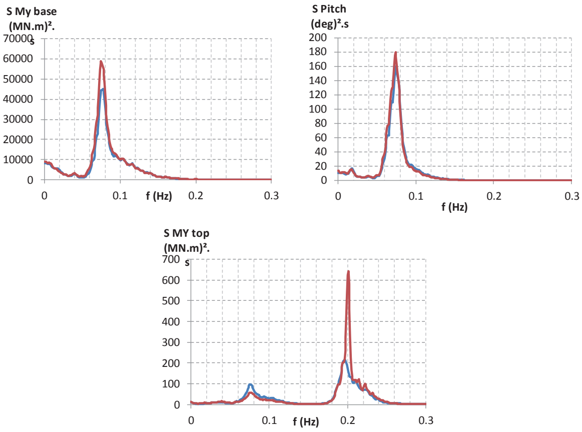

Figure 3. Comparison of response spectra for tower base moment (top left), pitch (top right), tower top bending moment (bottom). The blue curve is the measurement in combined wave / wind conditions and the red curve is the sum of spectra measured in the corresponding wave-only and wind-only model tests.

In general, it was shown that contributions of wind and wave conditions could be simply summed in most cases for the main parameters contributing to the floating foundation design. This was somehow shown by Molin *et al.* in [4]. This simplification could however not be applied safely for loads in the wind turbine drivetrain: the bending moment at the top of the tower is not conservatively estimated in the wave-frequency domain (around 0.07Hz), as shown on figure 3.

Simulation models calibration

Hydrodynamic simulation models were calibrated in order to account for viscous effects which cannot be accounted for in perfect fluid hydrodynamic analyses. The calibrated models consist in diffraction-radiation models to which drag elements model the damping skirt at the base of the hull. Figure 4 below compares calibrated and measured motion transfer functions.

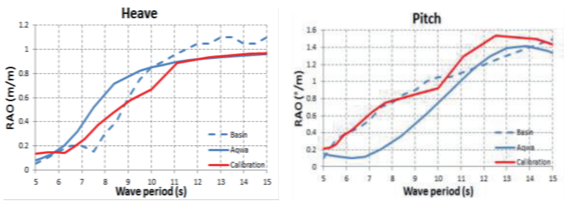

Figure 4. Comparison of measured (dashed) and calibrated (red) motion transfer functions. The Blue solid line stands for diffraction-radiation models.

The calibration enables to estimate in an accurate manner the loads on the mooring lines, wind turbine and hull as a whole. The models were extensively benchmarked against publicly available data and data from project partners.

LOADS ANALYSIS AND GLOBAL STRENGTH ASSESSMENT

Detailed operating loads analysis

Loads analyses of the generic wind turbine were integrated early in the design process. This enabled to adjust the motion performance of the floater. All power production cases specified in IEC 61400-3 were covered along with standby conditions. The loads obtained are acceptable for the wind turbine. Figure 5 compares the ratio of loads between the wind turbine fixed and floating.

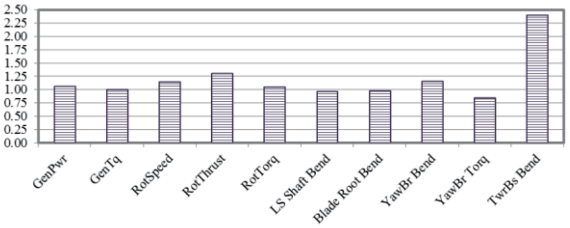

Figure 5. Ratio of loads [floating/fixed] turbine.

The allowable operating wave height is in excess of 9m for this 5MW wind turbine. This leaves less than 3hour downtime per year due to waves on the most severe site considered, and no downtime on the other two. Even better performance will be possible with larger wind turbines as the larger foundations will be hit by proportionally smaller waves.

Crossed wind and wave conditions were considered to derive the loads in the wind turbine as in most places wind and waves are not driven by the same meteorological phenomena.

The verification of a cyclone attack led to a maximum root bending moment 8% less than in onshore power production situations, whereas the rotor shaft torque, bending and thrust were respectively 70%, 10% and 10% lower than the same values in onshore conditions. The tower bending moment was increased by less than 30% compared to non-cyclonic events. This proves that the overall system is robust enough to survive cyclone attacks. Some optimization in its dimensions may be needed to reduce further its motions in these severe wave conditions.

Mooring system design

Given the differences in site conditions of the three sites distinct mooring system solutions were designed comprising chain only or combined with polyester ropes or cables.

The chain-only mooring systems have proven to be a cost-effective solution in intermediate water depth with rather benign wave conditions. In shallow waters, mixed cable and chain solutions are a good option provided the anchors can be installed far enough from the foundation.

Polyester mooring systems proved to be a more efficient option when wave conditions are high, and/or the anchoring radius needs to be reduced in order to accommodate several structures.

Table 3. Summary of mooring systems properties.

Site	Northern North Sea	East of UK Coast	West Mediterranean Sea
Number of lines	3 x 3lines	3 x 3 lines	3 lines + 2 x 2 lines
Composition	Chain and polyester	Chain and cable	Chain only
Breaking load	7 800kN	12 800kN	5 600kN

In shallow waters, polyester mooring systems need to be fitted with buoys in order to prevent them from chafing on the seabed, as shown on figure 6.

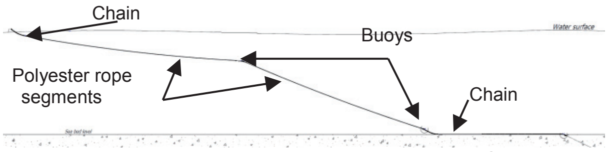

Figure 6. Typical polyester mooring line profile

Hull structural design

Specific numerical models were developed and used to derive the global loads transiting through the hull. These models are beam elements with distributed hydrodynamic properties and model the wind turbine in a simplified way. This is necessary due to the hyperstatic nature of the structure as evidenced by figure 7.

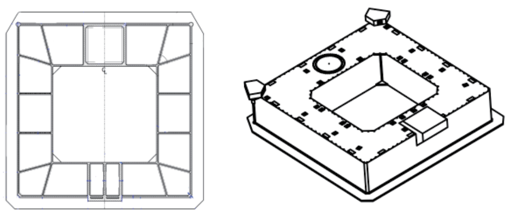

Figure 7. Hull Structural arrangement

The first models used by Ideol featured simplified hydrodynamic loads, modelled by means of Morison's equation. These models are now being superseded by more advanced models in which the full diffraction-radiation properties are included. This enables an easier preparation of the models. An example of the first set of models is shown on figure 8, left.

These global loads are combined in partial hull finite element models with local loads such as wave pressure and equipment support loads so as to detail the structure of the hull. This multiscale approach enables to ensure the global integrity of the structure.

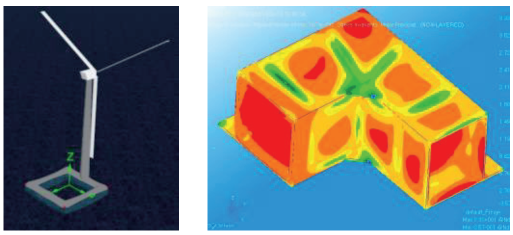

Figure 8. Hull verification models
global model (left) and local model (right)

The design of the hull made for Europe being made of reinforced concrete, the verifications do include strength verifications and durability and serviceability design criteria. These latter verifications include the confirmation that a minimum portion of the thickness of all walls remains in compression. This is aimed at ensuring that the hull remains watertight at all times.

It is also verified that the micro-cracks that grow over time in concrete structures remain sufficiently small to prevent excessive water migration through the concrete. This guarantees that the concrete and its reinforcements will not corrode during the life of the structure.

A similar procedure would be used for a steel hull except that the criteria would be the strength of the materials, the prevention of buckling and the deflection of structures in operational conditions.

OPERATIONAL AND CONSTRUCTION ASPECTS

Construction of the hull

The shape of the hull, with large flat panels, was chosen to ease the production process. Standard form works only is required for the construction of the concrete hull, and limited bending of the rebars is needed.

Thanks to its limited launching draught – around 6m – the hull can be built not only in a dry-dock but also on a quay. A construction in steel would be done by building in prefabricated blocks like any ship structure.

Offshore installation

The offshore installation and turbine integration aspects were incorporated in the design from the start. One of the guidelines followed was to minimize by design the number and time of offshore operations.

The analysis of the main sources of offshore installation standby proved that it is mostly caused by (i) high current speeds limiting diving operations and impairing ROV operations due to poor visibility, (ii) waves delaying vessels jacking-up downtime operations and personnel transfer, (iii) high winds limiting wind turbine components assembly at sea.

Hence the design integrated several features which allow reducing dramatically the weather downtime. One first feature is that all mooring line and cable connections to the floater are located above mean sea level so that no diving operation is required, and that operations can be done without the support of a ROV. This limits current downtime to very low values.

The wind turbine can be integrated in ports, which enables to plan wind turbine lifting operations as for an onshore wind farm *i.e.* with no offshore-specific down time. Typical mooring system laying operations significant wave height limitations range between 2.5m and 3.0m. Weather-critical operations can be split in tasks lasting around 6hours each. These windows are frequent enough not to wait long times on weather.

Wind turbine and floater integration

Given its limited draft at port and the position of the wind turbine close to one side, it is possible to assemble the wind turbine on its floater alongside. This saves the mobilization cost of large and scarce offshore installation vessels required to assemble a wind turbine on either fixed foundations or deep draft floaters. The position of the wind turbine on one side makes it in addition possible to use a crawler crane. This saves the need for specialized ship-building facilities equipped with large cranes.

The assembly of the wind turbine is done by compensating the weight of each lifted parcel by removing water ballast from the floating foundation. One can then work afloat and take advantage of the softness and accuracy of ballasting operations to limit shocks during wind turbine docking onto the floating foundation.

CONCLUDING REMARKS

Thanks to its simple design and shallow draft the structure can be built by civil works companies which have a track record of building similar sized caissons in large numbers. Installation can be done with locally available means which also increases the scalability to large wind farms.

The design is adaptable to any market worldwide and the hull can be built in reinforced concrete, steel, mixed concrete or steel and it is recognized that using composite materials could further ease construction and reduce the cost of energy.

The selection of the material should be closely linked by local fabrication capabilities and constraints. Although it would be technically possible to build the concrete hull in most countries, it is possible that in some areas where shipyards and steel workshops feature high productivity rates, a steel hull could be a better alternate.

The technology has been developed for 4 years now. Important milestones have already been reached: several model test campaigns were performed and detailed design of both the present MW unit, but also fo a first 2MW demonstrator planned to be launched in 2015. The next steps of the technology development will be to build and test the first 2MW unit, and then deploy the units in a pilot wind farm.

References

[1] Jonkman, J.M. "Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine" *Technical Report NREL/TP-500-41958, NREL November 2007.*

[2] Bureau Veritas Guidelines for the Classification and Certification of Floating Offshore Wind Turbines, *NI572.*

[3] Det Norske Veritas Offshore Standard "Offshore concrete structures", *OS C502.*

[4] Molin, B., Remy, F, facin, G "Etude expérimentale du comportement Hydro-Aéro-Elastique d'une Eolienne Offshore sur Ancrages Tendus", Sea-tech week 2004