BASIS OF STRUCTURAL DESIGN AND NUMERICAL MODELING OF OFFSHORE WIND TURBINES

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1. ABSTRACT

Offshore wind turbine structures are relatively complex structural and mechanical systems located in a highly demanding environment. Boundary conditions are highly time- and space-dependent, both as loads and as constraints. Adding to the complexity, different configurations must be handled: in fact, one has to pass from complete functionality to rotor stop. Furthermore, offshore wind turbine structures turbines are inevitably flexible and the time-varying loading system can produce complex aeroelastic and hydroelastic interactions which induce vibrations and resonances that can lead to high dynamic loading components. In the present study, a breakdown of the expected performances has been performed, in order to organize the qualitative and quantitative assessment in various sub-problems, which can be faced by sub-models of different complexity and levels of detail (macro- and meso-level) both for the structural behaviour and the loading model. In addition, some of the significant aspects of the established numerical modelling, taking

into account for many of the critical aspects, and allowing for the parametric exploration of different structural configurations, are briefly presented and discussed.

2. INTRODUCTION

In the recent years in order to make renewable power resources more competitive with respect to conventional exhaustible and a high environmental impact sources of energy, the attention has turned towards offshore wind power production. Besides being characterized by a reduced visual impact as they are placed far away from the coast, offshore wind turbines (OWT) can take advantage of more constant and intense wind forcing. This can increase the efficiency and the amount of the productive capacity and can make such a resource more cost-effective if the plant is durable and operates with minimum stoppage through its life.

In order to reach such a goal the numerical modeling of these structural systems plays a crucial role, as they are composed by different parts with several distinctiveness and subject to severe and more complex environmental conditions than inshore wind turbines, owing to the additional presence of the hydrodynamic and hydrostatic loads.

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Different aspects and various performances under several load conditions have to be investigated for this type of structures. Referring to all possible system configurations considered for the blades and the rotor, it is necessary to:

a. make certain that the components are designed for the extreme loads allowing a fair survivability;
b. assure that the fatigue life of the components is guaranteed for the service life;
c. define component stiffness with respect to vibrations and critical deflections in a way that the behaviour of the turbine can keep under control by a careful matching of stiffness.

In doing so, a breakdown of the structural system becomes an essential step in the early study [1].

3. PERFORMANCE REQUIREMENTS

In a numerical analysis of the structural behaviour of an OWT, the following general performance requirements regarding reliability and robustness have to be achieved:

- serviceability- structural characteristics pertaining stiffness and inertia have to be correctly distributed and appropriately balanced;
- durability- it should be ensured by keeping under control fatigue life and corrosion induced damages;
- safety- failure events must be avoided particularly when extreme load condition takes place. Buckling events of different structural components must be prevented by adequate measures.
- robustness- the system must ensure a suitable relationship between failure events and loss of structural integrity and load bearing capacity;

Moreover for an OWT the following performance criteria and limit states should be fulfilled [2]:

1. Definition of the requirements of dynamic behaviour for turbine operability;
2. Structural behaviour concerning turbine functionality (Serviceability Limit State);
3. Maintainability of the structural integrity over time (Fatigue Limit State);

4. Structural behaviour close to failure (Ultimate Limit State);
5. Structural behaviour in accidental load scenarios (Accidental Limit State);

4. CONTINGENCY SCENARIOS

The loading configurations adopted for the structural analysis and design of OWT have to be carefully selected in order to verify the structural integrity with the appropriate safety level of all load-carrying components for ultimate and fatigue strength.
In general, structural properties, induced forces and reactions may vary during the turbine lifetime (e.g. due to corrosion, marine growth, scour, plastic strain and fracture etc.): design load cases should be defined in such a way that conservative boundary conditions are defined for the entire operational life.
According to international Standards such as [3] a preliminary load analysis is based on site specific assumption concerning the wind turbine class (defined by an annual average of wind speed over many years U_{ave}) and associated marine conditions. In the present study a II class wind turbine has been assumed according to site-specific mean conditions; a significant wave height with a recurrence period of 100 years is representative of extreme events, while the return period of 1 year is representative of the operating conditions. At this initial stage of investigation, loading combinations for standstill or idling rotor have been considered (parked turbine with no structural damages). Moreover the attention has been focused on steady wind and wave condition.
Table 1 summarizes design load combinations and partial safety factors γF considered for the numerical analysis. Load cases are defined according to international Standards ([3] and [4]) in order to represent design conditions, combining extreme and normal events corresponding to different operating and functional conditions; nevertheless, in this case study a recurrence period T_R=100 years instead of 50 years has been prudentially assumed. Reduced values (U_{redTR}, H_{redTR}) have also been considered for specific load cases, as defined in [3]).

Design Situation	D.L.C. (GL 2005)	Wind Condition (steady)	Marine Condition (regular)	Analysis Type	Load Factors γF		
					Env.	**Grav.**	**Inert.**
Parked (standstill or idling)	6.1b	$U_{hub}=U_{e100}$	$H=H_{red100}$	Ultimate strength	1.35	1.1	1.25
	6.1c	$U_{hub}=U_{red100}$	$H=H_{max100}$	Ultimate strength	1.35	1.1	1.25
	6.3b	$U_{hub}=U_{e1}$	$H=H_{red100}$	Ultimate strength	1.35	1.1	1.25

Table 1: Design load cases and load factors for the numerical analyses

5. NUMERICAL MODELING

The principal geometrical and structural features adopted for the analyses are: Vestas-V90 turbine (www.vestas.com) with rotor diameter of 100m; the hub height is positioned 100m above mean sea level (m.s.l.); the tower, with a steel tubular section, has a diameter of 5m with a thickness of 50mm; water depth ranges from 15m to 35m; foundation length is 40m. In addition, in this study, three main support structures are considered:

a. Monopile. The mono-pile foundation consists of a welded steel pile which mainly transfers the loading on the wind turbine to the supporting soils by means of lateral earth pressure.
b. Tripod. The tripod foundation consists of a 3-leg structure, made of cylindrical steel tubes with driven steel piles.
c. Jacket. The jacket foundation consists of a 4-leg structure, made of cylindrical steel tubes with driven steel piles, with vertical pile sleeves.

During the design procedure different model types are adopted, each one with its own degree of complexity (both in structural resolution and loading specifications); both an appropriate scale and a level of detail is adopted accordingly to the specific performance or structural behavior to be analyzed.

In general four steps of structural analysis are defined, each one with a different model scale and level of detail [5]:

1. Systemic-level: the model scale comprises the whole wind farm and can be adopted for evaluating the robustness of the overall plant.
2. Macro-level or Global modelling (G): in these models the scale is reduced to the single turbine neglecting the connections between different structural parts and their shape; beam elements are adopted and aeroelastic and hydroelastic phenomena are accounted for.
3. Meso-level or Extended modelling (E): these models are characterized by the same scale of the previous level but with a higher degree of detail.
4. Micro-level or Detail modelling (D): this kind of models are characterized by the highest degree of detail and are used for simulating the structural behaviour of specific individual components, including joints.

A similar distinction can be made regarding the specification of the external loads. Concerning stochastic forcing (i.e. wind and wave) a preliminary investigation is carried out considering a mean steady wind field and a regular wave while neglecting the influence of the structure; non-stationary simulation are then performed considering random wave and (turbulent) wind loads and eventually reproducing the aeroelastic and hydroelastic effects through a fluid structure interaction model.

According to the above, at this initial stage of investigation structural analyses have been carried out with macro-level and meso-level models of the three OWT support structures previously described.

In particular macro-level models (G) have been realized with ANSYS finite element code (http://www.ansys.com) adopting beam elements. The following structural elements have been modeled: tower, substructure and turbine blades.

Meso-level models (E) have been set up by means of STRAUS7 finite element code (http://www.strand7.com) adopting both beam and shell elements. In addition to the previous case the transition piece, between the substructure and the tower, and the nacelle has been modeled; moreover the actual shape of the rotor blades is represented.

The effect of the foundation medium has to be simulated by means of a fully non-linear model, in order to account for possible plastic effects and load time-history induced variation of the mechanical properties. At this level of investigation an idealized soil has been simulated by means of:

- linear springs- such technique has been adopted for macro-level models. Springs are applied at the pile surface and act in the two coordinate horizontal directions; the corresponding mechanical parameters simulate the lateral resistance at the pile interface;

• brick elements- used for meso-level models. These three dimensional elements simulate the linear mechanical behavior of the soil. The extension of the foundation medium included in the model has been selected in order to minimize the boundary effects.

Both models have been used for evaluating the modal response of the structural system. Moreover meso-level models have allowed the investigation of the internal state of stress and possible critical conditions in the structural components.

Steady actions have been assumed for the principal environmental loading and no functional loads are present (parked condition): this is in accordance with some specific load cases selected from the International Standards at this early stage of the design.

6. MODAL ANALYSIS

The preliminary task of the dynamic analysis is to assess the natural modes of vibration for the investigated structural types (monopile, tripod and jacket) in order to avoid that non-stationary loads (e.g. wind and wave induced) could cause the system resonance when excitation and natural frequencies are closer.

Geometrical parameters of the three support structures have thus been selected with the aim of maintaining the corresponding natural frequency far from that of the non-stationary external forcing (wind and wave).

Subsequently the three structural systems have been simulated by means of both macro-level and meso-level models, (shown for the jacket support in Figure 1).

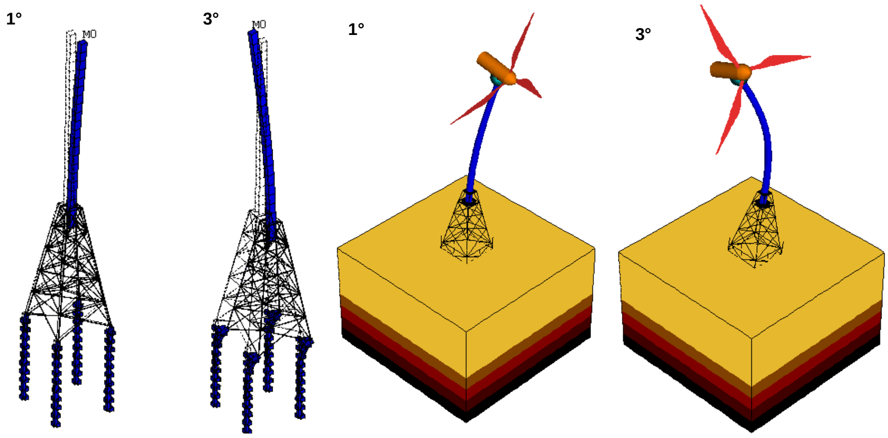

Fig. 1: Natural modes for the structural types analyzed (macro- and meso-level models)

From the obtained results it is found that the structural system falls in the soft-stiff range [6] only if the jacket support type is adopted. Furthermore, for the first couple of modes the dynamic behaviour of the jacket is more stiff than the other types, but the trend inverts from the third mode on. The modal analysis by the meso-level models confirm the results previously obtained by the macro-level models.

7. STATIC ANALYSIS

The numerical analysis for the selected support structure types has been carried out considering the three load cases summarized in Table 1, found in paragraph 4. Steady wind field has been assumed along with stationary and regular wave forcing; both forcing have been assumed to act in the same direction. No functional loads are present as the turbine is parked (standstill or idling).

The design wind exerts a force distribution which is dependent on the undisturbed flow

pattern: the resultant action on the rotor blades has been concentrated at the hub height while the drag forces are distributed along the tower and the exposed piece of the substructure (jacket type only).
The immersed part of the support structure is subject to combined drag and inertia forces induced by the undisturbed wave and current induced flow field.
In Figure 2, the calculated vertical profiles of the aerodynamic (left hand) and hydrodynamic actions induced per unit length on the tower and the substructure respectively are plotted.
The analyses carried out through macro-level models allowed for evaluation of both the reactions at the mud line (shear and overturning moment) and the induced displacement at the hub height.
Analytical results obtained by the analysis (here omitted for the sake of brevity), and with reference to the design situations of Table 1, found in paragraph 4, indicate that the maximum shear stress at the mud line is reached for load case 6.1c, i.e. those one characterized by maximum wave height and reduced wind speed on the other hand, combination giving the maximum bending moment at the mud line corresponds to extreme wind and reduced wave height (6.1b, central panel). From the above follows that wave and current exert mach more influence on the resultant shear force, while the wind appears to be more critical for the overturning moment being distributed at an higher distance from the bottom. Moreover it is found that the three structural types experiences approximately the same resultant shear and moment under each load combination, exception made for jacket type which shows smaller discrepancy between the overturning moment for load cases 6.1b and 6.1c.
Concerning the horizontal displacement at hub height, it is observed an increasing stiffness of the support structure moving from monopile to jacket type under each load combination. Maximum displacement occurs in all cases for load case 6.1b giving rise to the higher overturning moment; for the jacket type it is almost one third of the monopile one. Other results of the analysis carried out, indicate that the jacket support type is the best choice for what concerns the structural response (in particular for the maximum stress in the tower and for the nacelle displacement).

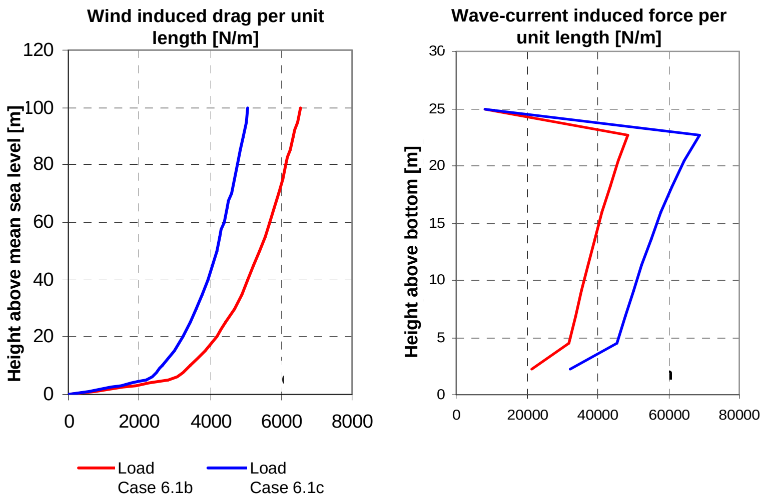

Fig. 2: Vertical profiles of wind and hydrodynamic induced loads on support structure

The connection between the tower (shell elements) and the Jacket is modeled by using of rigid beams elements (Figure 3b). This detail level allows the designer to investigate the internal state of stress for critical parts.
The meso-model is subjected to the load case referred to as 6.1b in Table 1, Paragraph 4 (most severe); the model gives a nacelle displacement of 2m and a maximum stress of 178 MPa in the tower (Jacket-tower connection). The results of the meso-level model are in harmony with the macro-level ones. The small differences are probably related to the variation in the tower diameter (ranging from 5 meters at the tower base to 3,4 meters at

the top) along the vertical direction and to the changing in the thickness of the tubular member at a fixed transition section (see Figure 3a).
These features are properly reproduced in the meso-level model, while in the macro-level model they are set equal to their maximum values.

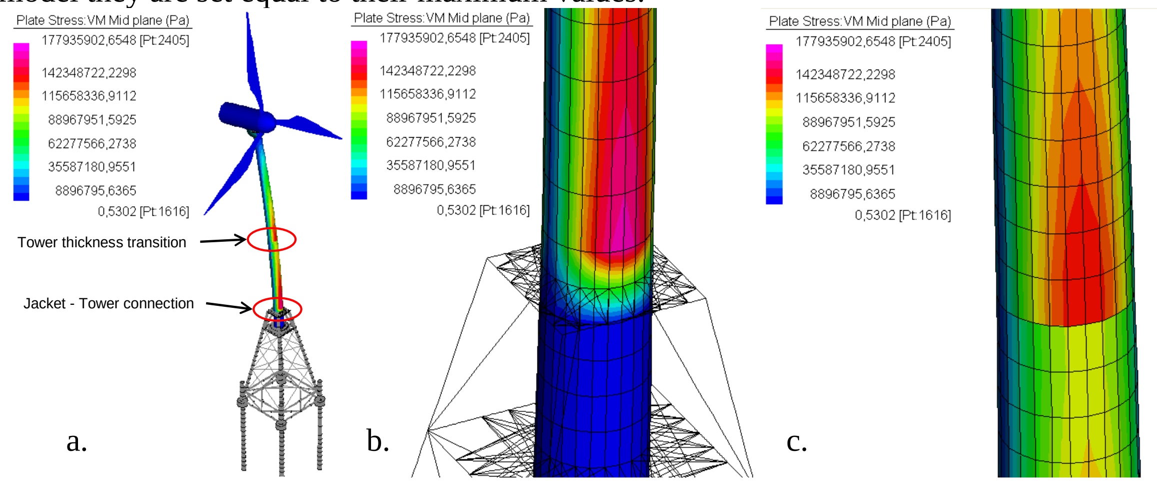

Fig. 3: Vertical profiles of wind and hydrodynamic induced loads on support structure.

8. CONCLUSIONS

In this paper the basic aspects concerning the numerical modelling for the analysis and design of OWT support structures have been dealt with. Reliability and robustness requirements have been accounted for in order to ensure that the components are designed for the extreme loads with a recurrence period of 100 years, as prescribed by international Standards for offshore wind design, allowing a fair survivability for the service life. An early analysis has been carried out for the investigation of the dynamic response for each one of the three support structure; subsequent static analysis has been carried out simulating three different load combinations as prescribed by international Standards.
Starting from the results presented here, future studies may take into account for other relevant effects influencing the dynamic response of the structure (e.g. scour, non-stationary loads, non-linear interactions etc.) by performing transient analyses.

9. REFERENCES

[1] BONTEMPI FRANCO, LI HUI, PETRINI FRANCESCO and GKOUMAS KONSTANTINOS, "Basis of Design of Offshore Wind Turbines by System Decomposition", *The 4th International Conference on Advances in Structural Engineering and Mechanics* (ASEM'08), 26-28 May 2008, Jeju, Korea.

[2] BONTEMPI FRANCO, LI HUI, PETRINI FRANCESCO and MANENTI SAURO, "Numerical modeling for the analysis and design of offshore wind turbines", *The 4th International Conference on Advances in Structural Engineering and Mechanics* (ASEM'08), 26-28 May 2008, Jeju, Korea.

[3] GL-OWT, Germanischer Lloyd Wind Energie GmbH: Guideline for the Certification of Offshore Wind Turbines. Edition 2005.

[4] IEC. Wind Turbine Generator Systems – part 3: Safety requirements for offshore wind turbines, IEC 61400-3, TC88 WG3: Committee draft, December 2005.

[5] BONTEMPI FRANCO, "Frameworks for Structural Analysis", *in Innovation in Civil and Structural Engineering Computing, B.H.V. Topping* (Editor), Saxe-

Coburg Publications, Stirling, Scotland, 2005, pp. 1-24.

[6] VAN DER TEMPEL JAN and MOLENAAR DAVID-PIETER, "Wind Turbine Structural Dynamics – A Review of the Principles for Modern Power Generation, Onshore and Offshore", Wind Engineering, Vol. 26, No. 4, 2002, pp. 211-220.

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ΠΕΡΙΛΗΨΗ

Οι θαλάσσιες ανεμογεννήτριες είναι σχετικά σύνθετα δομικά και μηχανικά συστήματα, τοποθετημένα σε ένα απαιτητικό περιβάλλον, με συνοριακές συνθήκες υψηλά εξαρτώμενες από τον χώρο και τον χρόνο. Επιπρόσθετα, διαφορετικοί σχηματισμοί πρέπει να ληφθούν υπ'όψιν, που ποικίλλουν από πλήρη λειτουργία της ανεμογεννήτριας εώς και σταμάτημα του ρότορα. Στην παρούσα εργασία, παρουσιάζονται αποτελέσματα ανάλυσης των απαιτούμενων επιδόσεων του δομικού μέρους των ανεμογεννητριών, με στόχο την οργάνωση της ποιοτικής και ποσοτικής εκτίμησης σε διαφορετικά υπο-προβλήματα, τα οποία μπορούν να αντιμετωπιστούν με την βοήθεια υπομοντέλων, διαφορετικής περιπλοκότητας και επιπέδου λεπτομερειών (μάκρο- και μέσο- επίπεδα), αμφότερα για τα φορτία και για την δομική συμπεριφορά. Επιπλέον, παρουσιάζονται αποτελέσματα μοντελοποίησης με την βοήθεια προγραμμάτων πεπερασμένων στοιχείων, πυλώνων τριών διαφορετικών τύπων, κατάλληλων για βάθη έως και 45 μέτρα, λαμβάνοντας υπ'όψιν για πολλά απο τα κρίσιμα χαρακτηριστικά του προβλήματος, και επιτρέποντας την παραμετρική διερεύνηση διαφορετικών δομικών συστημάτων.