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Comparative analysis of numerically simulated and experimentally measured motions and sectional forces and moments in a floating wind turbine hull structure subjected to combined wind and wave loads

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ABSTRACT

Multi-body time-domain finite element models, which implement a recently developed numerical approach for determining forces and moments in floaters, are developed to simulate rigid-body motions and sectional forces and moments of a reference 5-MW braceless semi-submersible wind turbine in turbulent winds and irregular waves corresponding to below rated, at rated and above rated conditions. The simulated responses are compared with measurements of a 1:30 scaled model test using a real-time hybrid testing approach. In general, agreement between simulations and measurements are very good. Differences in spectral densities of the measurements and simulations have been quantified while the reasons for the differences have been thoroughly analyzed and discussed based on comparisons of measurements in different conditions and numerical parametrical study. Effects of non-linear wave excitation loads and drag forces on the rigid-body motions and sectional forces and moments are analyzed while dominant load components in fore-aft bending moments in five cross-sections in the hull of the reference model are identified. The interface between the pontoons and central column of the reference model is identified as the most critical part. Both low frequency and wave frequency load effect should be accounted for. Mean forces and moments from wind and waves result in a change in configuration of mean wetted body surface of the hull when compared to its configuration in calm water. This may result in a considerable change in resultant sectional forces and moments even though change in resultant of the hydro pressure forces on whole of the wetted body surface could be very limited. For the analyzed model, simulated fore-aft bending moments of the model in wind and waves could be obtained by superimposing the results for wind only condition, and wave only condition except that the corresponding averaged wind induced forces and moments should be applied on the numerical model. This simplification can significantly reduce number of cases of short-term analysis required in long-term analysis. However, applicability of the simplification should be analyzed case by case in particular for a blunt structure with relatively large volume of displaced water in waves with relatively small wave length. Analysis and discussions given in this paper are based on available measurements of the model test. Hydroelastisity and structural vibration of the columns and pontoons of the hull are not accounted for by the numerical and experimental models. Suggestions for design of future model tests are given in this paper.

1. Introduction

Floating wind turbines are considered an attractive solution for harvesting offshore wind energy in relatively deep water, e.g. deeper than 80 m. In general, a floating wind turbine is composed of a Rotor Nacelle Assembly (RNA), a tower, a hull and a mooring system.

As required by relevant standards and guidelines for offshore wind turbines, e.g. [1–5], global responses, in terms of motions and sectional forces and moments, should be appropriately analyzed for limit state design checks. As the development of floating wind turbines is at an early stage, numerical simulations and model tests for analyzing the global responses of floating wind turbines in wind and waves are hot research topics.

Computer codes for analyzing floating wind turbines have been developed by combining the knowledge and computer codes for modelling hydro loads on offshore platforms and aerodynamic loads on land-based wind turbines for decades [6]. A review of conventional approaches for modelling aerodynamic loads on the RNA and tower, hydro loads on the hull and mooring lines of floating wind turbines is available in [7]. Features of some conventional time-domain computer codes are tabulated in [8]. Global responses of the RNA, tower, and mooring system, and rigid-body motions of a given floating wind turbine can be simulated in these codes by generating and solving finite element model for the floating wind turbine, while Morison formula and/or the conventional hybrid frequency-time domain approach [9] is used to model hydro loads on the hull of the floating wind turbine. Morison formula is an empirical formula and, in general, applicable when wave length is larger than five times the diameter of the slender

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structure's cross-section [10]. The computer codes which implement the conventional hybrid frequency-time domain approach cannot capture the sectional forces and moments in the hull since the hull is modelled as a rigid-body with 6 d.o.f.s in the finite element model. Luan et al. [9] recently developed an approach based on an extension of the conventional hybrid frequency-time domain approach, for which the hull is modelled as multi-bodies. The developed approach can be easily implemented in various state-of-the-art time-domain computer codes for floating wind turbines, e.g. Simo/Riflex/Aerodyn, OrcaFlex and FAST + CHARM3D, to extend their capabilities to analyze sectional forces and moments in structural components of a generic floater. A moderate wave-only experimental validation for this approach is made in [11].

Global responses of floating wind turbines in wind and waves can be measured (and analyzed) by carrying out model tests. Conventional model tests for measuring wave induced responses of a floating unit are designed to satisfy geometrical and kinematic similarities and equality according to Froude number ensure similarity between inertia and gravity forces of the experimental and actual models. However, similarity between inertia and viscous forces of the models cannot be achieved since, in practice, equality in Reynolds number cannot be satisfied at the same time. Different Reynolds number may indicate different patterns of fluid flows around the experimental and actual models. Necessary corrections are needed if the measurements are sensitive to the viscous forces. Due to the same reason, similarity between inertia and aerodynamic loads on the RNA, which are important to responses of floating wind turbines, cannot be achieved either, see [12–14]. To solve this problem, various forms of "non-geometrical scaling" of the wind turbine rotor have been developed to improve the aerodynamic load modeling in wind-wave model tests. For example, one form of non-geometrical scaling is to replace the wind turbine rotor with a drag disk, e.g. [15,16]. A more sophisticated method of non-geometrical scaling is to modify the wind turbine airfoil shape and chord length to obtain improved performance at low Reynolds numbers [17–20]. These non-geometrical scaled wind turbines can be designed to achieve the same non-dimensional thrust coefficient as the reference full scale wind turbine in a specified steady condition (calm water, constant wind speed, and fixed rotational speed and pitch angle of the blades). Therefore, the "non-geometrical scaled" wind turbines can be used to physically analyze static response of the experimental model of floating wind turbines in steady conditions. However, it is still a challenge, which has not been solved yet, to make a performance-matched wind turbine model, which means to use the non-geometrical scaled wind turbines in model tests to accurately mimic Froude scaled actual aerodynamic loads on the rotor of the corresponding full scale reference wind turbine in dynamic conditions (turbulent winds, and/or regular or irregular waves, and/or with or without controller for blade pitch angle and rotational speed). This is because it is a challenge to design a non-geometrical scaled wind turbine for which the non-dimensional thrust coefficient is always identical to the corresponding coefficient of the reference full scale wind turbine in an arbitrary steady condition. As shown in [17], the non-dimensional thrust coefficient versus tip speed ratio curves of the non-geometrical scaled wind turbines can be very sensitive to the wind speed (the Reynolds number). It is also a challenge to generate and/or measure constant and turbulent wind fields in a classical towing tank or ocean basin [21] as well. Implementation of real-time hybrid model testing approach, e.g. ReaTHM® [22], and reference [23], is a recent development for accurate modelling the actual aerodynamic loads in ocean basin. ReaTHM® relies on the assumption that actual aerodynamic loads on the full scaled reference wind turbine can be captured by the state-of-the-art aerodynamic computer codes, e.g. Aerodyn [24]. A numerical finite element model for the RNA and control system of the full scale reference wind turbine and numerical model of wind field are generated in a computer code which implements the state-of-the-art aerodynamic computer code to calculate the aerodynamic loads on the RNA in the wind field. The resultants of the calculated aerodynamic loads are down scaled (based on Froude scale) and physically applied on a Froude scaled model of the floating wind turbine, while in the computer code the hub of the RNA rigidly follows the measured rigid-body motions, which has been up scaled (based on Froude scale), of the experimental model. A 1:30 scaled braceless semi-submersible model test which implements the ReaTHM® testing approach was done by SINTEF Ocean in its ocean basin [25]. Sectional forces and moments in base of a side column and tower base of the model in different combined wind and wave conditions have been measured. ReaTHM® can appropriately address effects of the control system on the aerodynamic loads while the actual loaded forces can be measured in a straight-forward manner. A detailed description of the approach and its feasibility is available in [22,26].

This paper intends to shed more light on sectional forces and moments in the hull of semi-submersible wind turbines submitted to combined wind and wave loads by thoroughly analyzing the measurements of the 1:30 scaled model test in SINTEF Ocean and corresponding numerical simulations. A Simo/Riflex model which implements the approach presented by Luan et al. [9] has been generated. Sectional forces and moments in five cross-sections of the hull of the braceless semi-submersible wind turbine are analyzed. The hull of the braceless semi-submersible wind turbine is a static determinate structure. The external load on the hull is composed of wave excitation loads, added mass forces, potential damping forces, gravity, hydrostatic forces, and drag forces. Configurations of mean wetted body surface of the model in wind and waves and in wave only are different due to mean components of the wind loads on the rotor, tower and hull of the model. The difference means that hydrodynamic coefficients that are calculated for modeling hydro loads on the hull are different since values and distributions of hydro pressure forces on the hull are changed. Numerical sensitivity study and comparisons of measurements in different conditions are used to analyze effects of each component of the external loads, and inertial load on the sectional bending moments in different cross-sections of the hull. Simplifications for the numerical modelling are discussed based on the results of the parametric analysis. Sectional forces and moments in different cross-sections are compared. To quantify the differences between the numerical model and the experimental model, the simulated and measured fore-aft bending moments in the bases of the side column and tower are compared. The agreement is reasonably good.

In previously, comparisons of simulated and measured responses of floating wind turbines have been analyzed by some researchers, e.g. [27]. Geometrical scaled or non-geometrical scaled wind turbine, which cannot correctly mimic the Froude scaled aerodynamic loads on the corresponding full scale reference wind turbine in dynamic condition, are used in the model tests mentioned by the researchers in their publications, while these model tests are not designed for capturing sectional forces and moments in hull of floating wind turbines. For each model test, the wind turbine of the experimental model is modelled in its corresponding numerical model to simulate aerodynamic loads on the wind turbine while numerical wind field is generated based on measured wind speed at one specified fixed position in the model test. Consequently, the differences between the measurements and simulations are due to the differences between 1) the numerical wind field and actual wind field in the model test, 2) performance of the numerical and experimental models of the wind turbine and 3) mass properties of the numerical and experimental models and 4) hydro loads on the hull of the numerical and experimental models. These differences are mixed and make it difficult to analyze reasons for the differences between the measurements and simulations in quantity. To avoid this difficult situation, the aerodynamic loads which are actually loaded on the 1:30 scaled model analyzed in this paper are measured and loaded on their corresponding numerical model to ensure identical aerodynamic loads. As analyzed in detail later in this paper, although the aerodynamic loads are loaded as prescriptive loads the differences between the measurements and simulations only indicate differences in the hydro