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Model test investigation of a spar floating wind turbine

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Several floating wind turbine designs whose hull designs reflect those used in offshore petroleum industry have emerged as leading candidates for the future development of offshore wind farms. This article presents the research findings from a model basin test program that investigated the dynamic response of a 1:50 scale model OC3 spar floating wind turbine concept designed for a water depth of 200 m. In this study the rotor was allowed to rotate freely with the wind speed and this approach eliminated some of the undesirable effects of controlling wind turbine rotational speed that were observed in earlier studies. The quality of the wind field developed by an array of fans was investigated as to its uniformity and turbulence intensity. Additional calibration tests were performed to characterize various components that included establishing the baseline wind turbine tower frequencies, stiffness of the delta type mooring system and free decay response behaviour. The assembled system was then studied under a sequence of wind and irregular wave scenarios to reveal the nature of the coupled response behaviour. The wind loads were found to have an obvious influence on the surge, heave and pitch behaviour of the spar wind turbine system. It was observed from the experimental measurements that bending moment at the top of the support tower is dominated by the 1P oscillation component and somewhat influenced by the incoming wave. Further it was determined that the axial rotor thrust and tower-top shear force have similar dynamic characteristics both dominated by tower's first mode of vibration under wind-only condition while dominated by the incident wave field when experiencing wind-wave loading. The tensions measured in the mooring lines resulting from either wave or wind-wave excitations were influenced by the surge/pitch and heave couplings and the wind loads were found to have a clear influence on the dynamic responses of the mooring system.

1. Introduction

With the continually increasing worldwide demand for energy coupled with a growing public awareness of the need to protect the environment, clean renewable energy has become an important current research and development. The conversion of energy from the wind and solar sources are the most visible in terms of research and application to commercial enterprises. Because traditional fixed seafloor-mounted offshore wind turbines are prohibitively expensive in deep water [1], industry and researchers have gradually begun to focus on a variety of floating offshore wind turbines concepts. This research

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study deals with a deepwater spar-type offshore wind turbine concept that could be deployed beyond the line of sight of populous coastal regions and yet near enough to population centers that could benefit energy generating from steadier and stronger wind resources. The research with respect to floating offshore wind turbines is multidisciplinary, involving aerodynamics, hydrodynamics, multi-structure dynamics (elastic) and automatic control [2–6]. So that it is of great importance to reveal the nature of dynamic response characteristics for the in-depth analysis and accurate assessment with respect to a spar-type floating offshore wind turbine (FOWT).

In recent years, the study and analysis of floating wind turbines has mainly relied on simulation tools capable of predicting the coupled dynamic loads and responses of the floating system. In Phase IV of the Offshore Code Comparison Collaboration (OC3), it proposed a floating wind turbine using the specifications of the NREL 5-MW Baseline Wind Turbine [7], except the properties of support structure (tower and substructure) and control system [8]. The modified floater used to support the NREL 5-MW Baseline Turbine is called OC3-Hywind in Ref. [8], and the modified tower is called the "OC3 Hywind tower" in this paper. Soon afterwards, the Code Comparison Collaboration Continuation (OC4) Project was launched by the IEA as an extension of OC3. Both the OC3 and OC4 projects sought to verify the accuracy of the offshore wind turbine dynamics simulation tools (or codes) through a code-to-code comparison of simulated responses of various offshore structures [9,10]. Many simulation tools have been developed and improved for the fully coupled analysis of floating wind turbines [11–15] and many of these simulation tools have been compared and analysed in the OC3 and OC4 projects. However, due to the complexity of these models, the accuracy and reliability of these predictive tools still requires more validation with measured data from real floating offshore wind turbines or model tests.

Statoil and Principle Power Company have conducted field data collection for Hywind and WindFloat respectively, but their recorded field data have not been released for use to the general research community. Thus, model basin test programs focused on floating wind turbines are essential to verify the simulation tools being conceived and developed by researchers around the world. In 2006, Nielsen, Hanson, and Skaare, reported on a model 1:47 scale model test of a 5-MW spar floating wind turbine conducted at Marintek for the Hydro Oil & Energy Company [16]. It presented control schemes based on below or above rated wind speed condition for a basin model in line with those applied on real FOWT. The Principle Power Corporation performed a 1:67 scale model test in the development phase of the first full scale WindFloat platform [17]. Due to the unmatched Re number effect so that the lower model axial rotor thrust and the exceeding complication of control applications in model testing, a compromise was adopted by using a circular disc rather than turbine blades to obtain the equivalent thrust force. This scheme focused on the thrust force (one of the most important aerodynamic loads) and neglected other aerodynamic loads of turbine, providing an alternative solution to eliminate the undesired effect of unmatched Re number. In 2011, Shin conducted a model test with a 1/128 scale ratio in Ocean Engineering Wide Tank at University of Ulsan [18]. This work modelled the OC3-Hywind floating wind turbine and utilized model blades in place of drag disc, which can offer a reference for follow-up experiment and simulation researches with respect to OC3 FOWT. The WindSea Company conducted a model experiment for their WindSea spar-hull wind turbine concept at a 1:64,29 Froude scale [19]. It proposed a new FOWT concept and aimed at verifying their theoretical model. More recently, the University of Maine conducted a series of 1:50 scale model tests incorporating spar-type, semi-submersible-type and TLP-type floating wind turbine concepts [20–22]. These works described the test methodology, model specifications, instrumentation set-up and external environment definition in detail. Also reported in these publications are the primary results of the model basin tests. As a further stage of the basin experiment, a 1:50 scaled model test with respect to the GustoMSC Tri-Floater concept was performed at MARIN basin [23]. This work presented a new model rotor blade with a better Ct and Cp performance under Froude-scaled wind speed, and their control applications were also reported. Furthermore, a STC (spar Tours Combination) concept model test was conducted by Norwegian University of Science and Technology (NTNU) in the towing tank of MARINTEK with a 1:50 model scale [24]. A new combination concept of FOWT and WEC was proposed in this work, and the reliability of this combination concept in survival modes was also investigated. These aforementioned study approaches which involve computer simulation, prototype data measurement and model tests are summarized in Table 1.

Although some model tests have been conducted by MARIN and other research institutions, paper publications in public domain involving these basin test results are still relatively limited, which cannot keep pace with the current developing levels of corresponding simulation tools. More woks should be performed in an effort to satisfy the urgent validation need of existing floating offshore wind turbine (FOWT) simulation codes. In addition, as the research institution whose model test procedures regarding FOWT have the largest number and the most comprehensiveness, MARIN mainly published the test results based on semi-submersible floaters [20,23,25–29], publications of test results with respect to the spar-type supported FOWT are relatively rare, resulting in an inability to provide comprehensive enough validation data. Further, emphasises of these published papers were placed on describing test techniques, presenting raw test data or on comparisons between measured and simulation results to validate simulation tools. In-depth analysis of dynamic response characteristics and coupled behaviours of a spar-type FOWT was rarely conducted.

The intent of this research study was to provide new model test data regarding a spar-type FOWT that will complement that presently available to researchers and overcome the deficiency in shortage of test result publications of FOWT based on a spar-type floater. In addition, more important focus of this paper is on conducting in-depth analysis of response behaviour characteristics of the spar-type wind turbine and corresponding conclusions are subsequently presented. Particular attention is directed at the details that include of the spar model and rotor design, the mooring system, the careful characterization of the wind field, and the anticipated coupling of the response behaviour. Although this basin test is referred to that conducted by MARIN, unique approaches have been implemented in this test such as the rotor spinning was completely induced by the