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On intermediate-scale open-sea experiments on floating offshore structures: Feasibility and application on a spar support for offshore wind turbines

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ABSTRACT

Experimental investigation of floating structures represents the most direct way for achieving their dynamic identification and it is particularly valuable for relatively new concepts, such as floating supports for offshore wind turbines, in order to fully understand their dynamic behaviour. Traditional experimental campaigns on floating structures are carried out at small scale, in indoor laboratories, equipped with wave and wind generation facilities. This article presents the results of an open-sea experimental activity on a 1:30 scale model of the OC3-Hywind spar, in parked rotor conditions, carried out at the Natural Ocean Engineering Laboratory (NOEL) of Reggio Calabria (Italy). The aim of the experiment is two-fold. Firstly, it aims to assess the feasibility of low-cost, intermediate-scale, open-sea activities on offshore structures, which are proposed to substitute or complement the traditional indoor activities in ocean basins. Secondly, it provides useful experimental data on damping properties of spar support structures for offshore wind turbines, with respect to heave, roll and pitch degrees of freedom. It is proven that the proposed approach may overcome some limitations of traditional small-scale activities, namely high costs and small scale, and allows to enhance the fidelity of the experimental data currently available in literature for spar floating supports for offshore wind turbines.

1. Introduction

Nowadays, floating structures are used by several industries, including oil & gas, renewables (wind, wave, tidal), ports, and others, while the development and spread of new concepts is envisaged to take place in a near future [1]. In the case of offshore wind industry, several advantages in moving offshore wind energy production towards deep waters can be exploited, including the availability of larger areas, stronger and steadier winds, and the reduction of visual and acoustic impact. However, the development of such concepts requires a significant amount of research in multiple areas of knowledge, including the development of reliable dynamic models, able to represent the coupled behaviour of the floating wind turbines [2,3]. While such models are usually implemented by means of numerical codes [4,5], experimental activities play a crucial role for their validation, as well as for the system identification.

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The experimental activities on floating offshore wind turbines may be classified in two groups, namely small-scale and large-scale ones. Traditional small-scale activities (1:50–1:100) are carried out in controlled environment such as wave tanks and ocean basins, where the desired wind-wave conditions can be reproduced, to measure the dynamic response of the structure and to calibrate opportunely the numerical codes [6–8]. Although the controlled environment allows to achieve very precise and reliable results, these activities have some relevant disadvantages, namely high rental fees of the basins, limited duration of the experiments, and limitations in representing all the relevant physical phenomena at scale level, which may alter significantly the dynamic behaviour of the model with respect to the full-scale structure. On the opposite side, large-scale activities (1:1–1:10) are carried out in open sea and allow to represent all the relevant features of the offshore wind turbines, including turbine-support interaction, mooring system and grid connection, in relevant operational conditions [9–11]. Clearly, such projects are very expensive and usually represent pilot activities, which are carried out by big companies and/or public bodies for demonstration and commercial purposes, and whose results are rarely publicly available.

1.1. Literature review

Up to now, several small-scale and large-scale experimental activities have been conducted on spar support structures for offshore wind turbines, aimed to prove the feasibility of the concept and validate the corresponding numerical models. A full-scale prototype of a 2.3 MW spar floating offshore wind turbine was installed in 2009 by Statoil [12], off the coast of Norway, on a water depth of about 200 m. The project, called “Hywind Demo”, has proved the technical feasibility of the spar configuration for floating offshore wind turbines, but neither the detailed design characteristics of the offshore wind turbine, nor the recorded field data are publicly available. In 2006, a 1:47 scale model of a 5-MW spar floating wind turbine was tested by Nielsen et al. [13] at the Ocean Basin Laboratory of Marintek, in Trondheim (Norway). The model was tested in irregular waves and turbulent wind speed and various control strategies were adopted. The experimental data showed relatively good agreement with the numerical results obtained in SIMO/RIFLEX, however some information were not released, concerning the detailed characteristics of the model. In 2010, the Offshore Code Comparison (OC3) project [4] was established to verify the accuracy and correctness of the most commonly used numerical codes for coupled analysis of offshore wind turbines. Within this project, the OC3-Hywind spar buoy [14] was defined as the reference spar concept designed to support the NREL-5MW reference offshore wind turbine [15]. Since then, this concept has been widely used for experimental studies on offshore wind turbines, since Statoil's Hywind characteristics are not released for public use. In 2011, a 1:128 scale model of the OC3-Hywind spar platform was tested by Shin [16] at the Ocean Engineering Wave Tank of the University of Ulsan (South Korea). The experiment was conducted under various environmental conditions, including regular waves, associated to constant wind speed and rotating rotor, and irregular waves, associated to fixed rotor. Response Amplitude Operators (RAOs) and significant motions were obtained and compared to numerical predictions obtained using FAST and MOSES codes. In 2010, the Japanese Ministry of Environment started a national demonstration project which led to the installation of a 1:2.35 (2012) and a 1:1 (2013) grid-connected 100 kW and 2 MW spar wind turbines off Goto Islands (Japan), preceded by the testing of a 1:100 scale model, in the offshore structure basin of National Maritime Research Institute (NMRI) in Tokyo (Japan), and of a 1:10 model at sea [9,10,17]. The small-scale test was aimed to study the dynamic behaviour of the model, particularly concerning the effects of blade-pitch control, under regular and irregular waves and constant wind speed. The 1:10 model was aimed to further assess the safety and the performances of the chosen concept. Limited information is available concerning the 1:1 test activity, while experimental data collected in 2012 during a severe typhoon were compared to numerical predictions in FAST by Utsunomiya et al. [18], revealing quite good agreement. In 2012, a 1:50 scale-model of a spar floating wind turbine was tested within a project conducted by the University of Maine [19,20], aimed to compare it with a semi-submersible and a Tension-Leg Platform model. The three models were tested at Maritime Research Institute Netherlands (MARIN) in Wageningen (Netherlands) under various wind-wave conditions, including dynamic wind and bi-directional sea states. Full system identification was achieved, including estimation of the damping ratios and the RAOs. In 2013, a 1:100 scale model of a stepped-spar was tested by Sethumaran and Venugopal [21] at the curved wave tank of the University of Edinburgh (Scotland, UK). Only hydrodynamic behaviour of the model was investigated through regular and irregular wave tests and the experimental results in both the frequency (RAOs) and time domain were compared to numerical predictions obtained using OrcaFlex code. Also, different mooring systems were tested and their performances were compared. In 2016, a 1:50 scale model of OC3-Hywind spar was tested at MARIN by Duan et al. [22], who obtained response spectra for various load combinations and provided a deeper insight on the coupled dynamics of spar floating wind turbines. All these activities provided useful experimental results on the spar dynamic behaviour, but suffered from the above-mentioned limitations, in particular concerning the relatively high costs associated to basin rental, the restrictions in experimental duration and the insurgence of scale effects.

1.2. Aim

The purpose of this paper is to present the results of a 1:30 scale experimental activity on a spar floating support for offshore wind turbines, carried out off the Natural Ocean Engineering Laboratory (NOEL) of Reggio Calabria (Italy). The support model tested is inspired to OC3-Hywind and is represented in parked rotor conditions. The experimental activities carried out during this campaign were aimed at addressing and solving some of the problems inherent to the traditional experimental activities in ocean basins (some initial results were published in Refs. [23,24]).

In recognition of the fact that the well-known identification techniques adopted in indoor laboratories must be modified to work in a non-controlled marine environment, this paper offers a wide overview about the requirements, test methodologies,