Ocean Systems Engineering, *Vol. 5, No. 3 (2015) 139-160*
DOI: http://dx.doi.org/10.12989/ose.2015.5.3.139

Global performances of a semi-submersible 5 MW wind-turbine including second-order wave-diffraction effects

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(Received May 17, 2015, Revised August 19, 2015, Accepted August 27, 2015)

Abstract. The global performance of the 5 MW OC4 semisubmersible floating wind turbine in random waves was numerically simulated by using the turbine-floater-mooring fully coupled and time-domain dynamic analysis program FAST-CHARM3D. There have been many papers regarding floating offshore wind turbines but the effects of second-order wave-body interactions on their global performance have rarely been studied. The second-order wave forces are actually small compared to the first-order wave forces, but its effect cannot be ignored when the natural frequencies of a floating system are outside the wave-frequency range. In the case of semi-submersible platform, second-order difference-frequency wave-diffraction forces and moments become important since surge/sway and pitch/roll natural frequencies are lower than those of typical incident waves. The computational effort related to the full second-order diffraction calculation is typically very heavy, so in many cases, the simplified approach called Newman's approximation or first-order-wave-force-only are used. However, it needs to be justified against more complete solutions with full QTF (quadratic transfer function), which is a main subject of the present study. The numerically simulated results for the 5 MW OC4 semisubmersible floating wind turbine by FAST-CHARM3D are also extensively compared with the DeepCWind model test results by Technip/NREL/UMaine. The predicted motions and mooring tensions for two white-noise input-wave spectra agree well against the measure values. In this paper, the numerical static-offset and free-decay tests are also conducted to verify the system stiffness, damping, and natural frequencies against the experimental results. They also agree well to verify that the dynamic system modeling is correct to the details. The performance of the simplified approaches instead of using the full QTF are also tested.

Keywords: wind energy; FOWT (Floating Offshore Wind Turbine); OC4 semi-submersible; dynamic coupling; mooring tension; second order wave diffraction effect; QTF; FAST-CHARM3D; 5 MW wind-turbine; viscous drag

1. Introduction

The importance of more clean renewable energy has been underscored to secure new energy source and protect environments. Especially, wind energy is appealing since it is economically competitive, technologically proven, infinitely renewable, and does not make any waste or carbon

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http://www.techno-press.org/?journal=ose&subpage=7 ISSN: 2093-6702 (Print), 2093-677X (Online)

emission. Recently, several countries installed offshore floating wind turbines (Dominique et al., 2010). Although they are considered to be more difficult to design than fixed offshore wind turbines, floating wind turbines have many advantages compared to onshore or bottom fixed offshore wind turbines. In general, they are less restricted by regulation, with higher-quality wind, and less sensitive to space/size/noise/visual/foundation restrictions. In this regard, if the technology is completely developed, floating offshore wind turbines are expected to be more popular to generate considerable amounts of clean renewable energy at competitive prices compared to other energy sources (Henderson *et al*. 2002, Henderson *et al*. 2004, Musial *et al*. 2004, Tong 1998, Wayman *et al*. 2006).

One of the challenging issues on the floating offshore wind turbine is the coupled dynamics analysis among the mooring system, floating platform, and wind turbine. Therefore, for reliable design, it is necessary to develop the integrated tool to accurately analyze the fully coupled dynamics including control. Some efforts are in progress toward this direction for several selected types of floating offshore wind turbines. In this paper, the global performance analysis of the OC4 5-MW semi-submersible floating wind turbine was conducted by the fully coupled dynamic analysis tool, the combination of FAST (e.g., Jonkman 2004) and CHARM3D (e.g., Yang and Kim 2010, Kang and Kim 2012), developed by the second author's research group (e.g., Bae and Kim 2011, 2014). Previously, NREL organized the Offshore Code Comparison Collaboration (OC4) (Robertson *et al.* 2012) in order to verify the accuracy of offshore wind turbine dynamics simulation codes by comparing results among various numerical tools and against systematically obtained experimental results.

For the OC4 semi-submersible case, Masciola *et al*. (2013) analyzed the system by including only linear wave force and using quasi-static or lumped-mass methods for mooring model. Also, Coulling *et al*. (2013a, b) performed the validation for the semi-submersible platform including second-order wave-diffraction forces based on Newman's approximation. However, the mooring model in the analysis was also quasi-static, so the true dynamic coupling with mooring lines was missing in the study. Besides, the second-order wave-diffraction force was approximated by Newman's approximation method, and thus, there is a need to check the results by using the actual second -order wave-diffraction forces. Recently, Koo *et al*. (2014a) analyzed the OC4 semisubmersible wind turbine and compared their numerical predictions by their own code, MLTSIM-FAST against DeepCWind model test results. Moreover, the second-order wave-diffraction effects were briefly introduced and discussed in their work (Koo *et al*. 2014b). On the other hand, Zhao and Wan carried out motion simulations of the OC4 semi-submersible platform in waves by using their own CFD code, naoe-FOAM-SJTU. (Zhao and Wan 2015).

In this paper, the fully coupled wind-turbine/hull/mooring dynamics of the OC4 semi-submersible model are calculated by including viscous and second-order difference-frequency wave effects with FE(finite element)-based mooring dynamics module. Also, the complete second-order results (Kim and Yue 1989, 1990, 1991) are compared with first-order-wave-force-only results, Newman's approximation results, and DeepCWind model test results (Coulling *et al.* 2013b). The numerically modeled dynamic system was fully identified through the static-offset and free-decay tests. The system was further analyzed for irregular waves represented by white-noise input-wave spectra and the results were validated against experimental results. For the numerical examples shown in this paper, wind and current are not included to reduce the factors of uncertainties in the comparisons between numerical prediction and model test. The turbine-floater-mooring fully coupled dynamic analysis including blade control and wind-wave-current will be the subject of the next study after this kind of initial validation done in