Global performance of a KRISO semi-submersible multi-units floating offshore wind turbine; numerical simulation vs model test

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ABSTRACT

The global performance of the KRISO square-type semi-submersible multi-unit floating offshore wind turbine in irregular waves is numerically simulated by using the multi-turbine-floater-mooring coupled dynamic analysis program. The developed time-domain numerical-simulation tool is extended from the FAST/CHARM3D coupled dynamics program for the single turbine on single floater. FAST has been developed by the National Renewable Energy Laboratory for years for the single unit. Recently, KRISO has designed and studied the square-semisubmersible-type MUFOWT, in which four 3MW wind turbines are installed at each corner of a single floater. Additionally, twenty-four point-absorber-type linear-generator-based wave energy converters are set up - six wave energy converters at each side of the platform. For verification, KRISO performed a series of model tests for this MUFOWT with 1:50 Froude scale. In this paper, the MUFOWT simulation program is used to reproduce the KRISO’s model test results. In the fully coupled multi-turbine/hull/mooring dynamic simulations, the complete second-order difference-frequency wave forces are also included. The analysis results are systematically compared with the model test results, which shows reasonable correlation between them.

KEY WORDS: Multiple unit floating offshore wind turbine; MUFOWT; square type semi-submersible; coupled dynamics analysis; KRISO model test; Global performance; numerical simulation; second-order effect

INTRODUCTION

The importance of clean renewable energy has been underscored to secure new energy sources 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 emission. In particular, offshore wind energy is very attractive since its quality is much better than that on land or coastal regions. When water depth is greater than 50m, floating wind turbines are usually recommended. Although 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 governmental regulation and residents’ opposition, 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 amount 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). In addition, a Multiple Unit Floating Offshore Wind Turbine (MUFOWT) is also suggested as feasible and interesting concept.

Advantages and disadvantages of MUFOWT were discussed in Barltrop (1993) and simplified analytical tools for the preliminary analysis of the multiple-turbine floater were suggested by Henderson et al. (2004). MUFOWT enables many wind-turbines to be installed on one floater. Using a large floater, the overall dynamics and stability may be improved. MUFOWT may also save installation and mooring-line costs, since the whole unit can be fabricated at quayside, wet-towed, and simply connected to shared mooring system. It can also be used for a multi-purpose energy station including other ocean renewable energy sources to multiply its economic value. Its defects may include wake effect for downstream turbines and uncertainties due to lack of experience.

One of the challenging issues for the MUFOWT is the coupled dynamics analysis among the mooring system, floating platform, and multi-wind turbines. 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. As an extension of the fully coupled dynamic analysis tool for the single-floater wind turbine, the combination of FAST (e.g. Jonkman, 2004) and CHARM3D (e.g. Kang & Kim, 2012), a new tool that can fully analyze MUFOWT has been developed by the second author’s research group (e.g. Bae & Kim, 2011, 2014), and the tool has been validated as comparing the simulation results to the DeepCWind model test results (e.g. Kim & Kim, 2015, 2016).

Until now, several countries have installed single floating offshore wind turbines (Roddier et al., 2010, Hansen et al., 2011, Skaare et al., 2015, Utsunomiya et al., 2014). In the case of MUFOWT, several design concepts were suggested (Henderson and Patel, 2003). Ren et al. (2010) studied the performance of tension-leg type MUFOWT including two wind turbines by numerical simulations. Kallesoe et al. (2011) analyzed the platform motion and turbine loading in the demonstration hybrid plant including triple wind turbines and multi-
WECs, which is developed in the Posidon projects by Floating Power Plant A/S. Hanssen et al. (2015) showed the feasibility of combining wave and wind extraction in a W2P Power full hybrid system, which has twin turbines and several wave energy converters on a triangular semi-submersible type platform. Recently, South Korea has designed and studied the square-semi-submersible-type MUFOWT, in which four 3MW wind turbines are installed at four corners (Kim et al., 2015). Additionally, twenty-four point-power-absorber-type linear-generator-based wave energy converters (WEC) are set up - six wave energy converters at each side of the platform. The submerged platform size is unique having 150m side length compared to the traditional floating wind turbines. This can result in different dynamic characteristics in the global performance. For verification, the Korea research institute of ships and ocean engineering (KRISO) performed a series of model tests for this MUFOWT with 1:50 Froude scale (Kim et al., 2016b). In this model test, the dynamic motions of WECs were not considered, and WECs were fixed to the platform. In this paper, the global performance simulation of the KRISO semi-submersible floating wind turbine was numerically conducted by the fully coupled dynamic analysis computer program including viscous and second-order difference-frequency wave effects with FE(finite element)-based mooring dynamics module, which is included in the CHARM3D, in the irregular wave condition. The time-domain simulation results including the complete second-order diffraction/radiation results (Kim and Yue, 1990) are compared with first-order-wave-force-only results, Newman’s approximation results, and KRISO’s MUFOWT model test results. The numerically modeled dynamic system was first fully identified through the comparison of static-offset test, free-decay test, and current offset test against measurement. The system was further analyzed in the only-irregular-wave survival condition and the combined case of irregular wave, current, and steady wind, and the simulated results were validated against experimental results. The flexibility effect of the tower and blade and the aerodynamic force caused by the wind and platform motion are considered, and the wave energy converters are fixed to the submersible to reduce the factors of uncertainties in the comparisons between numerical prediction and model test. To the best of our knowledge, the rigorous coupled simulation and verification against experiments for the MUFOWT structure has not been reported in the open literature. The MUFOWT is unique in that its size is very large compared to traditional semi-submersible platforms and multiple wind turbines are mounted on it.

Numerical Analysis In Time Domain

In order to calculate the full coupling dynamics among multiple turbines, mooring lines, and a single floater, the aero-rotor-tower CAE program developed by NREL, called FAST (Jonkman, 2003; Jonkman, 2007, 2008; Jonkman and Buhl, 2004), was expanded and combined with the floater-mooring coupled dynamic analysis program, CHARM3D (Tahar and Kim, 2003). The dynamic response of MUFOWT can be derived from the full DOFs including floater 6-DOFs and additional multi-wind-turbine DOFs with proper platform-turbine coupling terms. The entire MUFOWT-coefficient matrix with forcing functions in the right-hand side was solved simultaneously at each time step. Assuming that the degree of freedom for a three-bladed turbine in FAST is turned on with 19 modes, the total DOFs of MUFOWT can be expressed as $6 + 19 \times N$, where N is the total number of turbines. The inertia and active forces from each turbine should be independently fed to couple with the floating floater. The coupled terms between a floating platform and each turbine in the coefficient matrix can be derived by accounting for every effect of inertia and active forces from both bodies. The detailed theory and equation are given in a paper by Bae and Kim (2014).

The hydro-dynamic loadings and mooring restoring forces are obtained from CHARM3D, which calculates all of the external forces acting on the floating platform and feeds the external forces to FAST at each time step. The transferred external forces include first-order and second-order wave forces, radiation damping force in terms of convolution integral, nonlinear viscous drag forces at respective instantaneous positions of Morison members, and mooring-induced restoring forces. Then FAST fills out the forcing function of platform DOFs using those transferred forces, and solves displacements, velocities, and accelerations of all degrees of freedom including elastic responses of towers and blades. The obtained platform kinematic data are then fed into CHARM3D side to update the external forces. The procedure is repeated for the next time step. The basic concept of rotor-floater coupling is schematically shown in Fig. 1.

![Fig. 1 Basic concept of FAST-CHARM3D coupling](image)

### Numerical Model Description

Figs. 3-9 and Tables 2-5 show various features of numerical and physical models. For body-surface discretization, a total of 5513 panels are used for the platform with x and y symmetry as shown in Fig. 3. For a convergence test, three mesh models, which have three different panel numbers, 4069, 5513, and 7148, are used and compared. For instance, the result of surge mean drift force, as the strictest measure of the first-order calculations, is shown in Fig. 2. Their differences are less than 1%. Based on this convergence test, the 5513-mesh model is chosen for all the subsequent simulations. Regarding the chain mooring property, drag coefficient=$2.4$ is chosen for calculating the drag force based on the Morison equation for a moving body. The mooring system is modeled by HARP which is the Hull and Riser/mooring Program including post-processor and pre-processor of CHARM3D. Total buoyancy is the same as the sum of total structure weight and the vertical tension of mooring. The high-order finite-element method (FEM) is used for the mooring dynamics modeling, and 43 elements for each line are used for the FEM analysis. For the system identification between the model test and simulation, static offset test and free-decay test are carried out. The obtained platform-6-DOF natural frequencies are tabulated in Table 6. The added mass and radiation damping are obtained through potential theory by WAMIT, and the 2nd-order effect is included by full quadratic transfer function (QTF) (or Newman’s approximation). The viscous effect is calculated by the Morison equation for the moving body. In this simulation, the platform is assumed as a rigid body, and the tower and blade’s fore-apt (FA) and side-to-side (SS) flexibilities are considered. The generic tower and blade properties used in the simulation were designed by KRISO. The natural frequencies and mode shapes of tower and blade are calculated from the BModes program, and the natural frequencies of tower are tabulated in Table 1. The dynamic motions of MUFOWT are also compared between with and without tower flexibility and the differences in surge, heave, pitch, and mooring top tension are less than 0.1%. Thus, the tower-flexibility effect on MUFOWT motions and mooring tensions is negligible.

<table>
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<tr>
<th>Title</th>
<th>1st FA</th>
<th>2nd FA</th>
<th>1st SS</th>
<th>2nd SS</th>
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<td>Natural frequency (rad/sec)</td>
<td>5.34</td>
<td>5.33</td>
<td>32.42</td>
<td>36.29</td>
</tr>
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Table 1 Natural frequencies of tower mode