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Coupled dynamic analysis of multiple wind turbines on a large single floater

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ABSTRACT

The present study has developed a numerical simulation tool for the coupled dynamic analysis of multiple turbines on a single floater (or Multiple Unit Floating Offshore Wind Turbine (MUFOWT)) in the time domain including multiple-turbine aero-blade-tower dynamics and control, mooring dynamics, and platform motions. The numerical tool developed in this study was designed based on and extended from the single-turbine analysis tool FAST to be suitable for multiple turbines. For hydrodynamic loadings of floating platform and mooring-line dynamics, the CHARM3D program developed by the authors was incorporated. Thus, the coupled dynamic behavior of a floating base with multiple turbines and mooring lines can be simulated in the time domain. The developed MUFOWT analysis tool can compute any type of floating platform with multiple horizontal-axis wind turbines (HAWT). To investigate the dynamic coupling effect between platform and each turbine, one turbine failure case with a fully broken blade was simulated and checked. The aerodynamic interference between adjacent turbines, including wake effect, was not considered in this study to more clearly demonstrate only the dynamic coupling. The analysis shows that some damage-induced excitations from one turbine in MUFOWT may induce appreciable changes in the performance of other turbines or the floating platform.

1. Introduction

Recently several countries started to plan and install Floating Offshore Wind Turbines (FOWTs). Compared to fixed OWTs, floating OWTs are generally more difficult to design due to floater motions. However, if water depth is greater than 60 m, FOWTs are considered to be more cost-effective. Moreover, wind farms in deeper waters are generally less sensitive to space availability, noise restriction, visual pollution, and regulatory problems. They are also exposed to much stronger and steadier wind fields to become more efficient. In designing those floating wind farms, the existing technology and experience of the offshore oil & gas industry can readily be applied. In this regard, if technology and infrastructure is fully developed, offshore floating wind farms are expected to produce huge amounts of clean electricity at a competitive price compared to other energy sources (Henderson et al., 2002, 2004; Musial et al., 2004; Tong, 1998; Wayman et al., 2006).

It is widely accepted that the cost increase of FOWT is not very sensitive to the increase of floater size. In this regard, another interesting and plausible FOWT concept is the Multiple Unit Floating Offshore Wind Turbine (MUFOWT). This model includes multiple wind turbines on a single floating platform rather than the typical concept of one wind turbine on one floater. The possible advantages and disadvantages of a MUFOWT over a single-unit floating turbine were discussed in Barltrop (1993) and an effort was made by Henderson et al. (2004) to develop simplified analytical tools for evaluating the performance of the multiple-turbine floater.

Compared to the single-unit floating wind turbine, MUFOWT has several advantages. First, many turbines can share the floating base and mooring lines to minimize respective costs. The whole unit can be fabricated at the quay side and towed to connect to a pre-installed mooring system. This way installation cost can be minimized. From a stability point of view, MUFOWT generally provides a more stable condition than a single-unit floater. The increased stability also enables higher towers and larger blades for higher energy capture. In random sea environments, better response characteristics are expected because larger floating units usually tend to have less response. A larger floating platform may be equipped with a helicopter port for access by air.

On the other hand, there are also several disadvantages of the MUFOWT concept. One of the most serious problems is the possible interference among turbines when one unit fails to operate with

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normality. Another anticipated problem is the possibility of a performance drop caused by the blade shade effect due to insufficient distance between them. This disadvantage may be overcome by adopting an ingenious floater design or turbine arrangement. In the earlier research of MUFOWT, such a large floating structure with multiple turbines was not regarded as cost-effective. However, recent technological developments and use of bigger turbines make this concept more viable.

In this regard, a fully coupled dynamic analysis computer program including multiple turbines on a single floater and mooring lines is developed by combining and expanding several computer-aided engineering (CAE) tools. Initially, for the dynamic analysis and control of a single wind turbine system, the primary design code of wind turbines FAST developed by National Renewable Energy Laboratory (NREL) was employed (Jonkman, 2003, 2007, 2008; Jonkman and Buhl, 2004). The aero-rotor-tower program FAST was then combined with the floater-mooring coupled dynamic analysis program CHARM3D (Kim et al., 1999, 2001; Tahar and Kim, 2003; Yang and Kim, 2010, 2011; Kang and Kim, 2012). For years, the coupling between FAST and CHARM3D has been successful and the developed program has been used for the fully coupled dynamic analysis of many floating platforms with a single turbine (Bae and Kim, 2011, 2013a, b). In this paper, the FAST-CHARM3D has been significantly extended to analyze the new system of multiple-turbines on a single floater. The equation of motion for the entire system, including multiple turbines with a single floating platform, is simultaneously solved in the time domain by a global combined matrix including all the relevant coupling forces and degrees of freedom. As a result, the dynamic responses of the MUFOWT system with full couplings among towers, blades, drive-trains, floater, and mooring system can be obtained simultaneously in the time domain by a single run. To the best knowledge of authors, the fully coupled dynamic analysis of the MUFOWT has never been published. The developed computer program is applied to investigate the dynamic coupling effects among multiple turbines on the same rigid floater when one turbine fails to operate normally. For the given example, platform size is not huge (size of typical offshore platform), therefore, the effect of the elasticity of the platform (floater) should be small. In case of much bigger platform, the flexibility of the floating base may play a role, which is beyond the scope of present study.

2. Dynamics of a multiple-unit floating offshore wind turbine

The time domain simulation tool for fully coupled dynamic analysis for multiple turbines on a single floater with mooring lines was developed in this study. The current FAST was designed to solve for one turbine on one floater. In order to solve multiple turbines on a single floating platform, FAST was considerably modified/extended so that it could account for full coupling among multiple turbines and a single floating platform. The dynamic behavior 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-system equations of motions were built by using one global coefficient matrix with forcing functions in the right-hand side and then the matrix equation was solved simultaneously at each time step. Assuming that every degree of freedom for a three-bladed turbine in FAST is turned on, the total DOFs of MUFOWT can be expressed as $6+18\times N$, where N is the total number of turbines. The generalized inertia and active forces from each turbine should be independently fed to couple with the sharing floater. The coupled terms between a floating platform and each turbine in the coefficient matrix can be derived by accounting for every effect of generalized inertia and active forces from both bodies. In the case of the coupling terms between one turbine and another, the corresponding coefficients are set to zeros because their kinematic coupling is not made directly but only through the sharing floater. The hydrodynamic coefficients including added mass, radiation damping, wave forces, and second-order mean a nd slowly varying drift forces of floaters were obtained by the 3D diffraction/radiation preprocessor WAMIT in the frequency domain (Lee and Newman, 1999, 1991). The information was then transferred to the time-domain analysis tool. The mooring dynamics coupled with the hull motions were solved at each time step by a generalized-coordinate-based FEM program using a high-order element (Kim et al., 2001).

The generalized active force on the entire MUFOWT system can be divided into turbine part and floating platform part. For the turbines on the platform, the generalized active forces can be obtained independently from each other (as mentioned previously, wake effects were not considered in the present paper) i.e. aero dynamic, elastic, gravity, generator, and damping forces for each turbine are summed up individually and arranged one by one. Then the generalized active forces on each turbine can be expressed as

$$\begin{cases} F_r^{Turbine\#1} = F_r|_{Aero}^{Turbine\#1} + F_r|_{Elastic}^{Turbine\#1} + F_r|_{Gravity}^{Turbine\#1} + F_r|_{Generator}^{Turbine\#1} + F_r|_{Damping}^{Turbine\#1} \\ \vdots \\ F_r^{Turbine\#N} = F_r|_{Aero}^{Turbine\#N} + F_r|_{Elastic}^{Turbine\#N} + F_r|_{Gravity}^{Turbine\#N} + F_r|_{Generator}^{Turbine\#N} + F_r|_{Damping}^{Turbine\#N} \end{cases} \tag{1}$$

So, the total generalized active forces of turbines excluding the floating platform can be written as a summation of Eq. (1).

$$F_r^{TotalTurbines} = F_r^{Turbine\#1} + \cdots + F_r^{Turbine\#N} \tag{2}$$

The generalized active force on the floating platform should be taken into account separately because the platform is not individually arranged but shared by all turbines:

$$F_r^{Platform} = F_r|_{Hydro} + F_r|_{Mooring} \tag{3}$$

The generalized active force on the platform comes from hydrodynamic forces and mooring-line restoring forces and they should be accounted for once. Mooring force in Eq. (3) also includes its gravity force. Platform gravity force is included in the platform inertia and restoring forces. The platform and mooring forces also include nonlinear viscous drag forces on them.

By combining Eqs. (2) and (3), the total generalized active forces on the MUFOWT can be established as shown below in Eq. (4):

$$\begin{aligned} F_r &= F_r^{TotalTurbine} + F_r^{Platform} = F_r^{Turbine\#1} + \cdots + F_r^{Turbine\#N} + F_r^{Platform} \\ &= F_r|_{Aero}^{Turbine\#1} + F_r|_{Elastic}^{Turbine\#1} + F_r|_{Gravity}^{Turbine\#1} + F_r|_{Generator}^{Turbine\#1} + F_r|_{Damping}^{Turbine\#1} \\ &\quad + \cdots \\ &\quad + F_r|_{Aero}^{Turbine\#N} + F_r|_{Elastic}^{Turbine\#N} + F_r|_{Gravity}^{Turbine\#N} + F_r|_{Generator}^{Turbine\#N} + F_r|_{Damping}^{Turbine\#N} \\ &\quad + F_r|_{Hydro} + F_r|_{Mooring} \end{aligned} \tag{4}$$

Similarly, the generalized inertia force can also be expressed for MUFOWT. First, the generalized inertia forces from each turbine are obtained. The inertial loadings of each turbine, such as tower, nacelle, hub, and blades are calculated based on the mass and inertia properties of each component and summarized with respect to the tower base origin for each turbine. The generalized inertia force of each turbine can be expressed as

$$\begin{cases} F_r^{*Turbine\#1} = F_r^*|_{Tower}^{Turbine\#1} + F_r^*|_{Nacelle}^{Turbine\#1} + F_r^*|_{Hub}^{Turbine\#1} + F_r^*|_{Blades}^{Turbine\#1} \\ \vdots \\ F_r^{*Turbine\#N} = F_r^*|_{Tower}^{Turbine\#N} + F_r^*|_{Nacelle}^{Turbine\#N} + F_r^*|_{Hub}^{Turbine\#N} + F_r^*|_{Blades}^{Turbine\#N} \end{cases} \tag{5}$$