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Discussion

Discussion on "Rotor-floater-mooring coupled dynamic analysis of mono-column-TLP-type FOWT (Floating Offshore Wind Turbine)"

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1. Introduction

The paper (Bae and Kim 2011) presented the theory and methodology for the coupled dynamic analysis among wind turbine, tower, floater, and mooring lines including aerodynamics, active control of blades, tower-blade elasticity, and floater-mooring dynamics in winds, waves, and currents for a 1.5MW mono-column TLP FOWT. Authors coupled the aero-elastic-control program FAST developed by NREL (e.g., Jonkman 2009) with the floater-mooring program CHARM3D/HARP developed by Professor Kim's research group (e.g., Kim *et al.* 2001, 2005, 2009) during the past decade to analyze full dynamic coupling of multi-floaters and mooring-riser. This kind of full dynamic coupling including all the aspects of FOWT is still very rare in the open literature and under continuous development in many countries.

The most important differences between the FOWT and conventional floating offshore oil-production platform are tower flexibility, rotational-blade inertia, active blade control, and the corresponding aero-dynamic loading. They influence the floater motions and mooring dynamics and, in turn, the platform motions affect the control scheme and aerodynamic/elastic loading. The two parts can be interfaced at each time step, as detailed in the paper.

One of the important design concerns is the maximum acceleration at the nacelle. The height and tip-mass of FOWTs are typically large, so high acceleration there may cause very large inertia loading on the tower and floater. It can also greatly reduce the system's fatigue life. In this regard, the correct estimation of the maximum acceleration at the nacelle position is very critical in the design of FOWTs.

In case of a rigid floating body, the horizontal acceleration at the top consists of two parts. The first one $\ddot{x}$ due to horizontal motions (surge-sway) and the second-one $l\ddot{\theta}$ due to rotational motions (pitch-roll) through the moment arm l from the center of rotation. In case of a flexible tower, there is additional contribution from the additional flexible modes. If we introduce the additional elastic modes, then the original rigid-body pitch natural frequency is slightly shifted due to dynamic

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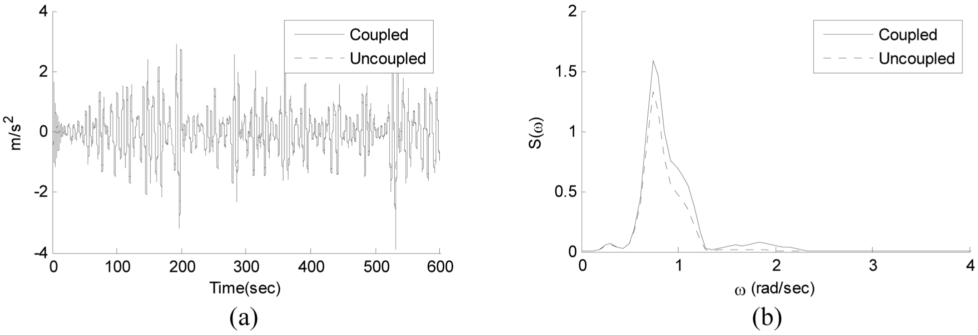
coupling. Similarly, the natural frequencies of the elastic modes for the fixed base are also slightly altered due to the mobile base. In this regard, there exist clear differences between the rotor-floater fully-coupled and uncoupled dynamic analyses. In the uncoupled dynamic analysis, the whole unit is treated as a rigid body like the way conventional offshore platforms are analyzed. The rotor-floater coupling effects are expected to be more significant as the size of turbine-blade-tower and tower-flexibility increase. This phenomenon is similar to that they can observe for vessel motions with liquid tanks (e.g., Lee *et al*. 2007, Lee and Kim 2011), in which the additional liquid sloshing modes alter the vessel's original 6DOF natural frequencies.

One example of the rotor-floater coupling and the comparison between fully-coupled and uncoupled dynamic analyses is given in Bae and Kim (2011) for a relatively small 1.5 MW mono-column-TLP FOWT. In the paper, the accelerations are over-predicted in Figs. 16-18 (also Fig. 20(b)) and Table 10 due to the error in superposing all the components with their phases. All the other results including motions and line tensions are correct. In the present discussion paper, we correct the acceleration results and also introduce very important physical insights related to the tower-floater dynamic coupling.

2. Numerical results and discussions

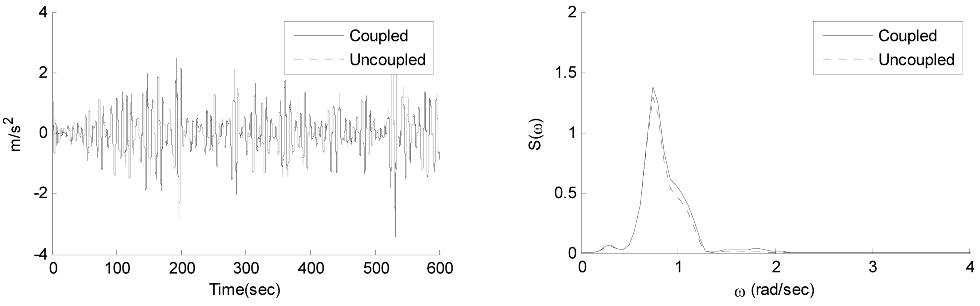
Fore-aft accelerations at 3 different locations of the tower were given in Figs. 16-18 of Bae and Kim (2011). For the coupled case, the total acceleration at a given height is calculated by the summation of the local tower acceleration from elastic vibration and the global acceleration due to the hull motion. Phase differences between the local tower acceleration and global acceleration are considered in the calculation of the total acceleration. In the uncoupled analysis, the whole system is treated as a rigid floating body, so only the global accelerations of the rigid body are considered at the respective heights. The corrected results corresponding to Figs. 16-18 of Bae and Kim (2011) are given in Figs. 1-3.

As can be seen in the corrected results, the actual increase of the top acceleration due to the tower elasticity and rotor-floater coupling is appreciable but not so significant as given in Bae and Kim (2011). In a larger, higher and more flexible FOWT, however, the coupling effects may be more pronounced. The statistics of the tower fore-aft accelerations given in Table 10 of Bae and Kim (2011) are also revised and presented in Table 1. It shows that the maximum acceleration of the coupled analysis is increased by 34% at the top position compared to that of the uncoupled analysis.



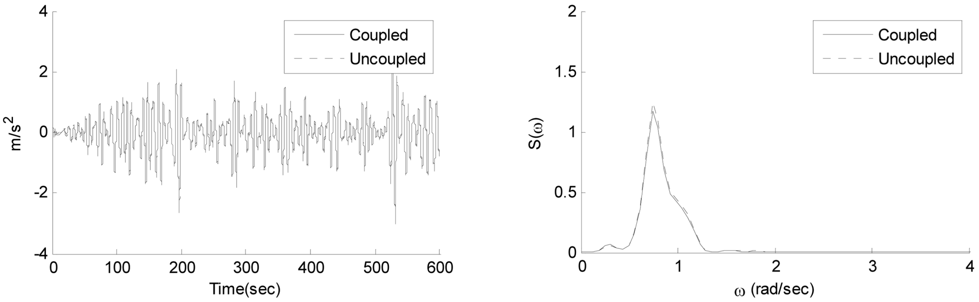
(a) (b)

Fig. 1 Tower acceleration time histories (a) and spectra (b) at the height of 78.27 m from MWL



(a) (b)

Fig. 2 Tower acceleration time histories (a) and spectra (b) at the height of 53.56 m from MWL



(a) (b)

Fig. 3 Tower acceleration time histories (a) and spectra (b) at the height of 4.12 m from MWL

Table 1 Tower acceleration statistics (UC: Uncoupled, C: Coupled)

		Max	Min	Mean	SD
78.27 m from MWL (m/s^2)	UC	2.63E+00	–3.23E+ 00	2.17E-03	7.33E-01
	C	3.53E+00	–3.90E+00	1.85E-03	8.57E-01
53.56 m from MWL (m/s^2)	UC	2.60E +00	–3.16E+00	2.15E-03	7.24E-01
	C	2.94E+00	–3.43E+00	1.69E-03	7.68E-01
4.12 m from MWL (m/s^2)	UC	2.53E+00	–3.04E+00	2.12E-03	7.05E-01
	C	2.37E+00	–2.99E+00	1.63E-03	6.85E-01

The increase is mainly due to the additional tower elastic modes, especially the lowest bending mode. As the position is lower, the increase due to tower elasticity becomes smaller. For example, at the middle position, the increase of maximum acceleration is 13%. On the other hand, at the near bottom position, the maximum acceleration of the uncoupled case is larger than that of the coupled case by 7%. For the acceleration at the tower base, the major contribution comes from the surge acceleration of the floater at the point.

In this regard, we also presented in Table 2 the floater 6DOF accelerations with respect to the coordinate origin at the MWL (mean water level). Similar to the tower base accelerations, the uncoupled surge acceleration is 7% greater than the coupled surge acceleration. This difference

Table 2 Floater-acceleration statistics (UC: Uncoupled, C: Coupled)

		Max	Min	Mean	SD
Surge (m/s^2)	UC	2.52E+00	–3.03E+00	2.11E-03	7.03E-01
	C	2.36E+00	–2.98E+00	1.69E-03	6.83E-01
Sway (m/s^2)	UC	8.08E-08	–8.46E-08	–9.20E-10	3.76E-08
	C	1.06E-02	–9.78E-03	–1.25E-05	1.74E-03
Heave (m/s^2)	UC	4.09E-01	–2.43E-01	–1.46E-06	4.27E-02
	C	4.25E-01	–2.42E-01	1.77E-05	4.11E-02
Roll (rad/s^2)	UC	1.04E-09	–1.14E-09	–1.65E-13	2.40E-10
	C	4.85E-04	–4.59E-04	4.42E-08	8.54E-05
Pitch (rad/s^2)	UC	2.70E-03	–2.74E-03	7.55E-07	4.32E-04
	C	4.94E-03	–4.02E-03	2.25E-06	7.92E-04
Yaw (rad/s^2)	UC	1.52E-08	–1.50E-08	–6.24E-12	4.83E-09
	C	5.58E-03	–6.22E-03	1.61E-06	1.13E-03

mainly comes from the blade-pitch-control action in the coupled analysis, which continuously reduces the wind loading by changing blade pitch angle when the wind velocity is larger than the rated wind velocity. The action is needed to generate constant power. As a result, the active control of the blade reduces the wind-induced surge forces on the system and the corresponding surge responses. On the other hand, the active control of the blade contributes to the increase of heave acceleration, as shown in Table 2. For this reason, the uncoupled analysis that does not include the tower elasticity and aero-floater-rotor dynamic coupling is not good enough to accurately estimate the tower acceleration at each location. The accurate estimation of the accelerations is very important since large accelerations may cause fatigue or structural failure through the large inertial loading on various parts of FOWT.

Another important aspect of rotor-floater coupling is the shift of original tower-bending natural frequencies due to the mobile base and vice versa i.e., the 6DOF natural frequencies of the floater as a rigid body are also altered due to the presence of elastic dynamics of the tower. In Bae and Kim (2011), the effects of softer foundation were also illustrated by reducing the tether axial stiffness by half. With the halved AE, the heave and pitch natural frequencies of the floater are still high, as 5.93 rad/s and 3.12 rad/s (see Table 5 of Bae and Kim 2011). In the present study, second-order sum-frequency wave excitations are not included. On the other hand, the original lowest elastic bending mode of the tower with fixed bottom is 2.59 rad/s (Table 4 of Bae and Kim 2011). Fig. 4 shows the top-tension spectra of tether 2 for the original and halved tendon stiffness. It is seen that due to mobile base, the lowest bending natural frequency of the tower is shifted to 2.3 rad/s for the original AE and 2 rad/s for the halved AE. As the tether AE is halved, we can see that the hull pitch acceleration is significantly increased near 2 rad/s, as shown in Fig. 5(a), mainly due to the interaction with the lowest bending motion of the tower. It results in the increase of tether-top tension at 2 rad/s in Fig. 4. In deeper water, the pitch-roll natural frequency may become closer to the lowest-bending natural frequency, and thus the coupling effect between the rotor and hull is expected to increase even more.

Finally, the effect of tower stiffness on platform pitch natural frequency is presented below. If the

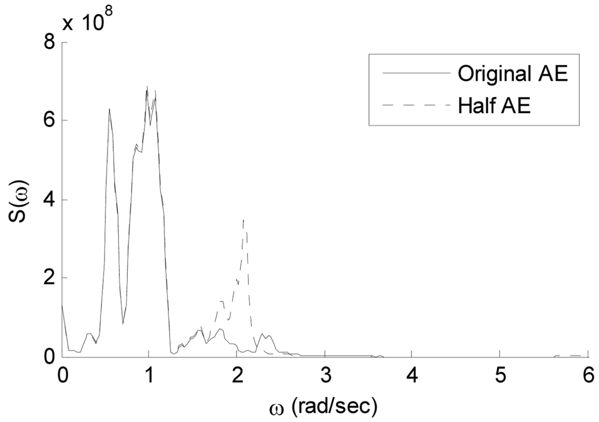
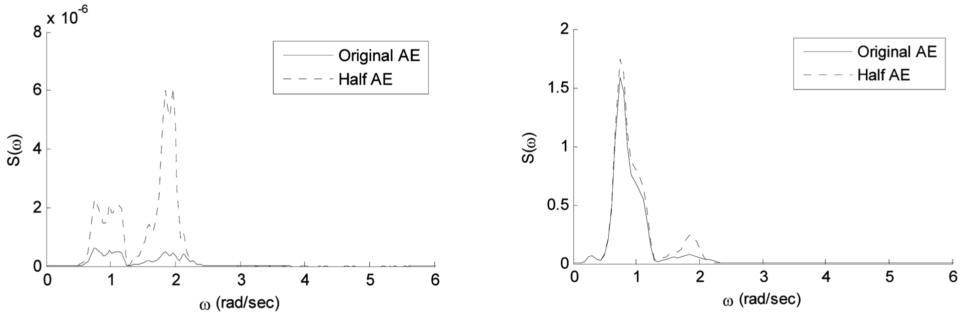


Fig. 4 Top-tension spectra of tether 2



(a) (b)

Fig. 5 Spectra of hull pitch acceleration (a) and tower-top acceleration (b)

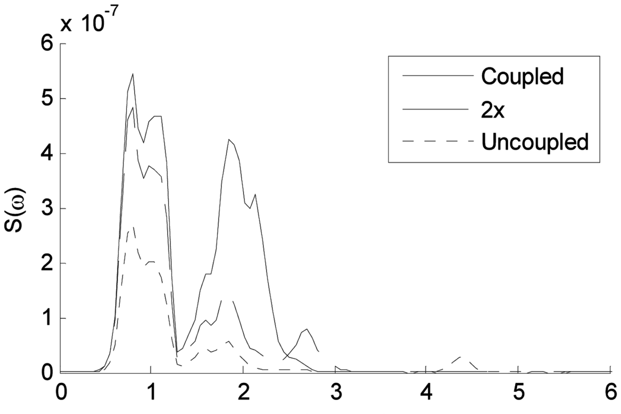


Fig. 6 Spectra of hull pitch acceleration with different tower stiffness

tower is infinitely stiff as in the uncoupled analysis, the platform pitch natural frequency is simply determined by the pitch moment of inertia with added inertia and pitch stiffness of the platform. This pitch natural frequency can be seen at 4.43 rad/s in uncoupled case in Fig. 6.

However, this platform pitch natural frequency moves down to 2.15 rad/s as the given tower elasticity is included in the coupled analysis. To observe this phenomenon more clearly, the tower stiffness is doubled and the same calculation is repeated. As expected, the pitch natural frequency with the twice stiffer tower is located near 2.7 rad/s between the two (infinite and original tower stiffness) cases. It is expected that the stiffer tower would increase the platform pitch natural frequency closer to that of the uncoupled case. So, the conventional method, which is widely used in oil and gas industries to estimate the platform pitch natural frequency, would not be sufficiently valid if tower elasticity is appreciable in FOWT analysis.

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