Coupled vs. Uncoupled Analyses for Seismic Assessment of Offshore Wind Turbines

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Abstract: - Seismic analysis of offshore horizontal-axis wind turbines is inherently non-linear, with interactions among aerodynamic, hydrodynamic and seismic responses to be accounted for by time-consuming fully-coupled time-domain simulations, for which only dedicated software packages can be used. For seismic assessment of land-based turbines, existing standards and guidelines allow uncoupled analyses, where aerodynamic and seismic responses are separately computed on a structural model with an appropriate additional damping, named *aerodynamic damping*, and then linearly combined. Although similar approaches are permitted also for offshore wind turbines, to date no specific recommendations have been released on crucial issues, such as how to implement the uncoupled analyses and which aerodynamic damping has to be used. This paper investigates these issues, considering a 5 MW turbine mounted on a bottom-fixed tripod as a study case.

Key-Words: - Offshore Wind Turbines, Seismic Response, Uncoupled Analyses, Aerodynamic Damping

1 Introduction

Seismic assessment of bottom-fixed offshore horizontal-axis wind turbines (HAWTs) is prescribed by recent international standards and guidelines [1-3]. This subject has become of particular interest considering that, while an increasing number of wind farms is being planned far from near-shore shallow waters (<30 m) to minimize visual impact, several transitional water depth (30-60 m) sites exist with high wind resources and medium-to-high seismic risk [4-6].

A few recent studies have investigated the seismic response of offshore HAWTs mounted on either monopiles [7-8] or support structures with a tripod or jacket [9]. Simplified [7-8] or full system models [9] have been used, considering earthquakes striking in the rotor parked state [7-9] or operational state [9]. While simplified system models include the support structure only, with the rotor-nacelle assembly (RNA) modelled as a lumped mass at the tower top, full system models involve the support structure and the whole turbine, i.e. nacelle, rotor blades and turbine components (power transmission, pitch/speed control devices). In a comprehensive study for a large set of earthquakes [9], the authors have shown that accurate predictions of the seismic response can be obtained only by fully-coupled non-linear time-domain simulations, on full system models including support structure and the whole turbine, in agreement with similar conclusions on the seismic response of land-based HAWTs [10-13]. Fully-coupled non-linear time domain simulations are indeed the most appropriate approach to capture the mutual dependence among aerodynamic, hydrodynamic and seismic responses: while tower top oscillations due to wave loads and earthquake ground motion affect rotor aerodynamics, in particular the relative wind speed at the blades, depending on which the aerodynamic loads (lift and drag forces on the blades) are calculated, wind loads and earthquake ground motion affect the support structure velocities and, consequently, the hydrodynamic loads. Also, only a full system model allows loads acting on all system components to be estimated, including those on key components as the rotor blades [9].

Although fully-coupled non-linear time domain simulations provide the "exact" numerical solutions, they involve some significant disadvantages: (i) a dedicated software package is needed, capable of accounting for inherent interactions between aerodynamic, hydrodynamic and seismic responses; (ii) computational costs are significant, almost prohibitive when several analyses have to be implemented for different environmental states and system parameters, as in the early stages of design. For these reasons, existing standards and guidelines allow performing uncoupled analyses, where the responses to wind, wave and earthquake loads are computed separately, and then combined by linear superposition [1-3]. Uncoupled analyses are allowed not only for seismic assessment of offshore HAWTs but also for land-based HAWTs [14-16]. However, while standards and guidelines on land-based HAWTs prescribe some recommendations on how to implement uncoupled analyses (see, in particular, ref. [16]), no specific indications are provided on offshore HAWTs [1-3].

Indeed the crucial recommendation of standards and guidelines for uncoupled analyses on land-based HAWTs is that a proper additional damping, named *aerodynamic damping*, has to be included in the structural model, in order to account for the inherent interactions between aerodynamic and seismic responses [16]. This is substantiated by extensive numerical simulations on land-based HAWTs showing that, if no aerodynamic damping is considered when applying the separate wind and earthquake loads on the structural model, the vibration response would be erroneously larger than the actual vibration response computed by a fully-coupled simulation where the aerodynamic and seismic loads are generated simultaneously [17-18]. This result is generally attributed to the fact that the tower top oscillations due to wind and earthquake loads, significantly affect the instantaneous thrust force, producing indeed damping effects [17-18]. In particular, Witcher [17] has noticed that, if the separate earthquake moment demand at the tower base is computed from a 5% fore-aft (FA) response spectrum and then linearly combined with the wind moment demand, being both earthquake and wind moment demands computed from a structural model including the full RNA on the flexible tower, a good matching is attained with the moment demand at the tower base computed from the fully-coupled, non-linear time domain simulations. Considering that steel structures can reasonably be given a 1% structural damping, using a 5% response spectrum does correspond to considering an additional 4% aerodynamic damping to be included in the FA modes when computing the separate earthquake response. A 4% value for the FA modes and a 0% value for the side-to-side (SS) modes are also the aerodynamic damping values recommended by ASCE/AWEA guidelines, regardless of wind conditions, local seismicity and wind turbine characteristics.

As for what concerns offshore HAWTs, however, neither numerical studies nor standards or guidelines recommendations exist on the appropriate aerodynamic damping to be adopted, when implementing uncoupled analyses for seismic assessment. This study aims to run some preliminary investigations in this respect. For this, the reference NREL 5 MW HAWT [19], mounted on a bottom-fixed tripod in a transitional water depth, is considered as a study case. Uncoupled analyses are implemented on a structural model with full modelling of the RNA, where hydrodynamic and seismic responses are computed from standard wave and earthquake analyses, while the aerodynamic response is computed by applying top loads taken from an aerodynamic simulation where the rotor is supposed to be mounted on a fixed support (in the following, referred to as fixed rotor); additional aerodynamic damping is included in all the three separate simulations, in the first two FA and SS support structure modes. The proposed approach mirrors a typical approach to uncoupled fatigue analyses, recently presented by Van der Tempel [20-24]. A comparison in terms of tower base moment demand with the corresponding value from fully-coupled non-linear time-domain simulations provides the appropriate aerodynamic damping values to be adopted in FA and SS directions. Results with a 4% aerodynamic damping in the first two FA support structure modes are also included, in order to assess to which extent existing recommendations on land-based turbines are applicable also for offshore wind turbines.

2 Structural Modeling

The turbine is the NREL 5MW three-bladed turbine [19]. The support structure is a steel centre column tripod resting on pile foundations, shown in Fig. 1, designed according to current practice. Details on the structural members are given in Fig. 2. It is assumed that the water depth is 50 m.

The full system is implemented in BLADED [25], modelling nacelle, blades, drive train, control system, as given in ref. [19]. In BLADED [25], the motion equations are derived from a combined multi-body dynamics and modal approach. Shear-deformable beam elements are used for support structure structural members, piles and blades. Steel parameters are: Young's modulus = 210 GPa, Poisson coefficient = 0.3, Mass density = 7850 kg m^{-3}. The structure is assumed to be fixed at the base.

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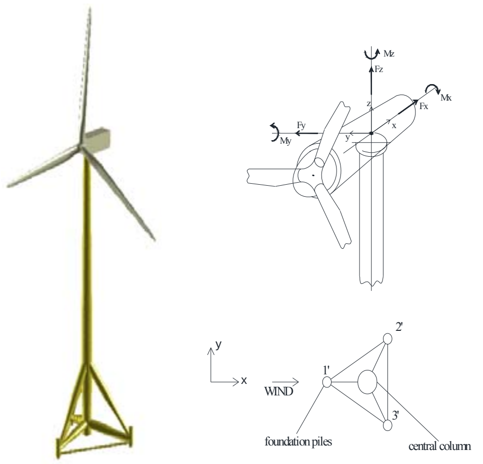


Fig. 1. Tripod support structure, pile foundations and positive stress resultants.

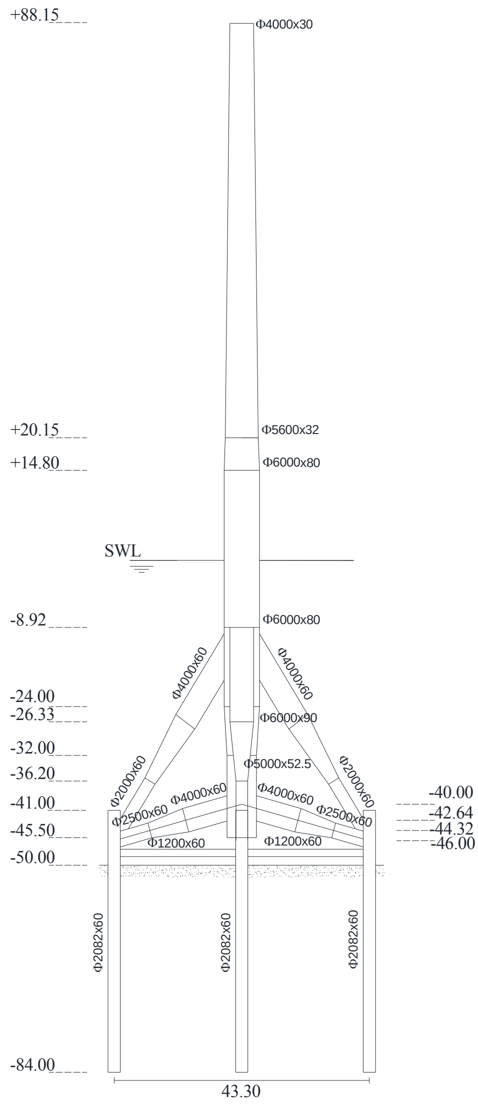


Fig. 2. Tripod support structure geometry (dimensions of structural members in mm; heights and depths in m).

Table 1 shows the frequencies of support structure modes and blades modes, in a parked state (no rotational speed) at 0° azimuth angle (one blade upward and two blade downward), in FA and SS directions, corresponding to *x* and *y* directions in Fig. 1. Shapes of first and second FA support structure modes are reported in Fig. 3; those in the SS direction are similar and are not reported for brevity.

Mode description	Freq. (Hz)
1st Tower Side-to-Side	0.309
1st Tower Fore-Aft	0.311
1st Blade Asymmetric Flapwise Yaw	0.645
1st Blade Asymmetric Flapwise Pitch	0.677
1st Blade Collective Flap	0.710
1st Blade Asymmetric Edgewise Pitch	1.081
1st Blade Asymmetric Edgewise Yaw	1.097
2nd Blade Asymmetric Flapwise Yaw	1.749
2nd Blade Asymmetric Flapwise Pitch	1.848
2nd Blade Collective Flap	1.996
2nd Tower Fore-Aft	2.206
2nd Tower Side-to-Side	2.277

Table 1. Natural frequencies.

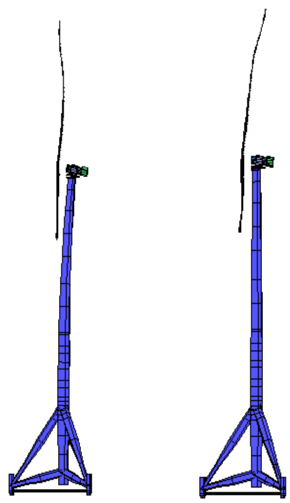


Fig. 3. First and second FA support structure modes.

It is assumed that wind and waves act both in *x* direction (Fig. 1). Samples are generated in BLADED based on pertinent power spectra [25].

The Kaimal spectrum is used for the wind process [14]:

$$S_k(f)=\frac{4\sigma_k^2 L_k/V_{hub}}{\left(1+6f L_k/V_{hub}\right)^{5/3}} \tag{1}$$

where f is the frequency (Hz), V_{hub} is the wind velocity at hub height, k is the index referring to the velocity component (1 = x direction, 2 = y direction and 3 = z direction), σ_k is the standard deviation and L_k is the integral scale parameter of each velocity component. Assuming medium turbulence characteristics, all parameters in Eq.(1) are set according to IEC 61400-1 prescriptions for a normal turbulence model [14]. In BLADED [25], the aerodynamic loads on the spinning rotor are generated based on classical concepts of combined blade element and momentum theory [26]. Wind loads acting along the tower are included.

The JONSWAP spectrum is used for the wave process [27]:

$$S_{JS}(f)=\alpha_2 H_s^2 T_p\left(\frac{f}{f_p}\right)^{-5} e^{-1.25\left(f/f_p\right)^{-4}}\cdot\gamma^{\beta} \tag{2}$$

where T_p is the wave period, H_s is the significant wave height, f_p=1/T_p, γ is the JONSWAP peakedness parameter [1]

$$\gamma=\begin{cases}5 & T_p\big/\sqrt{H_s}\le 3.6\\ \mathrm{e}^{\left(5.75-1.15T_p/\sqrt{H_s}\right)} & 3.6\le T_p\big/\sqrt{H_s}\le 5.0\\ 1 & T_p\big/\sqrt{H_s}\le 5.0\end{cases} \tag{3}$$

and

$$\alpha_2=\frac{0.0624}{0.230+0.0336\gamma-\dfrac{0.185}{1.9+\gamma}} \tag{4a}$$

$$\beta=\exp\left[-\frac{0.5}{\sigma^2}\left(\frac{f}{f_p}-1\right)^2\right] \tag{4b}$$

$$\sigma=\begin{cases}0.07 & f\le f_p\\ 0.09 & f>f_p\end{cases} \tag{4c}$$

In BLADED [25], the hydrodynamic loads on the structural members are computed based on Morison's equation [28-29], with drag and inertia coefficients set according to DNV recommendations [3].

Finally, earthquake ground motion is modelled in BLADED [25] as acceleration at the base, with two horizontal components in x and y directions.

3 Uncoupled vs. coupled analyses

The methodology used in this paper to estimate the appropriate aerodynamic damping for uncoupled analyses can be summarized as follows.

Step 1

Consistently with numerical evidence on the seismic response of offshore HAWTs [9], it is assumed that the sought aerodynamic damping affects the first two support structure modes in both FA and SS directions. Therefore, this study will seek for a couple of aerodynamic damping values: one for the first two FA support structure modes, and the other for the first two SS support structure modes. The aerodynamic damping is added to a structural damping chosen, in agreement with previous studies, as follows [19]: 10^{-2} for support structure modes, and 4.775×10^{-3} for the blades modes.

Step 2

For each couple of possible aerodynamic damping values, three separate analyses for wind, wave and earthquake excitations are performed on a structural model with the rotor in a parked state, and the corresponding results are linearly superposed. The aerodynamic damping is included in all the three separate analyses.

The wind response is computed by loading the structure with point forces/moments, taken as the forces/moments exerted by the spinning rotor (operational state) on the top of the support structure, when the latter is assumed to be infinitely stiff (fixed rotor configuration). In this respect, the computation of the separate wind response mirrors that by Van der Tempel in his uncoupled fatigue analyses [20-21]. Wave and earthquake responses are computed by standard wave excitation analyses (Morison's equation [28-29]) and seismic analyses (ground motion acting on the base). All the three separate analyses are implemented in BLADED [25], on the structural model with the rotor in a parked state.

Step 3

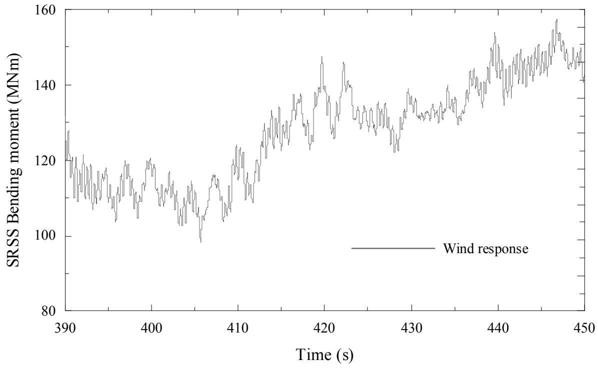
From the time history obtained by linear superposition of the three separate responses computed at Step 2, the maximum resultant bending moment at the tower base will be computed = (square root of the sum of the squares of the bending moments acting in the FA and SS directions), $M_r = \sqrt{M_x^2 + M_y^2}$, and compared with the corresponding value from fully-coupled non-linear time domain simulations $\bar{M}_r = \sqrt{\bar{M}_x^2 + \bar{M}_y^2}$. Fully-coupled non-linear time domain simulations are implemented in BLADED by numerical integration of the motion equations, considering the mutual interactions of aerodynamic, hydrodynamic and seismic responses [25]. The simulation length of both uncoupled and coupled analyses is 800 s; it is assumed that the earthquake ground motion starts at 400 seconds into the simulation, to ensure that the earthquake occurs as the structural response has already attained a steady state [11-13].

Step 4
The sought couple of aerodynamic damping values in FA and SS directions is estimated as the couple that, among all possible couples built in *Steps 1-3*, minimizes the following error:

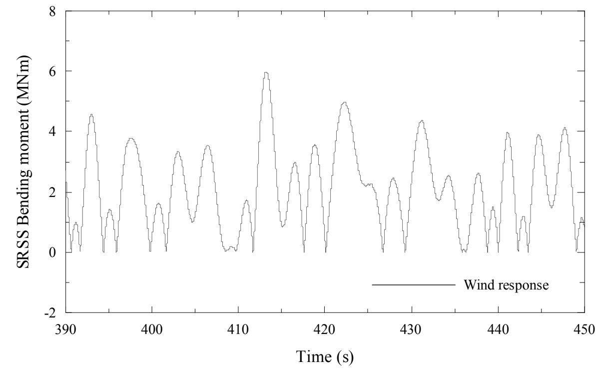
$$\varepsilon = \left(\frac{M_r - \bar{M}_r}{\bar{M}_r} \right)^2 \quad (5)$$

Step 5
To account for the inherent stochastic nature of wind, wave and earthquake realizations, a few joint realizations of wind/wave/earthquake processes will be built and, to each joint realization, a couple of aerodynamic damping values will be associated. The final estimate of aerodynamic damping in FA and SS directions will be derived by averaging the pertinent values over all joint realizations.

Step 6
Stress resultants demands at various locations in the support structure will be computed from uncoupled analyses results corresponding to the final estimate of aerodynamic damping built in *Step 5*. Those obtained for a 4% additional aerodynamic damping in the FA direction, recommended by ASCE-AWEA for land-based turbines [16], will also be constructed. For validation, the stress resultant demands at various locations will be compared with those from fully-coupled, non-linear time domain simulations.



(a)



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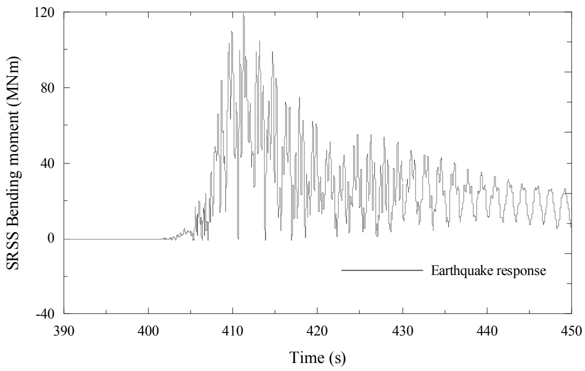

(c)

Fig. 4. Separate aerodynamic, hydrodynamic and seismic responses assuming 2% and 0% aerodynamic damping values in FA and SS directions.

To illustrate the proposed methodology, consider Fig. 4 and Fig. 5. Fig. 4 shows the separate responses to wind, wave and earthquake loads, for one of the potential couples of FA and SS aerodynamic damping values, specifically 2% in the FA direction and 0% in the SS direction, for the following environmental state: wind velocity at the hub V_{hub} = 11.4 ms^{-1} (rated speed); wave height H_s = 5.0 m; peak wave period T_p = 9.5 s; Imperial

Valley-06 El C.A. #3 [30], with fault normal component in *y* direction.

The time history obtained by linear superposition of the uncoupled simulations is reported in Fig. 5, and compared with the fully-coupled non-linear simulation. Fig. 5 shows that uncoupled and coupled analyses provide quite similar results.

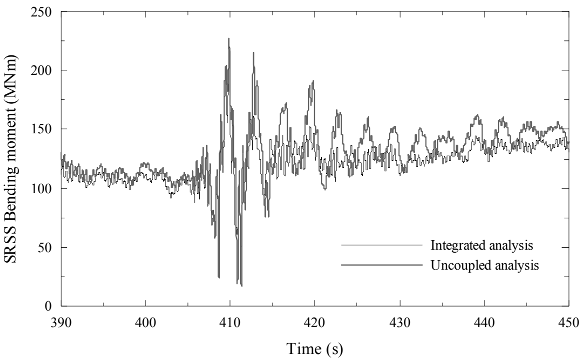

Fig. 5. Comparison between uncoupled and coupled analyses, when uncoupled analyses are performed with 2% FA and 0.% SS aerodynamic damping values.

In *Step 2* uncoupled analyses will be performed for a number of alternative possible couples of FA and SS aerodynamic damping values, producing a table of maxima resultant bending moments (*Step 3*), as reported in Table 2.

SS / FA	0.%	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%
0.5%	240.75	240.47	240.95	240.51	239.53	240.09	240.44	239.99	240.19
1.0%	234.76	235.48	234.75	234.74	236.01	235.09	234.49	234.41	234.29
1.5%	230.22	14.37	229.90	229.69	230.21	229.86	229.41	229.27	228.95
2.0%	226.98	226.78	226.71	226.12	225.99	225.64	225.48	225.25	224.62
2.5%	224.23	223.45	223.38	222.63	222.25	222.75	222.63	222.58	222.64
3.0%	220.92	220.89	220.44	220.70	220.28	220.43	219.95	218.89	219.95
3.5%	218.31	218.26	217.50	217.18	217.99	217.53	216.88	217.06	216.54
4.0%	216.35	215.78	215.52	215.53	215.40	214.25	214.68	214.04	214.32
4.5%	214.01	213.45	212.29	212.17	212.57	212.38	212.31	212.16	211.52
5.0%	211.77	211.50	211.57	211.16	210.73	210.38	210.23	210.34	210.10
Fully-coupled simulation reference value: **226.90 MNm**									

Table 2. Maxima resultant bending moments (MNm) from uncoupled analyses, for various potential couples of aerodynamic damping values.

In *Step 4*, the couple minimizing error (5) will be selected as the couple of aerodynamic damping values corresponding to the considered realization of wind/wave/earthquake processes. The final estimate of the aerodynamic damping values will be built by averaging over all realizations (*Step 5*), to finally compute the stress resultants demands at various locations as explained in *Step 6*.

4 Numerical results

Here, the methodology illustrated in Section 3 is implemented for the following environmental states:

- ✓ Wind velocity at the hub V_{hub}:
  -11.4 ms^{-1} (rated speed)
  -15 ms^{-1}
  -20 ms^{-1}
- ✓ Wave height H_s = 5.0 m
- ✓ Peak wave period T_p = 9.5 s
- ✓ Imperial Valley-06 El C.A. #3 [30], with fault normal component in *y* direction

That is, three different environmental states are considered, each corresponding to a given wind velocity V_{hub}.

4.1 Aerodynamic damping estimates

For each environmental state, five simulations are implemented considered different seeds to generate wind and wave samples. In all simulations, the Imperial Valley-06 El C.A. #3 [30] record is always used.

Fig. 6 shows the FA and SS aerodynamic damping estimates corresponding to the five simulations. It can be observed that, while certain fluctuations are encountered in the FA aerodynamic damping, the SS aerodynamic damping falls always within the (0, 0.5) range.

Fig. 7 shows the mean FA and SS aerodynamic damping estimates vs. the considered wind velocities at the hub V_{hub}. Clear trends can be noticed: while the FA aerodynamic damping increases with the wind velocity, the SS aerodynamic damping holds almost a constant value within the (0%, 0.5%) range.

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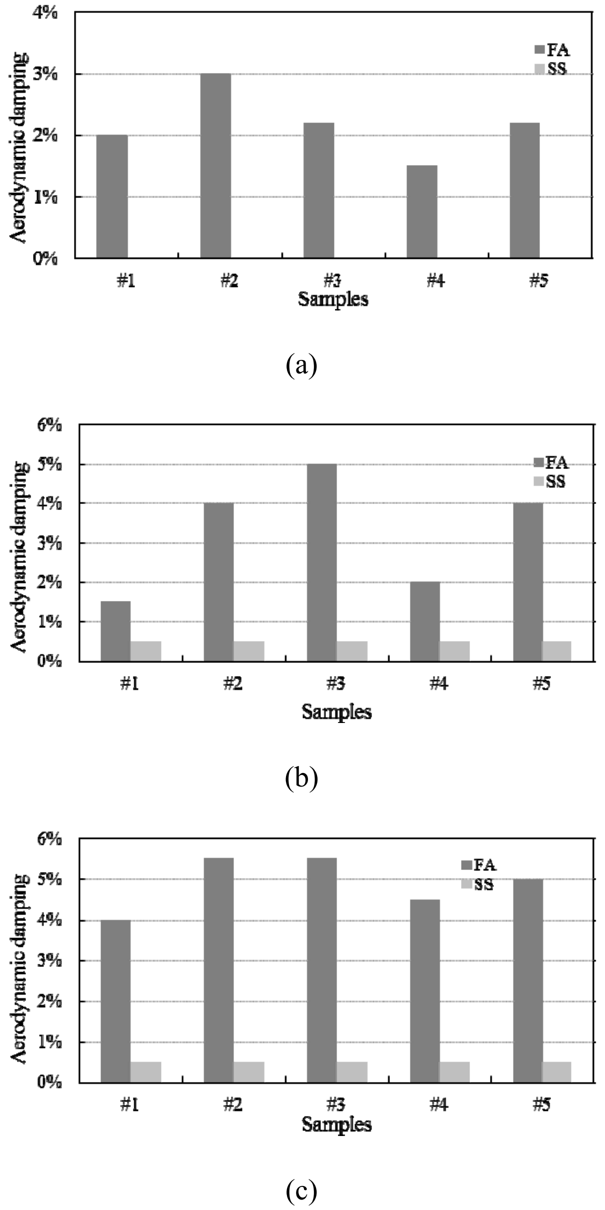

Fig. 6. Aerodynamic damping estimates for different simulations and environmental states: (a) V_{hub}=11.4 m/s; (b) V_{hub}=15 m/s; (b) V_{hub}=20 m/s;

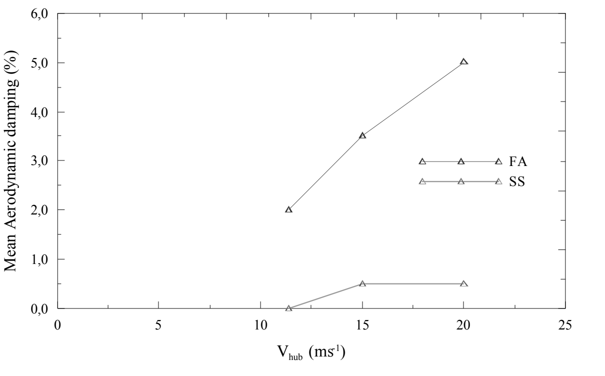

Fig. 7. Mean FA and SS aerodynamic damping estimates for various wind velocities at the hub.

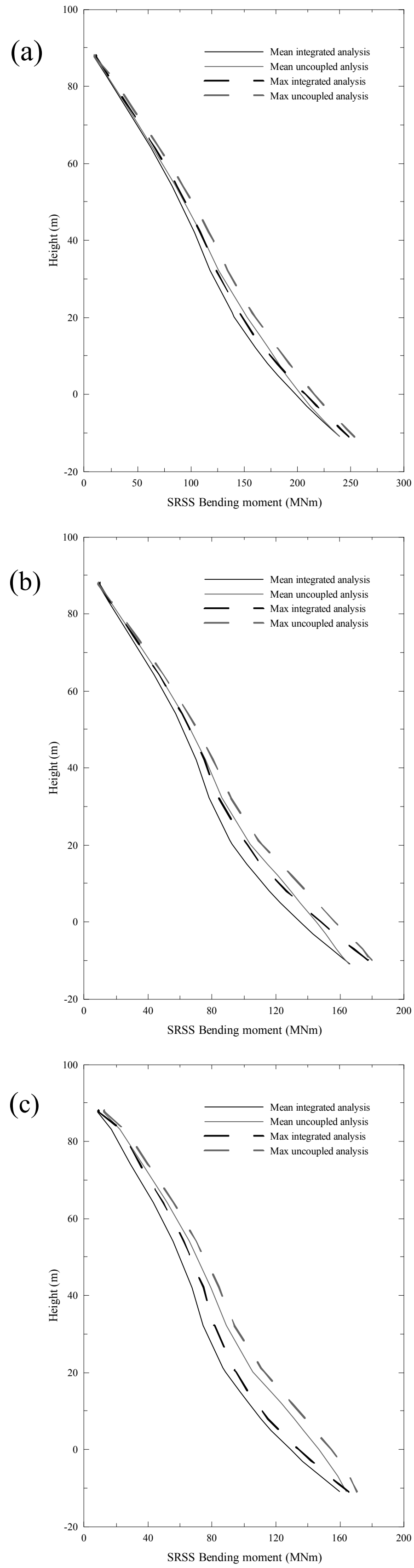

Fig. 8. Mean and maxima bending moment demands along the tower using mean aerodynamic damping estimates in Fig. 7, for different environmental states: (a) V_{hub}=11.4 m/s; (b) V_{hub}=15 m/s; (c) V_{hub}=20 m/s.

At this stage, the accuracy of the derived mean aerodynamic damping estimates is assessed by computing the bending moment demands along the whole tower, as obtained from the uncoupled analyses results corresponding to the mean aerodynamic damping estimates in FA and SS directions. In particular, the mean of the bending moment demands and the maximum bending moment demand are computed over the 5 simulations, run for each environmental state. Results along the tower are reported in Fig. 8 for all the considered environmental states. A very satisfactory agreement is encountered with corresponding results from fully-coupled, non-linear time-domain simulations, with highest errors within 15% for V_{hub}=20 m/s (see Fig. 8c).

4.2 4% FA aerodynamic damping

Numerical simulations presented in Section 4.1 show that aerodynamic damping estimates vary with the considered environmental state. This result is somehow expected, in recognition of the fact that aerodynamic damping arises as a result of relative motion between wind and rotor blades, to which several factor contribute in an offshore environment such as wind and sea states, earthquake ground motion and, obviously, specific structural characteristics of the support structure.

Here, in an attempt to suggest aerodynamic damping values that may be suitable, within engineering margins, for a large variety of environmental conditions and design solutions, it is of interest to assess whether reasonably accurate results can be obtained from uncoupled analyses with the aerodynamic damping recommended by ASCE/AWEA [16] for land-based HAWTs, i.e. 4% in the FA direction and 0% in the SS direction. The corresponding mean and maximum of the bending moment demands along the tower are shown in Fig. 9. Results are in a substantial agreement with those reported in Fig. 8, built for the mean aerodynamic damping estimates minimizing error (5). This can be attributed to the fact that, as shown in Table 2, no sensible differences are encountered, in general, for different values of the FA aerodynamic damping. Although certainly more investigations are needed, the results shown in Fig. 9 are very encouraging in the perspective of performing uncoupled analyses with a given value of aerodynamic damping, for several environmental states and structural characteristics.

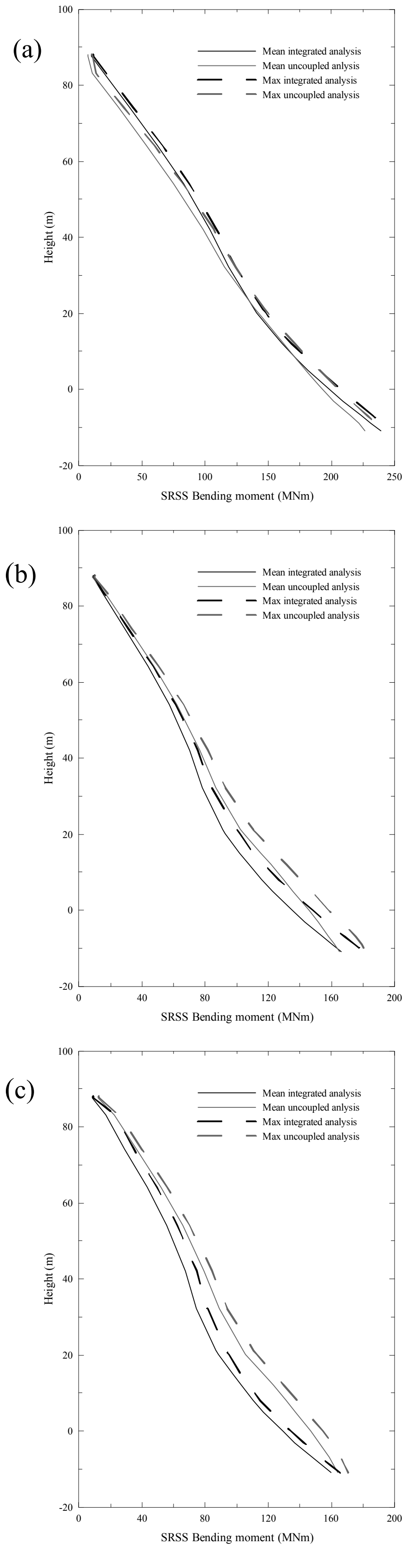

Fig. 9. Mean and maxima bending moment demands along the tower using 4% FA and 0% SS aerodynamic damping values, for different environmental states: (a) V_{hub}=11.4 m/s; (b) V_{hub}=15 m/s; (c) V_{hub}=20 m/s.

5 Conclusion

This paper has investigated the feasibility of uncoupled analyses for seismic assessment of offshore HAWTs. Separate wind, wave and earthquake responses have been computed introducing additional aerodynamic damping, and linearly combined results have been compared with those from fully-coupled, non-linear time domain simulations. Results have shown that aerodynamic damping estimates, built by minimizing the bending moment error at the tower base, varies depending on the environmental states. Using the so computed aerodynamic damping estimates, results obtained from the uncoupled analyses have proved in a satisfactory agreement with results from fully-coupled, non-linear time-domain simulations. Satisfactory results have also been obtained using a 4% additional aerodynamic damping in the FA direction and no aerodynamic damping in the SS direction, in agreement with existing prescriptions on land-based turbines.

Although a significant number of simulations has been run in this study (3 uncoupled analyses for each potential couple of aerodynamic damping values in Table 2 (90 couples), and five realizations for each of the 3 environmental states, totaling 2×90×5×3 (wind and wave uncoupled analyses) + 90 (earthquake uncoupled analyses) = 2790 simulations), certainly more extensive numerical tests are needed in order to provide a more definitive estimate of the sought aerodynamic damping. However, it is worth recalling that a similar result would be very useful, especially in the early stages of design: to implement the uncoupled analyses, see Section 3, only a standard aerodynamic simulator is needed for computing the point forces/moments to be applied at the top of the structural model (see *Step 2*), while the wave and seismic responses could be obtained by a standard finite element code. In contrast, to implement fully-coupled, non-linear time-domain simulations, only dedicated software packages must be used, capable of modeling the inherent interactions among aerodynamic, hydrodynamic and seismic responses in proper coupled motion equations. Also, uncoupled analyses are less time consuming and lend themselves to a straightforward implementation.

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