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Dynamics of two floating wind turbines with shared anchor and mooring lines

Dynamics of two floating wind turbines with shared anchor and mooring lines

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Abstract. Floating wind farms present the opportunity to harvest wind resources located in deep water sites. Shared mooring designs can contribute in making floating wind energy more cost-competitive, and it is important to understand the new system dynamics that arise. We are presenting here HAWC2Farm, an extension of HAWC2 that can model multiple wind turbines with shared mooring lines. We apply the new modeling capabilities to simulate two 15 MW floating wind turbines on spar floaters with shared mooring lines. We consider two different sites and we identify and compare the natural frequencies and mode shapes of the shared mooring designs with those of an individual moored turbine. Furthermore, we investigate the influence of design parameters on the systems' natural frequencies and we show that it is possible for a shared mooring design to achieve similar characteristics as a single turbine design. Finally, we test the response of the shared mooring design in steady wind and regular waves and find that the surge displacement of the upstream turbine and its mooring line loads are considerably larger compared to the single turbine case.

1. Introduction

Floating wind farms allow offshore wind energy to be harvested also in deep sea waters. In the initial demonstration projects each floating turbine has been moored individually. This approach is inherited from the oil and gas industry [1] where one platform is alone in deep waters. However, a floating wind farm will consist of dozens or hundreds of wind turbines, and shared mooring line and anchor point designs can bring a significant cost reduction [2, 3] but also introduce new design challenges. Wilson et al. [4] developed a quasi-static, linearized model for the force–displacement response of shared mooring systems, that can be used as a preliminary design tool to efficiently evaluate and optimize shared mooring system designs. Although this serves as an excellent starting point, there is a need to capture the additional dynamic effects. To capture these new dynamic effects we developed HAWC2Farm, an extension of the aero-servo-hydro-elastic software HAWC2 [5], that can model floating wind farms with shared mooring lines and anchors.

The IEA WIND 15 MW [6] reference wind turbine with the WindCrete spar floater [7] is used as the through-going example, with configurations both in the Gran Canaria and Morro Bay reference sites of the EU COREWIND project [8]. HAWC2Farm is used to investigate the shared mooring line designs which are evaluated in terms of mooring line forces, equilibrium states, frequencies and corresponding mode shapes, and responses to some steady wind and regular waves load cases. We also investigate the influence of design parameters to the system dynamics.

2. Methodology

The shared mooring line designs are modelled in HAWC2 [5] which is an aero-servo-hydro-elastic wind turbine analysis code. HAWC2 uses a multibody dynamic formulation with linear Timoshenko beams [9] for turbine structures. External super-elements can be used to represent e.g. radiation-diffraction models of wind turbine floaters. It computes aerodynamic forces by the blade element momentum formulation [10]. The hydrodynamic loads are computed either through the Morison equation in its full form, or by using the WAMIT [11] frequency response functions for the radiation and diffraction forces combined with the Morison drag. The controller is defined as an external dynamic link library (dll) and mooring line dynamics are also computed in its own dll developed by DTU.

The HAWC2 mooring line dll uses a dynamic mooring line formulation based on non-linear beam elements. The mooring line beam elements carry the loads only in axial direction and uses Green strain (ϵ_G) which is given in Equation (1). The current length and initial length of the element are shown as L and L_0 in the below equations. The current length L is computed at each iteration according to Equation (2) where x_n, y_n, z_n is the position of node number n in global HAWC2 coordinates.

$$\epsilon_g = \frac{L^2 - L_0^2}{2L_0^2} \tag{1}$$

where

$$L^2 = (x_{n-1} - x_n)^2 + (y_{n-1} - y_n)^2 + (z_{n-1} - z_n)^2 \tag{2}$$

The axial force that acts on an element can be found by using Equation (3), where E is the elastic modulus and A is the cross-sectional area.

$$f = EA\epsilon_g \tag{3}$$

There are 6 degrees of freedom (DoFs) in each mooring element, unlike standard structural members which have 12 DoFs for each beam element. The mooring line axial force has 3 force components. This results in 3 DoFs in each node and 6 DoFs in each element with 2 nodes. In other words, mooring line elements don't have any rotational DoFs. The element stiffness matrix is expressed in terms of axial force f and current length L as shown in Equation (4).

$$K_e = \frac{f}{L}\begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Mooring lines can be connected to each other or to the ground or to another structure such as a floater by using the constraint equations in the multibody formulation. These constraints lock the position of the selected node to another node on another structure or fix a node position in space (e.g. a connection to the ground). The mooring line nodes don't have any rotational constraints because they don't have rotational DoFs. Since the mooring line elements are assumed not carrying moments, only forces are transferred at the mooring line constraints.

Because mooring lines are defined by their initial lengths, the equilibrium point of the system must be found to initialize the computations. At the equilibrium state, the mooring lines have some tension forces and the turbines can move and rotate relative to their initial positions. In this study floating turbines (FOWTs) stand with non-rotating blades, without wind load and wave loads during the equilibrium point computation. Eigenvalue analyses are run at the equilibrium points. The mass matrix has added mass terms and constraint forces are also included in the stiffness matrix. Hence, the natural frequencies and corresponding mode shapes are computed by taking into account all mass and stiffness effects at the equilibrium points.

3. Configuration 1: Shared mooring line at Gran Canaria site

We start out with the simplest possible case of shared moorings, namely two connected turbines. For this configuration, we select the Gran Canaria with 200 m water depth and catenary mooring lines. In the single turbine configuration [12], each turbine has 3 mooring lines which are 120° apart from each other. The mooring lines have 50 m long delta lines, and 565 m long main sections. Both the delta sections and the main sections consist of the same material which has 561.25 kg m^{-1} dry mass and 2304 MN axial stiffness. Details about the mooring line properties are given in [12] whereas tower and floater properties are given in [7].

Figure 1 shows the single turbine design, the HAWC2 coordinate system, the general dimensions and the mooring line sections for the Gran Canaria site. The floater diameter is 9.3 m and the mooring line attachments are 65 m above the bottom of the floater. The total center of gravity of the system is 56.6 m above the bottom of the floater. The HAWC2 global coordinate system's y axis is in the wind flow direction and z is in the gravity direction. The floater is centered at $(x, y) = (0.0, 0.0)$ and the mean sea level is defined at $(z = 0.0)$. The mooring line ground connection points are 600 m away from the floater's center.

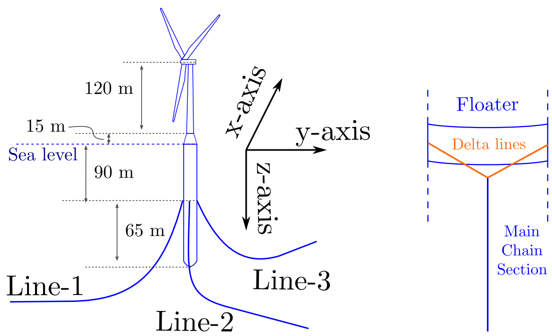

Figure 1. Single turbine design in Gran Canaria site and mooring line sections.

Figure 2 shows the shared mooring line design where the turbines are 1200 m (equals to 5 rotor diameters) away from each other. The shared mooring line has delta line sections at the floater sides, connected by a main section whose length is a design parameter. The mooring line material properties are the same as in the single turbine design. The turbine numbers are also shown in Figure 2 and the second turbine is located upstream in the wind direction.

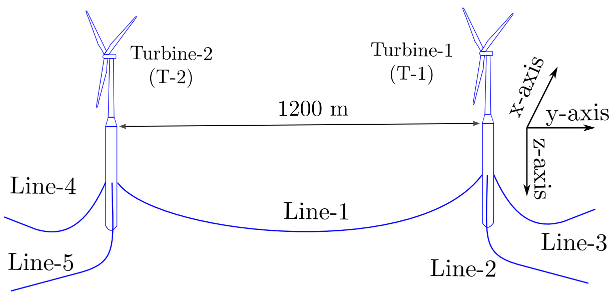

Figure 2. Shared mooring line design in Gran Canaria site.

3.1. Dynamic properties

We now investigate the dynamic properties of the two-turbine configuration with different lengths of the shared mooring line. The first design (Design-1) has a 1093.8 m long shared line whereas this length is 1150.7 m for the second design (Design-2). We also include the results of the single turbine configuration.

The mooring line forces, turbine rotations, turbine displacements, natural frequencies and mode shapes of the entire systems are computed at the equilibrium points of the system with no wind or wave loads. Table 1 shows pitch angles, surge displacement from the initial points to the equilibrium points with shared mooring. The table also shows the mooring line tension forces (Line-1 Line-2,3,4,5) at the fairlead locations for the equilibrium points and Line-1 length for three design cases. The turbine pitch angles are similar and less than 1° for all turbines. The single turbine doesn't move in the surge direction since the mooring lines have equal tension forces. The turbines get closer to each other by 23.6 m in Design-1 and move away from each other by 13.6 m in Design-2. When the mooring line forces are higher than in the single turbine case, the shared mooring line pulls the turbines towards each other. Conversely, the turbines are pulled by the side mooring lines if the shared mooring line force is lower than in the case of the single turbine.

In the single turbine case all three mooring lines have the same forces of 4.25 MN because of symmetry. However, shared mooring lines (Line-1) have slightly different forces than the side mooring lines (Line-2,3,4,5) in Design-1 and Design-2 since the direction of the force from the shared mooring line is slightly different than for the side mooring lines. Design-2 has 23 % lower mooring line forces than the single turbine whereas Design-1 has 75 % higher loads than the single turbine.

Table 1. Gran Canaria single turbine and shared mooring line pitch (T-1 / T-2), total surge, mooring line forces and Line-1 lengths at equilibrium points

	Single turbine	Design-1	Design-2
Pitch (T-1/T-2) [deg.]	−0.64	−0.64 / −0.66	−0.66 / −0.59
Total surge [m]	0.0	−23.6	13.6
Line-1/Line-2,3,4,5 forces [MN]	4.25	7.25 / 7.45	3.3 / 3.2
Line-1 length [m]	565	1093.8	1150.7

The different mooring line tension forces and inertia values result in different dynamics and thus different natural frequencies and mode shapes. Figure 3 shows the natural frequencies for the single turbine, Design-1 and Design-2 at their equilibrium points. Design-1 has a higher first natural frequency compared to the single turbine design. On the other hand, Design-2's first natural frequency is lower. This is consistent with the mooring line forces at the equilibrium points, so high mooring line forces result in high natural frequencies. The frequencies appear as groups such as frequencies lower than 0.02 Hz are in the surge and sway directions. Pitch and roll mode shapes are observed around 0.025 Hz and heave mode shapes are around 0.028 Hz. The yaw mode shapes occur around 0.055 Hz for the single turbine and Design-2. Design-1's first yaw frequency is at 0.082 79 Hz which is near the 1-P region. Design-2 is the only design to be free of natural frequencies in the 1-P region.

The configurations with two turbine designs have more natural frequencies and mode shapes than the single turbine since they have more DoFs. They generally have symmetric and asymmetric mode shapes whereas the single turbine has a single mode shape for each direction such as surge, sway, pitch and heave. Figure 4 shows the pitch mode shape for the single turbine at 0.024 35 Hz and, symmetric and asymmetric pitch mode shapes for Design-1 which are at 0.0247 Hz and 0.024 74 Hz, respectively. The blue lines show the undeflected state at the equilibrium position and red lines show the systems when they move in the mode shapes direction. For each plot the axes have identical scales. The two turbines move in the same

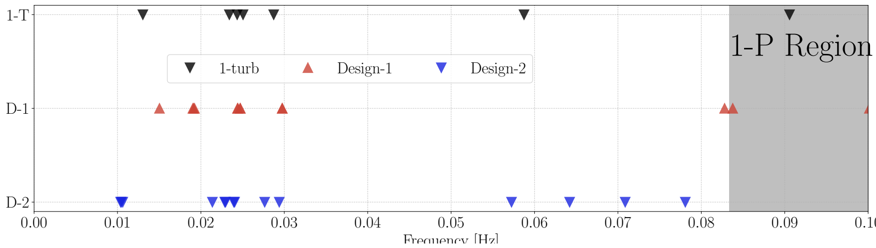

Figure 3. Frequencies for single and two turbine designs at Gran Canaria site.

direction (symmetric) at the first pitch mode shape of Design-1 and they move in opposite directions in the second pitch mode shape which is asymmetric pitch mode shape.

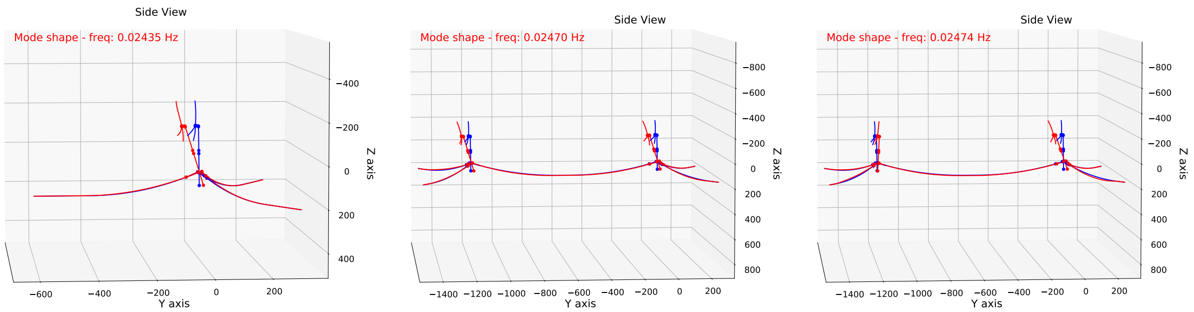

Figure 4. Single turbine pitch mode shape, Design-1 symmetric and asymmetric pitch mode shapes.

Since the mooring lines in Gran Canaria have very high dry mass ($561.25\,\mathrm{kg\,m^{-1}}$), the total weight of long shared mooring lines becomes very high. As a consequence, a part of the line is laying on the sea bed in both designs. Design-2 has a longer section on the sea bed than Design-1 since it has less forces on its shared mooring line. Although Design-1 has 75 % higher forces than for the single turbine, it still has some sections on the sea bed. This indicates that the shared mooring line concept at the Gran Canaria site with spar buoy and catenary mooring lines has some limitations due to the heavy chains. Therefore, further investigations with load cases are not given here for this site.

4. Configuration 2: Shared anchor at Morro Bay

We next investigate the dynamics of a shared mooring and anchor system at the deeper Morro Bay site. At the depth of 870 m, a shared anchor is placed between the turbines. The two turbines are connected to a vertical line that extends to the anchor about 200 m below the free surface. In comparison, the single wind turbine design has 4 taut mooring lines. Figure 5 shows the single turbine design, the HAWC2 coordinate system, the dimensions of the floater and a detailed view of a mooring line with its sections. For this site, the floater diameter is 9.7 m and its total length is 175 m. The turbine tower at Morro Bay is also different than in the Gran Canaria site and its properties can be found in [13].

Table 2 shows the properties of the delta lines, the main polyester lines and the chain sections of the mooring lines. The polyester section is the longest, most flexible and lightest part of the mooring lines, hence its contribution to the entire system dynamics is larger than for the other sections. There are four fair-lead positions on the floater which are 90° apart from each other and they are located 70 m above the bottom of the floater which is about 8 m above the total

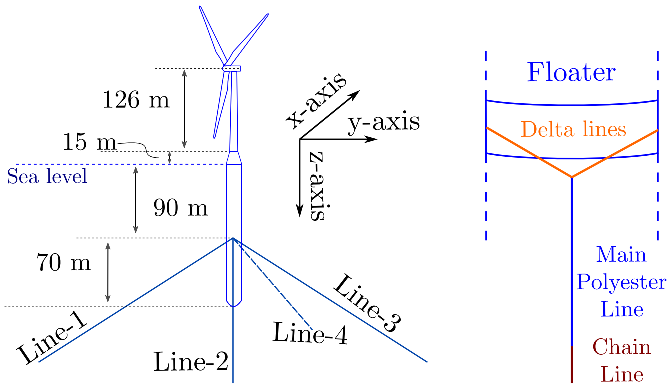

Figure 5. Single turbine design with 4 mooring lines and mooring line sections at Morro Bay.

center of gravity (CoG) of the system. The ground connections of the mooring lines are 1015 m away from the floater and at the sea bed.

Table 2. Properties of mooring line sections at Morro Bay.

	Delta line	Main polyester	Chain line
Length [m]	50.0	1020.8	183.7
Diameter [mm]	90	205	85
Equivalent D [mm]	162	164	171
Dry mass [kg/m]	161.0	28.6	179.6
Axial stiffness [kN]	6.92×10^5	2.68×10^5	7.71×10^5

The shared anchor design between two turbines for the Morro Bay site is shown in Figure 6. The distance between the turbines is 1680 m which is equivalent to 7 rotor diameters of the IEA WIND 15 MW. The lines have the same properties as for the single turbine case except for Line-1, Line-7 and Line-9. Line-1 and Line-7 have delta lines on the floater side whose properties are identical to the Delta line properties of Table 2. After the Delta line sections, the polyester section starts and Line-9 consist of only polyester section. Hence they do not have any chain section. The length of Line-9 is a design parameter and its effect on the dynamics of entire system is part of the present investigation. The cross-section properties of the main polyester lines are identical to the properties given in Table 2.

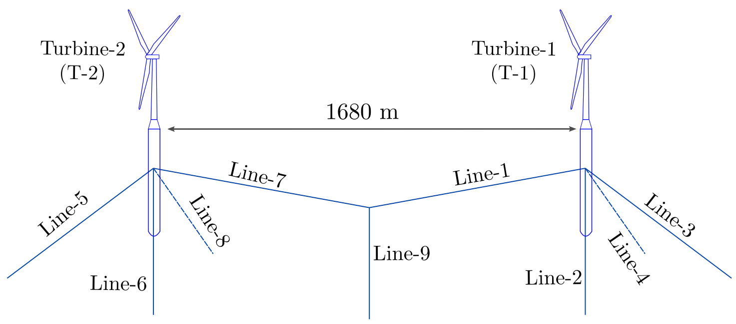

Figure 6. Shared anchor design with 2 turbines in Morro Bay site

We consider three shared anchor designs with different Line-9 lengths and buoyancy force at the intersection point of Line-1, Line-7 and Line-9. Table 3 shows the mooring line lengths and buoyancy forces for the three designs.

Table 3. Shared mooring lines polyester section lengths and buoyancy force at their intersection

	Design-1	Design-2	Design-3
Line-1 & Line-7 [m]	783.4	783.4	783.4
Line-9 [m]	670.0	670.0	657.12
Buoyancy [MN]	0.0	5.0	0.0

4.1. Dynamic properties as function of connection depth

We now investigate the natural frequencies and mode shapes as function of the connection depth for the vertical line. Table 4 shows pitch (Turbine-1/Turbine-2), total surge and maximum mooring line forces at the equilibrium point for the single turbine and the shared anchor designs. The shared anchor designs move very little compared to the distance between the turbines. Each Design-2 turbine move about 4.6 m in the surge direction which is maximum among the shared anchor designs. Their pitch values are also very small and comparable with the single turbine case. The pitch values of Turbine-1 (-0.4 deg) are slightly lower than those of Turbine-2 (-0.6 deg) for all the shared anchor designs and their average equals to the single turbine case. The maximum tension forces for the shared anchor designs are also comparable with the single turbine case. The maximum force occurs in Design-3 and it is 18 % higher than in the single turbine case.

Table 4. Pitch, total surge and maximum mooring line forces at equilibrium point for single turbine and shared anchor designs in Morro Bay.

	Single turbine	Design-1	Design-2	Design-3
Pitch (T-1/T-2) [deg.]	-0.5	$-0.4/-0.6$	$-0.4/-0.6$	$-0.4/-0.6$
Total surge [m]	0.0	-7.1	-9.1	8.4
Max Mooring F [MN]	5.18	5.44	5.62	6.14

Figure 7 shows the natural frequencies for the single turbine and the three shared mooring designs. The natural frequencies in Morro Bay also appear as groups similar to the Gran Canaria results. The frequencies lower than 0.02 Hz have surge and sway motions in their mode shapes. The frequencies between 0.02 Hz and 0.03 Hz have roll and pitch mode shapes. The heave mode shapes are found between 0.03 Hz and 0.04 Hz. Yaw frequencies are above 0.08 Hz and some of them actually fall in the 1-P rotor speed region.

Design-1 has the lowest first frequency (0.006 79 Hz) among all designs which is associated with a symmetric surge mode shape. This frequency is almost $\sqrt{2}$ times lower than the single turbine surge frequency (0.009 48 Hz), since the system mass is doubled and only Line-3 and Line-5 (see figure 6) contributes to the stiffness for symmetric surge mode shape. The mid-point moves together with the turbines for a pure symmetric mode shape. Hence no stiffness contribution comes from Line-1 and Line-7. We find that the Line-9 stiffness contribution is very limited in the surge direction since the surge motion is very small compared to the length of the line which results in a very small restoring surge force component. Also Design-2 and Design-3 have surge and sway motions in their first mode shape. When the pure symmetric surge motion is disturbed by sway motion, the frequency of the mode shape increases.

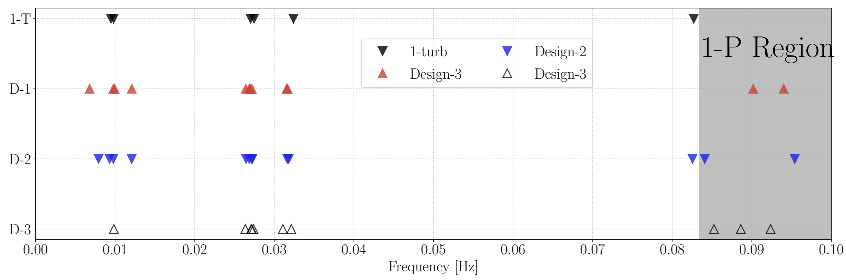

Figure 7. Frequencies for single turbine (1-T), Design-1 (D-1), Design-2 (D-2) and Design-3 (D-3). The gray region represents the turbine 1-P region.

Figure 8 shows the first mode shapes from side and front views for the three shared anchor designs. The first column contains Design-1 mode shape whereas the middle and last columns contain Design-2 and Design-3 mode shapes, respectively. The mid-point moves together with the turbines for the Design-1 mode shapes and no sway motion is present in the frontal view. On the other hand for Design-2, the mid-point has lower surge motion than the turbines and Turbine-2 has some sway motion. For Design-3, the sway motion is much larger than its surge motion and it can actually be called as sway mode shape.

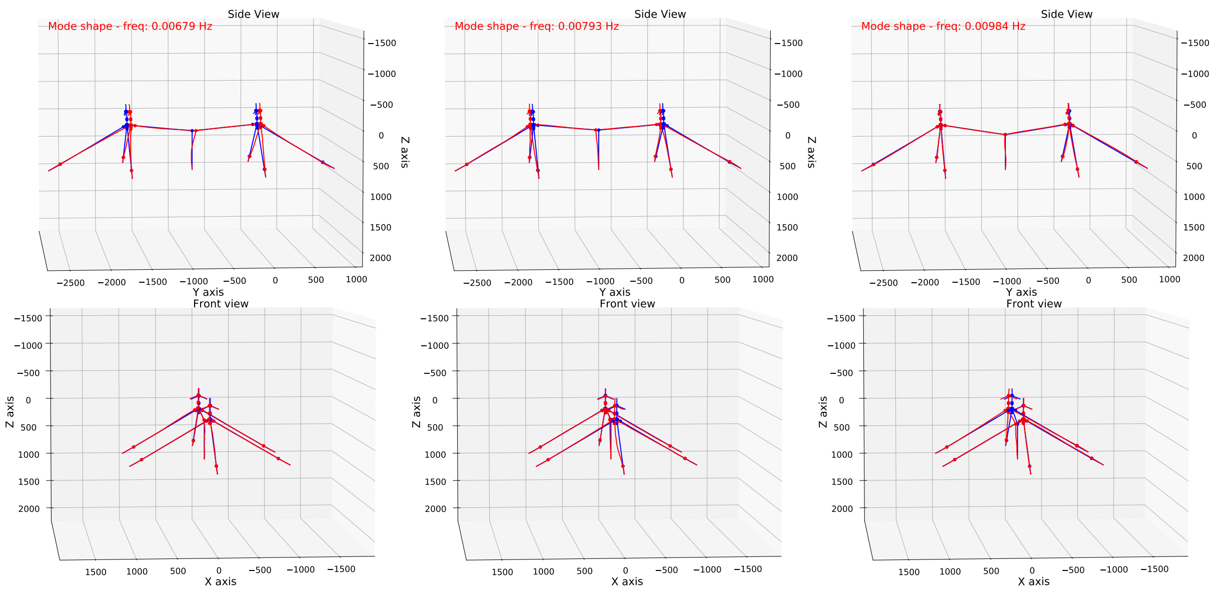

Figure 8. First mode shapes of shared anchor designs from side and front views. Design-1 (first column) has pure surge motion, Design-2 (second column) has surge-sway coupling and Design-3 (third column) has sway dominated motion.

4.2. Response to a step wind test and regular waves

After the dynamic analysis, steady wind load cases with and without waves were simulated to evaluate the controller response and investigate the turbine performance and mooring line loads. Design-3 and the single turbine were chosen for comparison, since the Design-3 frequencies are very close to the single turbine case, especially for the first frequency. Furthermore, the lack of buoyancy element lowers the construction cost compared to Design-2. First a step wind case without any waves is defined to see the controller response and check its performance. Then, mild and severe waves are applied with steady wind. Table 5 shows the wind and wave inputs for each load case. In the step wind case the wind speed is increased from $4\,\mathrm{m\,s^{-1}}$ up to $25\,\mathrm{m\,s^{-1}}$ by $1\,\mathrm{m\,s^{-1}}$ in every 200 s. Artificial damping forces were applied at the first 150 s of all simulations to speed up the initialization process. This phase was excluded from the results in the further analysis.

Table 5. Wind and wave definitions used in load cases for single turbine and Design-3.

	Step wind	Mild wave	Severe wave
Wind speed [m/s]	4 - 25	10	15
Wave height [m]	0.0	4.0	9.0
Wave period [s]	0.0	9.0	15

Figure 9 shows the relative hub wind speeds, power, thrust and tilt of the wind turbines for single case and for Design-3. From these results, the response and performance of all turbines are very similar when the same controller is used. Although the wind speed is constant between steps, the relative wind speeds show transient variations due to the surge and tilt motion of the turbines when the wind speed is changed. The largest variation in relative wind speed occurs at $11\,\mathrm{m\,s^{-1}}$ where the thrust force difference from $10\,\mathrm{m\,s^{-1}}$ (rated wind speed) to $11\,\mathrm{m\,s^{-1}}$ is the largest among all wind speeds. The tilt angles of the turbines reach their maximum at rated wind speed where the thrust force is also maximum. Turbine-1 has slightly higher tilt angles than the single turbine whereas Turbine-2 has slightly lower tilt angles than the single turbine. The reason is that the mooring line connections are slightly above the center of gravity (CoG) of the system which is about 62 m above the floaters' bottom.

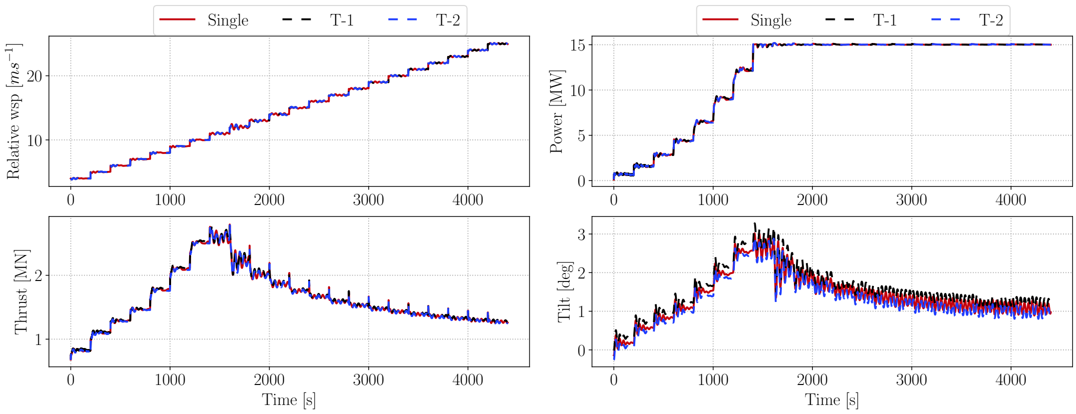

Figure 9. Relative wind speed at turbine hubs, power, thrust and tilt angle for single turbine (Single) and Design-3 turbines (T-1, T-2).

We now turn to the case of mild regular waves. Figure 10 shows the relative hub wind speed, free surface elevation, surge and tilt for the single case and Design-3. The mean wind speed is $10\,\mathrm{m\,s^{-1}}$ but the relative wind speeds vary around this value with $1.4\,\mathrm{m\,s^{-1}}$ amplitude. The wave amplitude at Turbine-1 and the single turbine are the same whereas there is a phase difference between them and Turbine-2. The surge values of the upstream turbine (Turbine-2) are almost double of those of the single turbine and of Turbine-1. This is due to the doubling of the total thrust force of the shared anchor design compared to the single turbine case, while Line-5, the main contributor in balancing the thrust force, retains the same properties as Line-1 for a single turbine. The mean force on Line-5 of Design-3 is 33 % larger than Line-1 of the single turbine whereas the mean force of Line-1 of Design-3 is 21 % lower than for Line-1 of a single turbine. The other line forces are similar between the single turbine case and Design-3. Similar to the step wind load test, the tilt of Turbine-1 is the highest and Turbine-2 the lowest. However, the difference between tilt angles are very small compared to surge values.

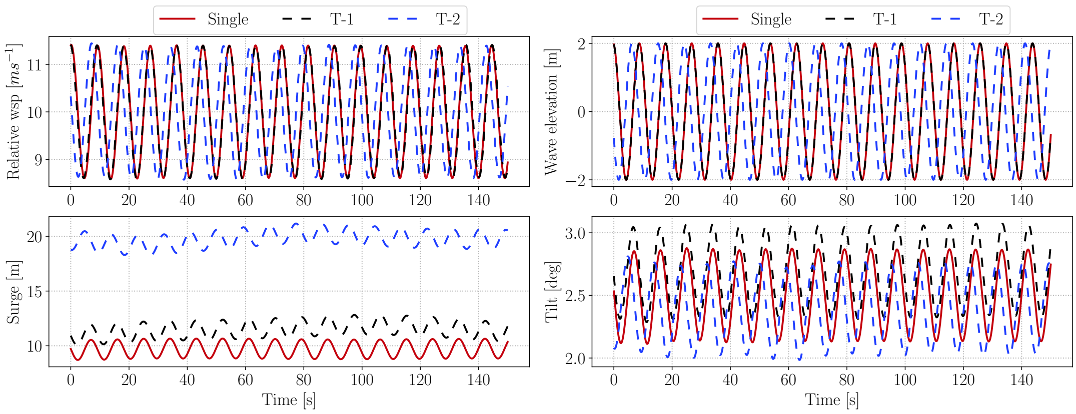

Figure 10. Relative wind speed at turbine hubs, wave heights at floaters, surge and tilt angle for single turbine and Design-3 turbines for the mild wave case.

Figure 11 shows the relative hub wind speed and response for the severe wave case. The mean wind speed is 15 m s^{-1}. The wave height is 2.25 times larger than for the mild wave case.

The surge values of the upstream turbine (Turbine-2) is again almost double of the single turbine and Turbine-1. Since the thrust force is lower at 15 m s^{-1} than 10 m s^{-1}, the mean surge displacement for the severe wave load case is lower than for the mild wave load case. The mean force on Line-5 of Design-3 is 30 % larger than Line-1 of the single turbine whereas the Line-1 mean force of Design-3 is 15 % lower than for the single turbine. Other line forces are similar between the single case and Design-3. The maximum tilt of Turbine-1 is lower than for the mild wave case. Similar to the surge motion, the tilt variation around the mean tilt values are almost doubled compared to the mild wave load case. All turbines have similar tilt angles.

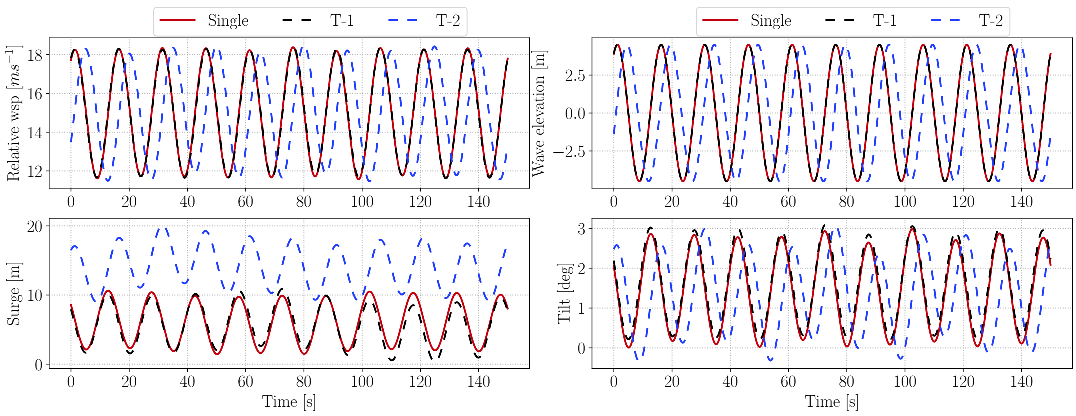

Figure 11. Relative wind speed at turbine hubs, wave heights at floaters, surge and tilt angle for single turbine and Design-3 turbines for the severe wave case.

5. Conclusions

This study shows that the structural dynamic properties of shared mooring line and shared anchor designs for floating wind turbine farms can be computed in HAWC2. In addition to natural frequencies and corresponding mode shapes at the equilibrium points, loads and performance of a shared anchor design and single design were computed. The design parameters are the shared mooring line length for the Gran Canaria site and the position of the shared anchor point and buoyancy force at the line intersections for the Morro Bay site.

The Gran Canaria site has catenary type mooring lines which consist of heavy chains. The natural frequencies of the system can be adjusted by changing the shared mooring line length, however the mid part of the chain section tended to touch the sea bed even for a tight mooring line design which had very large mooring line forces compared to the single turbine case.

The Morro Bay site has taut mooring lines with polyester lines at very deep water. Shared anchor designs were evaluated for the site and one design was chosen for further load and performance evaluation. The results show that the frequency of the shared anchor design can be very similar to the single turbine design by altering the Line-9 length. The turbines of the shared anchor design had similar performance and load values as the single turbine design when the same controller was used. Although the turbines had similar response and performance under steady waves and wind, the upstream mooring line of Design-3 had about 30 % higher loads than the single turbine. Furthermore, the upstream turbine's surge displacement was almost double compared to the downstream turbine and to the single turbine.

In the future, this work can be extended by evaluating loads and performance of shared anchor design with more realistic load cases which includes turbulent wind and unsteady waves. The aerodynamic wake effects for shared anchor design can also be added for future performance and load analysis.

Acknowledgements

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