Numerical analysis of unsteady aerodynamics of floating offshore wind turbines

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Abstract. The unsteady aerodynamics of a scaled model floating horizontal-axis offshore wind turbine is investigated numerically. Different aerodynamic models are used to analyze the complex unsteady flow, namely models based on unsteady Reynold-Averaged Navier-Stokes equations, free vortex wake and blade element momentum theory. The wind turbine base is subjected to imposed sinusoidal surge oscillations to reproduce the motions of the floating platform. The aerodynamic response of the rotor and the wake unsteadiness are investigated, while an evaluation of the numerical models is performed with help of wind tunnel data.

1. Introduction

Increasing global wind energy demand makes unconventional sites like deep water offshore location or complex terrain more and more attractive for energy production. In the case of floating offshore wind energy, the effects of platform motion, induced by the wind and waves, on the loads and power generation should be taken into account in order to appropriately assess the structural fatigue.

Matha et al. [1], who investigated the challenges in simulations of floating wind turbines, have shown that the most significant motions of spar-buoy stabilized floating wind turbines for rotor unsteadiness are surge and pitch motions. Several studies have been dedicated to the study of offshore wind turbines under only surge motion ([2], [3], [4], [5]), only pitch motion ([6], [7]), or a combination of different platform motions ([8], [9]). Bayati et al. [8] evaluated the unsteady aerodynamics of floating offshore wind turbines as function of the amplitude and frequency of mono-harmonic surge and pitch motions. Micallef and Sant [10] confirmed numerically the experimental statement of Sant et al. [3], that the amplitude of thrust cyclic response to surge motion increases with increasing tip speed ratio. He underlined the importance of an adequate aerodynamic model of the wake for an accurate estimation of the structure fatigue. A few analyses also evaluated the ability of engineering models to predict the loads. For example, while de Vaal et al. [2] showed that current dynamic wake models in blade element momentum models (BEM) are suitable for global load analysis, Micallef and Sant [10] showed that BEM suitability highly depends on the wave conditions. Most of the numerical analyses are based on simplified approaches, like wake dynamic models, BEM theory or Generalized Dynamic Wake model (GDW), and take as reference simulations with the actuator disc model. Only
Farrugia et al. [5] used a lifting line method in a free-wake vortex code to perform a detailed analysis of the rotor and wake unsteadiness under surge motion, and Tran and Kim [9] performed high-fidelity Computational Fluid Dynamics (CFD) simulations. In the same way, the current investigation aims at performing high-fidelity simulations of a floating wind turbine under monoharmonic surge motion, allowing a more detailed insight into the wake flow physics. Moreover, an evaluation of two numerical approaches based on free vortex wake and BEM theories is done by means of comparison with experimental results.

The results presented here are part of the joint experiments performed in the UNAFLOW project, in which the unsteady aerodynamics of a floating offshore wind turbine are investigated numerically and experimentally in PoliMi’s wind tunnel and in the Technical University of Denmark (DTU) 2D wind tunnel. The model wind turbine is a dynamically scaled model of the DTU 10MW reference wind turbine ([11], [12]) and has a radius of $R = 1.19$ m. The turbine is considered working at rated operating conditions, corresponding to an inflow velocity of $u = 4$ m s$^{-1}$, a tip speed ratio of $\lambda = 7$ and a rotational velocity of 241 rpm. No real-time controller is used neither in the experiments nor in the simulations. A more detailed description of the experimental setup, on which the current numerical study is based, and of the background and purposes of the project is to be found in [13].

The goal of the present paper is two-fold. On the one hand, it aims at getting a deeper understanding of the physics behind floating wind turbine rotors. On the other hand, it aims at evaluating different models and highlighting advantages and shortcomings.

2. Numerical approach
2.1. URANS simulation setup
(Unsteady) Reynolds-Averaged Navier-Stokes equations ((U)RANS) numerical simulations are performed with the block-structured, finite-volume flow solver FLOWer developed by the German Aerospace Center (DLR) [14], with extensions for wind turbines simulations by the University of Stuttgart ([15], [16]). The code solves the finite three dimensional, compressible (Unsteady) Reynolds-Averaged Navier-Stokes equations using the second order central Jameson-Schmidt-Turkel scheme (JST) to determine the convective fluxes. To accelerate the convergence, implicit residual smoothing, local time stepping and multigrid algorithms can be enabled for steady computations. For time accurate simulations, dual time stepping is used as semi-implicit scheme. To close the Navier Stokes equations, turbulence is modeled for the present investigations by the Menter Shear Stress Transport equation model [17].

First, steady simulations of a single blade and a third of the hub are performed in a 120$^\circ$ azimuth background mesh with rotational periodicity, in order to validate the rotor meshes and to perform a grid convergence study. Then, a translation motion of the structural components is imposed in order to investigate the rotor and wake dynamic response to surge motion.

The one third model setup, shown in Fig. 1, consists of one rotor blade, a 120$^\circ$ section of the hub and a background mesh, which represents a 120$^\circ$ section of an axisymmetrical cylinder with periodic boundary conditions. The spatial dimensions of the background mesh have been determined according to Sayed et al. [18], who investigated the influence of the far-field distance in a 120$^\circ$ model. The structure meshes are overlapping making use of the Chimera technique [19] and all the components are meshed with a fully resolved boundary layer according to the Reynolds number. The total setup consists of 15 Mio cells, including 6.2 Mio cells for the blade mesh only. The blade mesh has a CH-topology around the airfoil and has been generated via the in-house tool Automesh [20], ensuring $y^+ < 1$ for the finest grid layer.

2.2. Aero-Module simulation setup
Aero-Module is an ECN software featuring current state-of-the-art wind turbine aerodynamic models [21]. The two aerodynamic methods included in Aero-Module are respectively based
on the classical blade element momentum theory and on the free vortex wake model coupled to the lifting line model, named Aerodynamic Wind turbine Simulation Module (AWSM). The unsteady simulations of the turbine undergoing surge motion are performed using both models, by specifying, as input, rotor kinematics and blade sectional polars. In this study, the blade sectional polars have been provided by DTU, that performed 2D static and dynamic experiments of the blade sectional airfoil [8].

3. Results

3.1. Grid convergence study

A grid convergence study has been performed on the CFD 120° model setup. Three refinement levels of the blade mesh, namely a coarse one with 2.7 Mio cells, a medium one with 6.2 Mio cells and a fine one with 10.7 Mio cells have been studied. The background mesh has been adjusted to the outer cell size of the blade mesh, hence its refinement has not been modified in the grid
study. The evolution of the thrust coefficient on each setup, as represented in Fig. 2, shows that after 15,000 iterations, the simulations have converged to a level that allows an assessment of the grid dependency. The fine and medium meshes converge to a thrust coefficient of $C_T = 0.29$, while the coarse one converges to the lower value of $C_T = 0.25$. While the coarse mesh leads to a different solution than the fine mesh, the medium one leads to a solution close to the fine one. Thus, the medium mesh is retained for following investigations of this wind turbine, as it significantly reduces computational costs.

3.2. Results without platform motion

CFD results of the one blade setup without platform motion are compared with Aero-Module results. The out-of-plane forces along the blade show a good agreement with AWSM simulations, both in steady and unsteady FLOWer computations (Fig. 3). The rotor loads, also available from wind tunnel experiments [13], are presented in Table 1. Considering that the far-field boundary conditions of the 120° model CFD simulations, the AWSM and BEM simulations neglect the wind tunnel, resulting in lower loads, there is a good agreement with the experimental data.

![Figure 3. Radial distribution of the out-of-plane forces](image)

|                  | Experiments | FLOWer | $\Delta$ | AWSM | $\Delta$ | BEM  | $\Delta$ |
|------------------|-------------|--------|----------|------|----------|------|----------|
| Thrust [N]       | 35.9        | 34.2   | -4.7%    | 34.8 | -3.0%    | 34.6 | -3.5%    |
| Torque [Nm]      | 3.32        | 2.91   | -12.3%   | 2.99 | -9.9%    | 2.93 | -11.7%   |

Table 1. Unsteady rotor loads without platform motion

3.3. Results of the dynamic simulations

The rotor and wake response to typical surge motions of a floating platform are presented here and analyzed. The choice of the wave characteristics is based on previous floating offshore wind turbine investigations, and has been motivated by getting operating conditions with high aerodynamic unsteadiness. An indicator about the unsteadiness of the rotor aerodynamics is the wake reduced velocity $V^*_{W}$, introduced by Bayati et al. [8],

$$V^*_{W} = \frac{V}{2fR}$$  \hspace{1cm} (1)
V being the inflow wind velocity and $f$ the motion frequency. The higher its value, the steadier the flow state at the rotor. Above $V^*_W = 5$, aerodynamics can be regarded as quasi-steady. The chosen motions of the offshore platform are characterized by an amplitude of 0.008 m with a frequency of $f = 2$ Hz and an amplitude of 0.035 m with a frequency of $f = 1$ Hz, which correspond to respectively $V^*_W = 0.84$ and $V^*_W = 1.68$. These values are much lower than the threshold, and thus lead to a highly unsteady state with high contribution of non-linear unsteady aerodynamics. These motions correspond to a scaled realistic motion in the wave-frequency range for a 10 MW floating wind turbine [8].

In this section, an evaluation of the dynamic response of the rotor loads and of the aerodynamic power to the platform motion is performed and the near-wake dynamics are analyzed.

### 3.3.1. Dynamic rotor loads response

Figure 4 shows the dynamic response of the rotor loads to the surge motion at $f = 2$ Hz. Here, the response is evaluated by means of free vortex wake, BEM and CFD approaches. As the mean force value slightly differs in each approach, compare Table 1, only the thrust fluctuations are presented. The thrust response is characterized by the same frequency as the imposed surge motion, a phase shift of about $-90^\circ$ and a thrust amplitude of about 3% of the value without platform motion. The phase shift is due to the combination of the aerodynamic damping, which induces a phase shift of $-90^\circ$, and dynamic inflow effects, which induce a small additional phase shift.

![Figure 4. Response of the rotor thrust to a surge motion at $f = 2$ Hz](image)

| Surge motion | Experiments | FLOWer | AWSM | BEM |
|--------------|-------------|-------|------|-----|
| $f = 1$ Hz   | 2.15        | 2.49  | 1.81 | 2.15|
| $f = 2$ Hz   | 1.09        | 1.17  | 0.95 | 1.07|

**Table 2. Amplitude of the rotor thrust [N] as response to surge motion**

The amplitude of the thrust variation obtained with each approach is highlighted in Table 2 for both motions, together with the corresponding experimental data. As the experimental data
present a high noise level, the thrust response has been filtered at the surge frequency using a Fast Fourier Transform. To ensure consistency in the comparison, the same post-processing method has been applied to the other data sets. The thrust amplitude at $f = 2$ Hz is consistently twice the amplitude at $f = 1$ Hz for all the methods. Moreover, a normalization with the surge displacement, i.e. 0.035 m and 0.008 m, shows for all methods a quasi-linear evolution with the motion frequency. Although the numerical methods neglect the influence of the tower and of the wind tunnel environment, the BEM results show a surprisingly good agreement with the experiments, compared to the higher fidelity CFD and free vortex wake methods. Further investigations are currently undertaken to understand the reasons for this.

3.3.2. Aerodynamic power response Figure 5 shows the response of the aerodynamic power to the platform motion at $f = 2$ Hz, evaluated by means of CFD, free vortex wake and BEM. In accordance with the thrust fluctuations, the aerodynamic power varies over one surge period. This leads to a time-varying power output when integrated over one rotor revolution. In comparison to a bottom-fixed offshore wind turbine, the generated power experiences fluctuations of up to 7.8% (FLOWer), 6.8% (AWSM) or 7.7% (BEM) of the mean power value. Table 2 shows thrust fluctuations of only 2.7% to 3.4%, depending on the method used. This shows a higher impact of the surge motion on the power than on the loads.

![Figure 5. Response of the aerodynamic power to surge motion at $f = 2$ Hz](image)

3.3.3. Near-wake analysis Beside the rotor loads and the power, the wake dynamics are of particular interest when designing wind turbines, especially due to the effects on the downstream turbines in wind farms. Moreover, as highlighted by Micallef and Sant [10], an adequate determination of the wake dynamics is crucial for an accurate evaluation of the structural loads. As most of the energy of the wake is transported by the tip vortices, the current analysis focuses on their dynamics.

The influence of the rotor displacement at $f = 2$ Hz on the tip vortex position from the CFD simulations are made visible in Fig. 6. The normalized value of the $\lambda_2$ vortex criterion are represented in the axial-radial plane, the coordinates being normalized by the rotor radius $R$. The time-resolved evolution is represented after 1 rotor revolution, 1.125 revolutions (which means the blade is located 45° out of the plane), 2 revolutions and 2.125 revolutions. Let’s
identify the first vortices of each time step with A, B, C, and the older ones with X, Y and Z. After one rotor revolution, the platform is back to its neutral position after having moved downstream. At this position, the rotor experiences its fastest upwind negative velocity. Thus, the vortices B, Z and X, which correspond to this position, have been released with a smaller velocity than without platform motion. After the second revolution, the rotor is back to its neutral position after having moved upstream. At this position, the rotor experiences its fastest downwind velocity. Thus, the vortices A, Y and C have been released with a higher velocity than without motion. A pattern of successively accelerated and decelerated vortices appears in the wake, leading to the vortex pairing observed in Fig. 6. Vortices X and Y are merging, then Z and A, and so on, in a very stable merging pattern. Note that the emerging pattern is particular to the chosen frequencies, namely the surge frequency being equal to half of the rotor rotational frequency. Other frequencies, in particular if not harmonics of the rotor rotational frequency, could lead to much more complex wake dynamics. Compared to numerical wake analyses by Tran and Kim [9] under 6 degrees of freedom of the platform motion, or Farrugia et al. [5] under surge only motion, the wake here is much more unstable, with vortex merging beginning already 1.5 rotor radii downstream of the turbine. This difference can be explained by the highly unsteady conditions of the chosen wave motion due to the low wake reduced velocity.

4. Conclusions and outlook
The unsteady aerodynamics of a floating offshore wind turbine have been numerically analyzed with help of URANS, BEM and free vortex wake theory based approaches. To mimic the offshore conditions of a floating platform, sinusoidal surge motions have been imposed to the wind turbine.
First, the results without platform motion have shown a good agreement of the numerical methods with each other. Comparison with the experimental data has shown a satisfying agreement too, considering that the numerical results neglect the presence of the tower and of the wind tunnel environment.

Then, the influence of surge motion on the rotor loads and power has been analyzed. The loads analysis has shown that all numerical approaches catch well the dynamic rotor response to the surge motion, with a phase shift of about $-90^\circ$ and a thrust amplitude of 3% of the mean value. The estimation of the power output has shown a proportionally higher impact of the surge motion on the power than on the thrust.

A wake analysis has also been performed based on the CFD results, by means of the $\lambda_2$ vortex criterion. It has shown that the investigated amplitude and surge combination leads to a very stable vortex merging due to the particular relationship between surge and rotational frequencies.

After this initial study, which aims at verifying the baseline numerical approach and a comparison to methods of lower fidelity, higher order spatial schemes like the fifth-order WENO approach will be applied in the future to study the wake in more detail and the tower and wind tunnel will be taken into account.

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