Comparison of the free vortex wake and actuator line methods to study the loads of a wind turbine in imposed surge motion

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Abstract. To enable the development of floating offshore wind farms, it is important to have a clear understanding of the aerodynamic forces applied on a floating offshore wind turbine. The paper presents comparisons between a lifting line free vortex wake method and an actuator line method in the case of a wind turbine in surge with blade-resolved CFD data as a reference. Each model is compared to a quasi-steady estimation of the loads to understand the variations due to the surge movement. The near-wake flow field is investigated in order to give an insight into the flow features leading to the observed behavior. Both methods predict a higher axial velocity at the position of the rotor and one radius downstream of the rotor in surge conditions compared to the fixed case.

1. Introduction

As wind turbine development moves offshore to harness available wind resources, floating offshore wind turbines (FOWT) are a solution for deep-water sites where fixed bottom foundations are not economically feasible. Various floater designs exist, and are subject to different motions of their structure as discussed by Sebastian & Lackner [1]. From this, it is clear that the understanding of the unsteady aerodynamic loads of a floating offshore wind turbine in surge motion is an important topic for the energy production estimation of floating wind farms.

Several aerodynamic models exist for studying floating wind turbines, each with their strengths and weaknesses. The blade element momentum (BEM) method (see Burton et al. [2]) models the induction of the rotor while wake and dynamic effects are reproduced through the use of empirical or physics-based correction models. Those models have difficulties to reproduce the loads of a moving rotor, as reported by the LIFES50+ project [3] and by Bayati et al. ([4],[5]) because the correction models were initially developed for fixed bottom wind turbines. On
the opposite side of the complexity scale, blade-resolved CFD simulations (e.g., Lienard et al. [6]) represent the geometry of the wind turbine directly and model the flow turbulence. These models are computationally costly. Thus, only a limited number of operating conditions can be explored with them. Lifting line models are a family of intermediate fidelity models that represent the blades as lifting lines and reproduce the efforts through the use of airfoil polars and dynamic stall models. The lifting line free vortex wake model (FVW) uses a Lagrangian vortex formulation to model the flow around the wind turbine while the actuator line (AL) method solves the Navier-Stokes equations with turbulence models. Actuator line models are superior than FVW to compute wind turbine wakes as they include turbulence and viscosity effects. However, the actuator line formulation does not reproduce well the loading at the tip of the blades when a correction model is not used, as explained by Martínez-Tossas & Meneveau [7].

The loads on floating wind turbines have been investigated with the FVW method by Wen et al. ([8, 9]). They studied the NREL 5MW reference wind turbine [10] which is the wind turbine which will be used in this paper. They have shown that the mean power level is increased with higher reduced frequency of the imposed movement for a fixed tip speed ratio. This was found both with a FVW [8] and a CFD code [6] for high tip speed ratios. For a fixed reduced frequency of the surge motion, Wen et al. [8] have shown with FVW simulations that the mean power level is increased when the tip speed ratio increases. In both cases, the NREL 5MW was studied with a fixed rotational speed and a fixed zero blade pitch angle. The wake of a floating wind turbine is not yet well understood. Sebastian & Lackner [11] have shown that most of the influence of the wake on the rotor is due to the near-wake. Some insights on the near-wake flow field were given by Lienard et al. [6] with blade-resolved CFD computations.

This paper aims at assessing the ability of a lifting line free vortex wake model and an actuator line model to evaluate the loads and near-wake flow field of a surging wind turbine. The relative variations of the thrust and power obtained with the FVW, AL, blade-resolved CFD and a quasi-steady estimation are studied. Comparisons of the near-wake flow field for different turbine positions during a surge period are done in order to explain the observed load behavior.

2. Numerical Methods

2.1. Free vortex wake method: CACTUS

To study the effects of imposed motions on the loads of a floating wind turbine, the FVW code CACTUS [12] from the Sandia National Laboratory was used. It has already been used for similar purposes by Leroy et al. [13]. The blades are represented as lifting lines located at the quarter chord of the airfoils. The lifting line is divided into several elements for which the local angle of attack and relative velocity is evaluated at half the spanwise length. Vortex line elements are shed into the wake to account for temporal and spanwise variation of the lift force along the blades. The code has been improved by implementing functions to impose harmonic translations and rotations to the rotor. For efficiency, the computation of the self induced velocity of the wake has been parallelized on Nvidia GPUs using the CUDA language. The wake self-induced velocity is computed at every time step through equations 1 and 2.

\[
\frac{dx_p(t)}{dt} = u(x_p, t) = \sum_n u_{\Gamma,n}(x_p, t) + U_{\infty}(x_p, t)
\]  

\[
u_{\Gamma,n}(x_p) = \frac{\Gamma_n}{4\pi \lVert r_1 \rVert \lVert r_2 \rVert \left(\lVert r_1 \rVert \lVert r_2 \rVert + r_1 \cdot r_2\right)} \left(\lVert r_1 \rVert + \lVert r_2 \rVert \right) (r_1 \times r_2)
\]
where \( r_1 \) and \( r_2 \) are vectors pointing to both ends of a vortex line element from a point at position \( x_p \) and \( \epsilon \) is a desingularisation core radius taken equal to 0.2 times the local chord of the blade when the vortex element is shed into the wake. \( U_\infty \) is the undisturbed inflow velocity and \( u_{\Gamma n} \) is the velocity induced by the \( n^{th} \) vortex line element of circulation \( \Gamma_n \).

To enable comparisons between the flow field of the FVW and actuator line methods, the velocity field around the wind turbine is computed from the vortex wake of the FVW computation on a Cartesian 3D mesh using the Biot-Savard law. The same desingularisation core sizes as the one used during the computation of the free vortex wake are used. This operation which is run as a postprocessing was also parallelised on a GPU.

2.2. Actuator line method: Code_Saturne

The actuator line method of Sørensen and Shen [14] has been implemented in the finite volume Navier-Stokes solver Code_Saturne [15]. The Reynolds stress SSG [16] turbulence model is used, as second-order closure models are more suitable than first-order closure models to solve rotating flows [17] such as tip vortices, which are the main flow features of wind turbine flows. A Gaussian smearing \( g \) is applied with a Gaussian radius \( \epsilon = 2\Delta_{\text{grid}} \) as recommended by Troldborg [18].

The velocity sampling of the flow field to compute the sectional efforts along the blade with a lifting line approach is done with the integral velocity sampling method described both by Merabet & Laurendreau [19] and Churchfield et al. [20]. The Gaussian smearing \( g_i \) for the \( i^{th} \) actuator point is:

\[
g_i(x, y, z) = \frac{1}{\epsilon^3\pi^{3/2}} \exp\left( -\frac{(x-x_i)^2 + (x-y_i)^2 + (z-z_i)^2}{\epsilon^2} \right)
\]

where \((x_i, y_i, z_i)\) are the coordinates of the \( i^{th} \) actuator point. The integral average velocity at this actuator point can then be computed as:

\[
u_i = \frac{\sum_{n=1}^{N_{\text{cells}}} \Omega_n g_i(x_n, y_n, z_n) u_n}{\Omega_{\text{total}}}
\]

where \( u_n \) is the velocity at the center of cell \( n \), \((x_n, y_n, z_n)\) are its coordinates, \( \Omega_n \) is its volume and \( N_{\text{cells}} \) is the total number of cells in the domain. The tip loss model of Prandtl modified by Glauert is used [21] to prevent an unphysical tip behavior due to the Gaussian smearing, which is reducing the velocity induction and therefore increasing the local effective angle of attack near the tip of the blade [7].

Two meshes were used for the actuator line computations. The first one has 23 million cells. A finer mesh of 44 million cells was used to check if the results were independent of the mesh while keeping the smoothing size constant. Minimal differences were found between the results obtained with the two meshes. Therefore, results obtained with the 23 million cells mesh are presented in the following. The topology of this mesh can be seen on Fig. 1. It has size \( 20R \) in the axial direction and \( 16R \) in both the horizontal and vertical directions with \( R \) the radius of the wind turbine. The mesh cell size is of \( R/50 \) at the position of the rotor and in the near-wake until the axial position \( x = 10R \). The mesh has larger cells away from the rotor. The AL uses a time step of a duration that corresponds to a \( 1^\circ \) rotor motion while the FVW uses larger time steps equivalent to a \( 6^\circ \) rotor motion.
2.3. Test conditions

The same polars and geometry definitions of the wind turbines are used in both the FVW and the actuator line simulations. Thus, the differences between the two models are due to the underlying physical models and not the simulation inputs. The tower, hub and nacelle are not modelled in either model. No dynamic stall model were used in both the FVW and AL models to focus on wake dynamic effects rather than local airfoil aerodynamics. For 16 rotations of the NREL 5 MW wind turbine at rated conditions, the computational times are reported in Table 1. The actuator line simulations have a much higher computational cost than the FVW simulations.

Table 1: Computational time for 16 rotations of the NREL 5 MW wind turbine. The GPU used is a NVidia V100 GPU and the processors used are Intel Xeon Gold 6140 (total of 630 cores).

|                      | Free Vortex Wake | Actuator Line |
|----------------------|------------------|---------------|
| GPU time             | 30 min           | 7979 CPU hours|

The studied case is the surging wind turbine used by Lienard et al. [6]. It is the NREL 5MW reference wind turbine with included cone and tilt angle running at rated conditions: $U_\infty = 11.4 \text{ m/s}$, tip speed ratio $\lambda = \omega R/U_\infty = 7$ with $\omega$ the rotation speed, for 16 rotations. The surge frequency is half the rotational frequency of the rotor. One of the blades is at the top position at the beginning of a surge period. The amplitudes of the surge movements tested are $\Delta x_s = 8\text{m}$ and $\Delta x_s = 16\text{m}$. The inflow wind is not turbulent. The axes used for the study are defined of Fig. 2.

3. Results

3.1. Power and thrust variations

When the FVW approach is used, a surge movement of the wind turbine is equivalent to a fixed turbine in an oscillating wind field in the reference frame of the wind turbine. If the oscillation
of the wind speed is considered quasi-steady, the thrust and power of the wind turbine for surge induced wind can be estimated from the static loads around the conditions of interest. The surge induced wind is expressed $u_{dyn}(t) = \omega_s \Delta x_s \cos(\omega_s t)$ for an harmonic surge motion of amplitude $\Delta x_s$, circular frequency $\omega_s$ and reduced frequency $k_s = \omega_s \Delta x_s / U_\infty$.

The power and thrust corresponding to the harmonic total velocity can be interpolated from a thrust and power curve computed around the current operational point at a constant rotation speed. The mean value of the thrust and power in quasi-steady behavior is then computed as the integral over a period of surge motion of the interpolated quantities. The results is the quasi-steady behavior i.e. the behavior that would happen if no dynamic or viscous effects are present in the blades or wake aerodynamics. This can be taken as a first approximation of the expected behavior.

Figure 3 shows the static power and thrust computed with CACTUS at constant rotation speed $\Omega = 12.1$ rpm around the rated conditions for the NREL 5MW wind turbine. $P^*$ and $T^*$ are the power and thrust normalized by the available power and thrust in the wind at the rated conditions. Figure 4 shows an example of the temporal relative variations of the power and thrust over a period of the surge motion extrapolated from the static power and thrust curve around the rated conditions. For this quasi-steady estimation, Figure 4 shows that the mean thrust will be lower than the static case while the mean power will be higher. This is because the static power curve for constant rotation speed shown in Figure 3 is slightly convex around the rated condition $U_\infty = 11.4$ m/s, while the thrust curve is concave.

Figures 5 and 6 show the quasi-steady behavior computed with the method presented above as well as dynamic results from FVW (CACTUS) and AL (Code_Saturne) compared to blade resolved CFD from Lienard et al. [6] (elsA). The relative variation of the mean thrust and power in surging cases compared to the fixed bottom thrust and power are represented for each code. This is done to highlight specifically the changes induced by the surge movement.

The quasi-steady behavior does not cover the full range of surge reduced frequency because for low wind speeds, lower than 3.8 m/s, the FVW simulations used to compute the static power
and thrust curves are unable to converge because the tip speed ratio is too high and the rotor blocks the incoming flow. This is not a problem in the dynamic case because the low total wind speed is only experienced by the rotor for a fraction of the surge motion.

The quasi-steady behavior is predicting an increase of the mean power and a decrease of the mean thrust when the reduced frequency is increased. This quasi-steady behavior is related to the local shape of the static power and thrust curve around the rated conditions, respectfully convex and concave. The dynamic FVW results, taking into account the temporal movements of the rotor, show variations close the quasi-steady estimation with a difference growing with the reduced frequency for both the power and thrust. The mean power variation of the AL is similar to the FVW, while it predicts a smaller decrease of the mean thrust than the FVW. The blade resolved CFD results of Lienard et al. [6] show a bigger increase of the mean power and a smaller decrease of the mean thrust than the three other models. The difference between the blade resolved CFD and the other models grows with the reduced frequency.

The larger difference between the FWV and AL to the CFD results at high surge reduced frequency could be explained by the fact that the angle of attack is reaching higher values in the stall region and therefore the local loads on the blade become more difficult to predict with the lifting line approach that both the FVW and AL use. Here, no dynamic stall model is used, for both methods to focus on the wake induced dynamic effects. However, Barnaud et al. [22] have shown that even with a high fidelity WMLES, the behavior of an airfoil near stall is difficult to predict.

For reduced frequencies lower than \( k_s = 0.22 \), the FVW results are in good agreement with the quasi-steady estimation of the relative variations of the mean power and thrust. For small reduced frequencies, unsteady effects appear to be minimal.

3.2. Near Wake Flow Field

The induced velocity field of an actuator disc in surge motion has been investigated by de Vaal et al. [23]. They have shown that for larger values of the reduced frequency \( k_s = \omega_s \Delta x / U_\infty \), the mean value of the induced velocity at the rotor plane is reduced compared to the static
case. This is an interesting effect and it might be related to a faster wake breakdown due to
tip vortex interactions, so when analyzing the thrust and power of a surging turbine one has to
take into account the combined effect of the oscillating apparent wind speed due to the surge
motion as well as the additional wind speed at the rotor plane due to the lower induction of the
rotor. The reduced induced velocity at the rotor plane means a higher axial velocity at the rotor
disc and thus could increase the thrust. This could explain the higher mean thrust computed
in the dynamic case by the FVW and the AL, compared to the quasi-steady estimation. Both
methods take into account the wake and therefore any faster wake breakdown associated to the
surge motion.

To verify this, the axial velocity along a line has been extracted from both the FVW and actuator
line results, for the fixed case and for the surging case, with an amplitude of $\Delta x_s = 8$m to avoid
any influence of dynamic stall on the comparisons. These velocity profiles are plotted in Fig. 7
for four different positions of the turbine during the last simulated surge period. Recall that the
surge frequency is half the rotational frequency of the rotor and therefore the rotor is always at
the same position during a surge period. The velocity profiles are extracted along the axial line
for $y/R = 0.0$ and $z/R = 0.8$. The blade is therefore passing over the extraction line in Fig. 7a
and 7c.

The axial velocity profiles of FVW and AL are very similar for axial positions between
$x/R = -0.5$ and $x/R = 0.5$. The AL results predict consistently slightly higher values of
the axial velocity than the FVW results. Further into the wake, stronger differences between
the FVW and AL results can be seen, which can be related to the absence turbulence modeling
in the FVW.

The axial velocity at the position of the blade is lower in the surging case than in the fixed case
when the rotor is moving downwind (Fig. 7a). The opposite behavior is observed when the rotor
is moving upwind (Fig. 7c). Figures 7b and 7d show the axial velocity in the rotor plane away
from the blade. They show the deceleration of the incoming flow due to the blockage effect of the
wind turbine. The axial velocity in the rotor plane away from the blade is higher in the surging
case than in the fixed case. This velocity difference can be seen most clearly at the position of
the rotor (noted as the vertical line in the figure). This behavior is observed both for the AL
and FVW methods. It confirms the results of de Vaal et al. [23] which were obtained with an
actuator disk method. It explains why the FVW, the AL and the blade resolved CFD predict
a higher mean thrust than the quasi-steady estimation: the axial velocity in the rotor plane is
higher than in the fixed case and is not taken into account in the quasi-steady estimation.

Figure 8 shows further comparisons of the near-wake axial velocity obtained with both models
at position $x/R = 1$ in the wake. In Fig. 8a and 8c, the FVW results show a more rapid
velocity change between the inner part of the wake ($|z/R| < 1$) and the outer part of the wake
($|z/R| > 1$). It is a sign of the difficulty to properly model tip vortices with the actuator line
method which has been reported by several authors ([7],[24]). Figure 8 shows that both the
FVW and AL predict a higher axial velocity in the near-wake when the rotor is surging. This
means that a surging rotor has a lower velocity deficit than a fixed rotor in the near-wake. If
this behavior is also verified in the far wake, it would be valuable for the power production of
other turbine in the same wind farm. Thus, studies of the velocities in the far wake should
follow the present work in order to know the velocity deficit in the far wake of a surging wind
turbine.

Comparisons of the axial velocity flow fields in Fig. 9 show that FVW and AL results are similar
for positions near the rotor ($x/R$ close to 0). Further downwind in the wake, the differences are
larger while some similarities can still be found. The axial velocity is stronger in the hub region
with the actuator line.
Figure 7: Axial velocity profiles for different positions during a surge period. $\phi$ is the phase of the surge movement. The vertical lines represent the position of the wind turbine in the fixed (solid) and surging (dashed) cases. The extraction line coordinates are $x/R \in [-0.5, 2.5], y/R = 0, z/R = 0.8$ where the origin is at the center of the rotor hub in the fixed case.

4. Conclusion

For surge movements with a high reduced frequency, the quasi-steady estimation predicts a lower mean thrust than the actuator line, free vortex wake and blade resolved CFD results. For the mean power, the opposite behavior is observed. The lifting line FVW and actuator line approaches have a limited ability to predict the aerodynamic loads of a floating wind turbine in large surge movements with dynamic stall, because the local flow around the blade profile is not resolved. Analyses of the near-wake velocity field have shown that the axial velocity at the position of the rotor is higher when the wind turbine is surging. This explains the higher mean thrust obtained with the FVW and AL compared to the quasi-steady estimation. A strong agreement between the axial velocities at the position of the rotor is found between the FVW and AL. At one radius behind the rotor, both the free vortex wake and actuator line results show that the surge movement is increasing the axial velocity in the wake. This could be of great interest for the wind farm layout of floating offshore wind turbines.
Figure 8: Axial velocity profiles along a vertical line at $x/R = 1$ and $y/R = 0$

(a) $\phi = 0, x = R$
(b) $\phi = \pi/2, x = R$
(c) $\phi = \pi, x = R$
(d) $\phi = 3\pi/4, x = R$

- fixed FVW
- surge 8m FVW
- fixed AL
- surge 8m AL

Figure 9: Axial velocity fields when the wind turbine is surging upwind ($\phi = \pi$) in the plane $y/R = 0$.

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