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The effect of blade-tower interaction on the structure loading of multi megawatt horizontal axis wind turbine

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Abstract. The aim of this work is to investigate the blade-tower interaction of multi megawatts upwind horizontal axis wind turbine (HAWT). With the increasing of the tower height, tower base becomes bigger and transportation problems appear. Nowadays, the tower dimensions are almost reached roads limits. To optimize tower dimensions there is the need to get a better understanding of what loads act on the tower.

In this work, a CFD simulation of a 3MW upwind HAWT is performed to predict tower load for nominal operation conditions considering blade-tower interaction. It was found that blade-tower interaction induces significant dynamic load. The tower suffers pressure fluctuation called 3P oscillation (for three blades rotor) leading to cyclic fatigue and influences rotor stability. Moreover, because of blade passage in front of the tower, the stagnation point position changes and displacement of separation points on tower sides occur. The tower suffers different shedding frequencies on the upper and lower parts and side forces are resulted.

1. Introduction

The purpose of the wind turbine is to extract wind energy by decelerating wind velocity and transform it into mechanical energy and subsequently into electrical energy. The design / development trend of the horizontal axis wind turbines is to increase rotor size while keeping rated power constant. Not only increasing the rotor diameter will increase the turbine power, but duplicate wind velocity will increase the power eight times. For these reasons and in addition to wind shear, it makes sense to increase tower height so that more energy can be captured by the rotor.

The importance of the tower is based on the facts that the tower is the most expensive part of the machine (counts to 26% of the total cost [1]), and the structure should endure operation loads. In addition, the tower should ensure safety requirements and being durable during the expected life time of the machine. In general, wind turbine support structure is required to undertake the extreme loads (like wind gusts) and fatigue loads. Additionally, tower natural frequency should be considered to avoid cyclic load excitation [2].

However, scaling up the size of the machine is not an easy task. One of the critical problems that faces the multi megawatts wind turbines is the transportation problem. As the tower becomes larger, tower base gets bigger. Nowadays the dimensions of the wind turbines towers are almost reached the limits of Europe roads capacity (maximum 4 m height [3]). In addition, longer blades need bigger rotor-tower clearance to avoid blade-tower strike. The IEC 61400-1 states that blade deflections must be multiplied by a safety factor of 1.5, [4]. Rotor-tower clearance is also achieved by shifting the nacelle...
forward to keep the minimum required safety clearance. As a result, additional moments are generated at the tower foundation, which must be considered in the tower design. To optimize the dimension of large towers, there is the need to improve the understanding of what tower loads are.

Operation tower loads are basically divided into two categories: ultimate and fatigue. Ultimate loads are the static permeant loads like machine mass and wind pressure while the fatigue loads are the temporary or dynamic loads that are strongly related to wind turbulence [5]. Fatigue damage can occur when the structure component is subjected to aerodynamic loads. It starts by micro cracks and grow up over time and ends up with component failure.

Extracting wind energy will create a lower velocity field behind the rotor called wind turbine wake. The difference in flow volume between the outer flow and the wake region will create a pressure jump. The later leads to shear layers, generates sheet of vorticities along the blade span, tip and root vortices that moves in a helical path downstream. Furthermore, the turbine itself (as a solid body) interrupts the flow and generates additional mechanical turbulence. Finally, the turbulence and the decelerated flow expand the wake and mix the outer with the inner flow leading to a blur way.

Although studies showed that the effect of tower shadow of the upwind turbine is relatively small on the turbine overall performance [6], a lift reduction of 5% to 57% can occur when a blade passes the wake of a tower [7]. Downwind wind turbine blades suffer fatigue loads due to its own tower shadow. Vice versa it can be stated that the tower of an upwind turbine suffers frequent unsteady load because of blade passage. The 2D simulation of Gomes [8] showed a change of stagnation point and velocity distribution on the tower and tower shedding frequency when the blade passes an upwind turbine tower. Since the fatigue and the excitation of the structure are highly depend on the aerodynamic loads, it is important to take blade-tower interaction into consideration when designing machine structure. The effect of blade-tower interaction is not critical for small wind turbines, however it becomes more relevant for big machines like modern multi megawatt wind turbines [9-14]. At these dimensions the aerodynamic forces occur with a high degree of nonlinearity on the system while the blade passage by the tower.

However, there is still limit of high fidelity studies considering the effect of the blade-tower interaction on the support structure loads. The aim of this work is to get a better understanding of the dynamic loads on a multi megawatt upwind horizontal axis wind turbine tower taking into account blade-tower interaction by means of CFD simulation.

![Refinement mesh domains](a)

**Figure 1.** Simulation domains: (a) Full turbine domain, (b) only tower domain.

2. **Numerical model**

CFD simulation allows to investigate the unsteady blade-tower interaction with a great amount of details and accuracy. A model of an upwind HAWT has been simulated using the software Ansys Fluent. The simulation has been performed in two parts: first only the tower is exposed to wind stream. The drag
force and shedding vortices are recorded over the time until study conditions reached. The second part is to simulate the complete machine while considering the blades rotating in front of the tower.

After creating the turbine geometry, it has been imported into the CFD environment. The rotor has three NREL blades of varying profiles along the blades span with a total length of 61.5 m and a maximum chord length and twist angle of 4.65 m, 13.3° respectively [15]. The hub is a simple 3 m diameter half sphere and the tower height is 112 m, as can be seen in Figure 1.

The simulation domain of the full turbine consists of two subdomains, a fixed subdomain that contains the stationary parts (nacelle and tower), and a cylindrical subdomain that contains the rotor. For this model, the sliding mesh method has been adopted by giving a relative motion to the rotor subdomain to avoid using dynamic mesh and to get better results accuracy.

\[ V(z) = V_m \ast \left( \frac{Z}{Z_{hub}} \right)^{0.1} \]

**Figure 2.** Velocity profile at the inlet.

The inlet is placed 2D upstream with a prescribed velocity profile following the power law function in Figure 2 and a turbulent intensity of 8% (onshore), Where: \( V(z) \) is the velocity at any height in m/s, \( V_m \) is the mean velocity, \( Z \) is the height in meter and \( Z_{hub} \) is the hub height. The outlet is placed 2D downstream and set to ambient pressure, the surrounding boundaries to symmetry and the turbine surface to no-slip condition. The flow is considered to be incompressible, turbulent and the Navier-Stokes equations are solved in transient state. The k - \( \omega \) SST turbulent model is utilized, where the k - \( \omega \) turbulent model is solved near the walls and k - \( \varepsilon \) away from the walls for better flow characteristics prediction. The 3 MW wind turbine operates at a rated wind speed of 11 m/s and a tip speed ratio of 7.5. To predict accurate blade-tower interaction effect, deformed blades are considered in the CFD simulation. A structure simulation for the blades has been performed to compute the deformed shape of the blade for the CFD simulation model for the same operation conditions.

The full model domain is meshed with approximately 5.3x10^6 unstructured tetrahedral elements while the tower model needed about 1.4x10^6 elements. The grid has been refined in different levels towards the turbine geometry and additional prismatic layers are attached to the surfaces to capture the boundary layer accurately, Figure 3.

### 3. Results and Discussion

For both models (i.e. tower model and full turbine model), the same operation conditions mentioned above have been used in the simulation. The simulations were run until quasi-steady state reached. Convergence levels of 1x10^-4 are achieved for both the momentum and turbulent variables at each time step. Figure 4 illustrates the normal and side forces on the whole tower model plotted in percentage of the maximum normal force. It’s clear that the normal force is almost constant over the time with an average value of 19500 N. A small fluctuation of the side force can be noticed (12%), where the effect of the von Karman vortices appears. Tubular tower produces a free shear layers, this effect can be observed in the velocity streamlines that are plotted at the middle of the tower height, Figure 5. For this operation conditions, the von Karman vortices resulted in a fluctuated side forces in the range of ± 2300 N.
Considering rotating blades in front of the tower, many changes will take place in the flow filed. The important blade-tower interaction effect will be addressed for the following aspects below:

3.1 Normal force and torque
Passage of the blade near the tower disturbs the flow field and deflect its direction, therefore the position of the stagnation point on the tower changes. This interaction has a large impact upon the tower aerodynamic loading. The tower suffers pressure fluctuation known as 3P oscillations (for three blades rotor) where the self-shed wake occurs three times per revolution. Figure 6 shows the plot of the tower normal force over the azimuth angle for 1/3 rotation for the full turbine model, where 0° is when the blade in front of the tower. The forces are plotted in percentage of the maximum normal force (in this case when the blade is away from the tower). As the blade passes the tower, the tower responds very significantly, the minimum tower load is occurred when the blade is few degrees away from the tower centreline as the blade shadow reaches the tower. For the rated power conditions, a reduction of the normal force of about 92.4% (17770 N) is achieved causing fatigue cycle every time the blade passes it. The numerical model of this work has been validated with a wind tunnel test of a scaled model [16].
Pressure sensors have been attached on the tower of the scaled model to measure the pressure during the rotation of the blades. Results showed a good agreement between test model and the simulation model.

In addition to the large reduction of the tower normal force, the blade-tower interaction has an influence on the tower side force. This interaction may sound trivial, but its effect is magnificent to a level that it creates a side force over 54% (10500 N) in a short period. These forces are caused by bound vortex circulation of the blades that disturb flow streamlines on both tower sides. In addition, due to the shedding vorticities, the lift force that generated from the tower induces additional circulation in the flow. As the blade moves away from the tower, the disturbed flow dies out and the stagnation point begins slightly to return to its original position. However, the effect of the blade-tower interaction is not only restricted to the tower, but the blade itself suffers normal force fluctuation in the range of 9% (19238 N) as well. In general, for the mentioned operation conditions, the full machine suffers a cyclic normal force in the range of 4.1% (27581 N) three times per revolution.

The movement of the blade in a relatively high-pressure field in front of the tower leads to torque losses. The simulation showed an abrupt torque loss of 17.7% (181537 N.m) occurs when the blade gets close to the tower and an overall torque drop of 4.4%, Figure 7. It is likely that movement of the blade in the tower vicinity field causes change of the angle of the attack that leads to momentarily decrease of blade torque. This is followed by a raped increase of the torque because of pressure suction associated with the tower field.
Although the change of the blade load for the upwind wind turbine is less than the downwind [7], the induced fatigue loads are still considerable and cannot be neglected. This fast change of the tower loading is restricted to ± 20° of the blade azimuth angle before and after the tower. However, the recovery of the blade is apparently longer than the tower.

3.2 Wake structure
The reduction of the tower normal force found to be directly related to the vortex shedding from the blade. The tower shedding frequency was strongly affected by the presence of the rotor. Stagnation point displacement causes change of separation point on the tower surface. Tubular tower shape suffers an energized shedding vortex every time a blade passes it. Figure 8 indicates that the interaction induces a pressure distribution alters the normal force on the structure and blade moment. However, these vortices are more related to the rotation of the blades than the known von Karman vortices of a cylinder and synchronized with the inflow velocity vector in the field.

![Figure 8. Pressure contour at r = ½ R.](image)

Displacement of the separation points can be noticed in the pressure coefficient ($C_p$) plots on the tower surface. Figure 9 illustrate the evaluation of the pressure coefficient distribution across the tower sections at different blade azimuth angles. Rotation of the blades in front of the tower cause rotation of the separation points on the tower sides and make them lose their periodicity in a short time, as a result a skewed tower vortex is generated. This displacement is corresponded to the history of the tower side force in Figure 6. The largest $C_p$ is located at the tower front side, where the stagnation point is in the middle. A sudden drop of the initial $C_p$ value occur as soon as the tower falls into the wake of the blade. The front stagnation point dissipates and the pressure at this position drops even to less than the back side. In addition, rotation of the blades causes different shedding frequencies on the upper and lower parts of the tower. While tower wake is extended up to 3 diameters downstream the tower for the upper part, the lower part wake expands up to 2.5D, Figure 10.

3.3 Velocity excess.
In general, the tower is subjected to a lower velocity field when there are turbine blades rotating in front of it as can be seen in Figure 11. As known in the potential flow over a cylinder, the maximum velocity is located at the cylinder sides 90° from the stagnation point. As discussed above, movement of the blade in front of the tower leads to displacement of the of the separation points on the tower sides, which causes flow acceleration on the tower left side over the predicted potential velocity field, Figure 10 (a). As the blade moves away from the tower, the flow field starts to recover, the undisturbed flow condition is reached, and finally the stagnation point moves back to its original positions.
Figure 9. Pressure coefficient on the tower at: (a) 30% R, (b) 60% R, (c) 80% R (where R is the blade radius).

Figure 10. Velocity contours at: (a) 50% R (Full turbine model), (b) 40% tower height (Full turbine model), (c) 40% tower height (tower model).
4. Conclusion

A numerical simulation has been performed to investigate the size of the blade-tower interaction of a 3MW upwind HAWT. The simulation confirmed that the tower suffers serious fatigue oscillation every time it falls in the blade shadow. Moreover, there is a reduction of the normal force on the tower leads to dynamic load exceeds 92.4% and an overall normal force reduction of 4.1% due to the blade passage.

The important feature of the blade-tower interaction is the modification of the tower shedding characteristics. The tower suffers different vortex shedding frequencies for the upper and lower parts. Rotation of the blades in front of the tower changes stagnation point location and rotate the separation points resulting in side force fluctuation over 54% on the tower in short period. In addition, the blade near the tower experiences an abrupt torque decrease up to 17.7% and a reduction of blade normal force up to 9% while the other two blades generates normal torque.

These transient loads have significant influence on structure lifetime and considered as an essential part of the design loads. Therefore, it is necessary to take aerodynamic rotor-tower interaction into consideration in the design process to optimize the tower dimensions and to reduce production cost.

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