Numerical Simulation of Airflow around Horizontal Axis Wind Turbine

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Abstract: This paper predicts the aerodynamic and aeroacoustic characteristics of a horizontal axis wind turbine via a two-way fluid-structure interaction approach. In this study, STAR-CCM+ is used to model the flow around a rotating wind turbine, whereas ABAQUS is employed to estimate the blade deformation during the rotation motion of rotor. A weak-coupling approach switching between rotating frame calculations and sliding mesh computations is adopted in the studied problem. The Ffowcs Williams-Hawkings analogy is further employed to forecast the noise spectrum of the investigated wind turbine. The full-scale flow simulation under the rated condition is conducted to study the influence of blade deflection on the aerodynamics and aeroacoustics of a horizontal axis wind turbine. The flow computation of wind turbine with deformable blades is believed to be more close to the industrial practice and can deliver more accurate and realistic information of aerodynamics, as well as aeroacoustics, in operation.


Introduction
Horizontal axis wind turbine is a very promising and attractive renewable energy device due to its balance among capacity, efficiency and cost, when compared with other currently available renewable energy devices. For ensuring high efficiency and sufficient structure safety in operation, the aerodynamic characteristics of wind turbine, is, therefore, of great industrial interests. However, the aforementioned issues are typical examples of flow-structure interaction (FSI), especially focused on the impact caused by the blade deformation, arising in the wind turbine operation. This paper is to simulate the airflow around a single wind turbine and to predict the aerodynamic and aeroacoustic performance of a horizontal axis wind turbine, where the numerical predictions of inflexible and flexible blades are compared and discussed.

Method
The governing equations to describe the airflow around a rotating wind turbine is described by the time-averaged continuity and Navier-Stokes equations. Because the airflow around the investigated wind turbine has a relatively high Reynolds number, the transport equation of the turbulent kinetic energy, as well as the specific dissipation rate, is adopted to account for the corresponding turbulence effects, where a shear-stress-transport (SST) k-ω model [1] is employed in this study. The governing equations of flow field are discretized by a finite volume method, where the velocity and pressure are decoupled via a SIMPLE-type algorithm [2]. The aforementioned approach is implemented in the software STAR-CCM+, which is adopted in this study to predict the turbulent flow field around a wind turbine. The rotor blade is considered as a generalized cantilever beam with structure property variation along its axial direction. The structural analysis of wind turbine blades is numerically conducted via a finite element method, where the software ABAQUS is employed in this study to deliver the deflection prediction of wind turbine blades. The blade orientation is described by the azimuthal angle (β) measured from the blade position at the 12 o’clock location, Fig.1. The blade deflection at several key azimuthal angles is first determined from the co-simulation of STAR-CCM+ and ABAQUS, where a fully two-way FSI calculation is achieved with a rotating frame approach. The sliding mesh approach is used in the subsequent airflow computation, where the mesh block discretizing the computation domain enclosing the rotor of wind turbine is simultaneously updated at prescribed key azimuthal angles using the deformed blade geometry obtained from the previous co-simulation results. This two-step calculation is regarded as a weak coupling approach of FSI, which can substantially reduce the computational cost required by a fully two-way FSI coupling in a sliding mesh approach. In the noise calculation, a SST k-ω turbulence model considering detached eddy effect is adopted to improve the prediction accuracy of noise spectrum.

Results and Discussion
The airflow around a full-scale NREL 5MW wind turbine [3] under the rated condition is studied in this paper. The wind turbine is modeled as an inland wind turbine with zero yaw angle, where a logarithm-law velocity profile [4] is adopted for the incoming wind. The material property of blade is referenced from a recent study [5], where the structural characteristics of a wind turbine blade with similar size are disclosed.
The rated condition is defined as a wind velocity of 11.4 m/s at the hub height, and a rotor speed of 12.1 rpm. The origin of the coordinate system is defined at the intersection point of the tower axis and the ground plane. The negative y- and z-coordinates are the downstream direction and the direction of gravitational acceleration, respectively, Fig.2. The reference point of noise calculation is defined at (0, −15 m, 0). Table 1 summarizes the principal dimensions and operation parameters of the NREL 5MW wind turbine [3], where \( V_{r} \) is the rated wind speed at the hub height, \( V_{ci} \) is the cut-in wind speed at the hub height, \( V_{co} \) is the cut-out wind speed at the hub height, \( \omega \) is the rated rotor speed, \( P_{r} \) is the rated output power, \( D \) is the rotor diameter, \( L_{b} \) is the length of rotor blade, and \( H \) is the hub height. Figure 3 depicts the prediction of the axial velocity distribution along with the vector plot of the tangential velocity at \( x=10 \) m for the wind turbine at \( \beta=60^\circ \) via a co-simulation computation with a rotating frame approach. The region within the rotor diameter showing a low wind speed area implies the energy transfer from the incoming wind to the wind turbine system via its rotor blades. Figure 4 shows the numerical result from the calculation using a sliding mesh approach with deformed blade geometry. Both figures give similar tendency of flow behavior, but the later one is an unsteady calculation that is believed more close to the experimental result of on-site measurements. In the sliding mesh calculation, a vortex flow moving in the opposite direction of the rotor is found near the nacelle. Figure 5 further discloses the axial velocity distribution at the center plane, i.e., \( y=0 \) m. In the upstream region, the rotating blades result in a substantial suction effect on the incoming airflow, which readjusts flow velocity in the vicinity of rotor blades and makes the flow velocity less height dependent. A substantial high axial velocity of airflow is found behind the rotor blade, and a relatively uniform distribution of axial velocity occurs in the wake region extending several diameters of rotor in the downstream direction. It is interesting to note that an axial flow acceleration can be expected in the space above the nacelle. The deformation of the rotor blade at \( \beta=0^\circ \) is given in Figure 6, where \( d \) denotes the displacement between the cross-sectional centers of rigid and flexible blades, and \( r \) is the radial distance measured from the outer surface of hub. The negative value of \( d \) indicates a downwind deformation. The blade sections with \( r \) less than 27.75 m have an upwind displacement, whereas farther blade sections delivers a downwind translation. For the blade at \( \beta=0^\circ \), the blade displacement \( d \) varies between −4.55 m and 1 m. The time history of power output is compared for the wind turbines with rigid and flexible blades in Fig. 7. The average power output of non-rigid blades is about 4.91 MW, whereas the average power output of rigid blades is close to 5.02 MW. Due to the blade deformation, the flexible rotor has a smaller effective rotor diameter to convert the incoming wind energy, and it, therefore, delivers less power output. The rigid-blade wind turbine delivers a plateau-type power curve with a subsequent sharp decline, whereas a strongly oscillating behavior is observed in the power curve of the flexible-blade wind turbine. The maximum power output of the flexible case is estimated at \( \beta=20^\circ \), instead of at \( \beta=0^\circ \). This phenomenon clearly shows the non-trivial non-linearity of the flow-structure interaction in the wind turbine problem due to the blade deflection and its rotational motion. Figure 8 illustrates the predicted noise spectrum of rigid and flexible blades calculation. The deformed blade geometries of \( \beta=0^\circ \) is employed in the noise prediction of flexible blades, where this deformed blade geometry is fixed for all azimuthal angles visited in a sliding mesh approach. In the frequency domain between 38 Hz and 43 Hz, the wind turbine of deformed rotor is predicted to deliver greater noise level (10 dB higher) than the wind turbine of inflexible blades. The total noise level of the wind turbine with inflexible and flexible blades at the reference point is predicted as 94.14 dB and 93.55 dB, respectively.

**Conclusion**

A weak-coupling approach combining the rotating frame and sliding mesh computations is employed in this paper to predict the aerodynamic and aeroacoustic characteristics of a NREL 5MW wind turbine with rigid and flexible blades. The full-scale wind turbine flow is simulated at the rated condition. The downstream deflection of the flexible blade tip at \( \beta=0^\circ \) is estimated to be about 7.3% of the rotor radius. The average power output of non-rigid blades is about 2% less than that of rigid ones. The noise level of the wind turbine with flexible blades decreases by about 0.6% when compared to that of the wind turbine with inflexible blades.

**References**


Table 1 Definition of NREL 5MW wind turbine

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<tr>
<th>Parameter</th>
<th>Specification</th>
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<tr>
<td>$V_R$ (m/s)</td>
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<tr>
<td>$V_{CI}$ (m/s)</td>
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<td>$V_{CO}$ (m/s)</td>
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<td>$\omega_R$ (rpm)</td>
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<td>$P_R$ (MW)</td>
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<td>$D$ (m)</td>
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<td>$L_B$ (m)</td>
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<tr>
<td>$H$ (m)</td>
<td>89</td>
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Fig.1 Definition of the azimuthal angle $\beta$ and the rotor diameter $D$.

Fig.2 The coordinate system of wind turbine.

Fig.3 Flow prediction using a rotating frame approach at $\beta=60^\circ$.

Fig.4 Flow prediction using a sliding mesh approach at $\beta=60^\circ$.

Fig.5 Flow prediction using a sliding mesh approach at $\beta=60^\circ$.

Fig.6 Blade deformation at $\beta=0^\circ$.

Fig.7 Comparison of power prediction between rigid and flexible blades.

Fig.8 Comparison of noise spectrum between rigid and flexible blades.