Time-accurate aeroelastic simulations of a wind turbine in yaw and shear using a coupled CFD-CSD method

D O Yu and O J Kwon
Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, South Korea
E-mail: ojkwon@kaist.ac.kr

Abstract. In the present study, aeroelastic simulations of horizontal-axis wind turbine rotor blades were conducted using a coupled CFD-CSD method. The unsteady blade aerodynamic loads and the dynamic blade response due to yaw misalignment and non-uniform sheared wind were investigated. For this purpose, a CFD code solving the RANS equations on unstructured meshes and a FEM-based CSD beam solver were used. The coupling of the CFD and CSD solvers was made by exchanging the data between the two solvers in a loosely coupled manner. The present coupled CFD-CSD method was applied to the NREL 5MW reference wind turbine rotor, and the results were compared with those of CFD-alone rigid blade calculations. It was found that aeroelastic blade deformation leads to a significant reduction of blade aerodynamic loads, and alters the unsteady load behaviours, mainly due to the torsional deformation. The reduction of blade aerodynamic loads is particularly significant at the advancing rotor blade side for yawed flow conditions, and at the upper half of rotor disk where wind velocity is higher due to wind shear.

1. Introduction
Since Horizontal-Axis Wind Turbines (HAWTs) practically operate under the influence of atmospheric shear layer, and are also frequently exposed to off-axial flow conditions due to yaw misalignment, the rotor blades experience significant time-changing inflow for significant portion of the operating time. As a result, the blade aerodynamic loads vary dynamically with the rotor azimuth. The unsteady load is one of the largest contributors of degrading the power supply quality and also causing structural failure of turbines. Therefore, it is quite important to better understand the unsteady time-varying load behaviours at realistic operating situations, if more efficient and reliable wind turbines are to be designed in the future.

In the past few years, investigation about the unsteady aerodynamics of HAWT rotors under yaw misalignment and wind shear has been a serious subject in the wind energy community [1, 2]. An example is the Work Package 2 (WP2) of the UpWind Project [2], in which unsteady blade aerodynamic loads and rotor inflow characteristics at a wind shear condition were extensively studied for the National Renewable Energy Laboratory (NREL) 5MW wind turbine rotor [3]. One of the main objectives of the work was to improve the prediction capability of the engineering aerodynamic models, such as the Blade-Element Momentum method (BEM), by using Computational Fluid Dynamics (CFD) solutions. To achieve this goal, a series of CFD studies were carried out using a structured mesh Navier-Stokes flow solver [4-6], and the results were used for assessing various types of BEM models [7]. Also, information about the effect of wind shear and ground proximity on the...
power production and the wake development was provided. However, these studies were performed after ignoring the blade flexibility, despite of the fact that aeroelastic blade deformation and its effect on overall turbine performance are fairly significant for long and slender rotor blades typically adopted for multi-megawatt HAWTs. Recently, the aeroelastic behaviour of the NREL 5MW wind turbine rotor blades was studied by Yu and Kwon [8] using an unstructured mesh Navier-Stokes CFD solver, coupled with a blade Computational Structural Dynamics (CSD) solver based on a nonlinear beam theory. It was shown that blade aeroelastic deformation results in a significant reduction of aerodynamic loads, compared to rigid blade calculations. The unsteady blade load behaviour and the rotor wake structure are also changed due to the blade deformation. However, the observations were made for uniform freestream winds, similar to other previous coupled CFD-CSD studies [9, 10], and the aeroelastic behaviours of rotor blades under practical operating conditions involving non-uniform sheared wind and yawed freestream have not been previously studied.

In the present study, time-accurate aeroelastic simulations of the NREL 5MW wind turbine rotor blades were conducted by using a coupled CFD-CSD method, and the unsteady blade aerodynamic loads and the dynamic blade response due to yawed freestream and non-uniform sheared wind were investigated. The effect of blade deformation on the rotor blade aerodynamic performance was also investigated by comparing the results with those of CFD-alone rigid blade calculations.

2. Numerical Methods

2.1. CFD Solver

The blade aerodynamic loads were calculated by using an in-house incompressible Navier-Stokes CFD solver based on unstructured meshes [11]. In the flow solver, the convective fluxes were evaluated using second-order Roe's flux-difference splitting scheme, whereas the diffusion terms were computed based on central differencing. A second-order accurate linearized Euler backward method was used to advance the solution in time, coupled with Newton-like sub-iterations. The effect of turbulence was estimated by adopting the transition $k-\omega$ SST model [12]. Combination of an overset mesh method [13] and a deforming mesh technique [14] was used to handle the relative blade motion involving blade rotation in the azimuthal direction and the elastic blade deformation, respectively. The effect of mesh movement was taken into account in evaluating the convective fluxes of both the mean flow and turbulence equations such that the geometric conservation law [15] is satisfied. On the solid wall surface, the no-slip boundary condition was imposed by setting the flow velocity equal to the wall velocity itself. The flow solver was parallelized using MeTiS and MPI libraries.

2.2. CSD Solver

The in-house CSD module for predicting the blade aeroelastic deformation was developed based on a nonlinear Euler-Bernoulli beam theory [16]. In figure 1, the blade coordinate system and the blade deformation kinematics are presented. The blade at a precone angle of $\beta_p$ rotates in the azimuthal direction with a constant angular velocity of $\Omega$. Then the blade undergoes spanwise ($u$), edge-wise bending ($v$), flap-wise bending ($w$), and torsional ($\phi$) deformations. By modeling the blade structure using a finite-element discretization and after the assembly procedure, the nonlinear equations of motion governing the blade elastic motion can be obtained as

$$ M \ddot{q} + G \dot{q} + K q = F_0 + F_{NL} + F_{\dot{\phi}} + F_{\text{core}} $$

where $q$ is the nodal displacement vector, and $M$, $G$, and $K$ are the mass, gyroscopic, and stiffness matrices, respectively. $F_0$ indicates the inertial force arising from blade azimuthal rotation and rigid
pitch motion, and is independent to the solution vector $q$. $F_{NL}$ represents the internal elastic force nonlinearly proportional to $q$. $F_g$ and $F_{aero}$ indicate the external loads acting on the blade due to the gravitational force and the aerodynamic loads, respectively. This nonlinear system of equations governing the blade elastic motion is solved using the generalized-$\alpha$ time integration [17]. For the coupled CFD-CSD analyses in the present study, the aerodynamic loads, $F_{aero}$, are evaluated using the CFD flow solver. The current CSD solver is also equipped with a built-in aerodynamic module based on the BEM method, in which the unsteady effects due to shed wake are considered by the indicial response method [18]. This built-in aerodynamic module is used to provide the aerodynamic loads for initializing the coupled analyses.

### 2.3. Coupling Methodology

The coupling of CFD and CSD solvers was made by adopting the delta-airload loose-coupling methodology [19]. In this methodology, the blade aerodynamic loads and the blade elastic deformation for the complete rotor revolution are exchanged after each rotor revolution on a periodic basis. The overall procedure of the loose-coupling methodology is presented in figure 2. At first, the CSD calculation is made using the built-in BEM-based aerodynamic model. Once a converged periodic blade response is obtained, the deformation data as a function of spanwise location and azimuthal step ($q^\phi(r,\psi)$) are transferred to the CFD solver, including the pitch control angle ($\theta$) for power control, if necessary. Then, the CFD calculation is performed for the deformed blade. This initial CFD calculation usually requires three rotor revolutions until a physically meaningful flow field is obtained in a periodically repeated manner. Then the integrated blade aerodynamic loads are calculated from the surface pressure and skin-friction distributions to setup a complete $F_{CFD}^n(r,\psi)$ data for one rotor revolution. This information is provided back to the CSD solver. At the subsequent coupled iterations, the aerodynamic loads are fed back to the CSD solver by taking the CFD airloads and the difference of the BEM loads between the current and previous coupled iterations as

$$F_{aero}^n = F_{CFD}^{n-1} + (F_{BEM}^n - F_{BEM}^{n-1})$$

The blade deformation in response to this modified blade aerodynamic loads is transferred back to the CFD solver, and the CFD calculation is conducted again by following the specified blade motion as predicted by the CSD solver. From this stage, the CFD calculation for one rotor revolution is usually sufficient for obtaining periodically-converged blade aerodynamic loads when the calculation is restarted from the previously-converged solution. This iterative coupling procedure is repeated until the BEM aerodynamic loads, and as a result the CFD aerodynamic loads also, remain unchanged between the subsequent iterations. This implies that the converged blade response solely depends on the CFD aerodynamic loads alone, as shown in Eq. (2).

### 3. Results and Discussion

In the present study, the coupled CFD-CSD analyses were performed for the NREL 5MW reference wind turbine rotor [3]. In figure 3, the turbine model used for the present CFD calculations is presented, along with the definitions of coordinate systems, rotor azimuthal position ($\psi$), and wind...
direction ($\beta$). The modelling of blade and tower is achieved based on the data provided by NREL [3], whereas the hub and nacelle geometries were approximated. The rotor is installed with a shaft tilt angle ($\alpha_s$) of 5º, and rotates clockwise as viewed from upwind. To further increase the tower clearance, the blade is set at a precone angle ($\beta_p$) of 2.5º.

At first, the coupled calculations were made at yawed freestream conditions, and the results in terms of the unsteady blade aerodynamic loads and the dynamic blade response were compared with those of un-yawed freestream cases [8]. Then, the effect of wind shear was investigated by estimating the profile using a power law, similar to the study by Zahle and Sørensen [6]. The coupled CFD-CSD results were compared with those of CFD-alone rigid blade calculations to investigate the effect of blade deformation on the rotor blade aerodynamic performance. All calculations were conducted by adopting a time-step size equivalent to a rotor azimuthal increment of 0.5º.

**Figure 3.** Solid modelling of the NREL 5MW reference wind turbine and definitions of coordinate systems, rotor azimuthal position, and wind velocity direction.

### 3.1. Yawed Freestream Wind

To investigate the effect of yaw on the aeroelastic behaviour of rotor blades, the NREL 5MW wind turbine at 30º and 60º yaw misalignment angles ($\beta$) was simulated at the rated wind speed of 11.5 m/sec. At this wind speed, the rotor operates with a rotational speed of 12.1 RPM, and the blade pitch control angle is set to zero. To focus the study on investigating the isolated effect of yaw, the wind was assumed to be uniform, and no attempt was made to include wind shear in these simulations.

In figure 4, the computational mesh and the boundary conditions used for the CFD calculations are presented. The unstructured overset mesh is composed of a stationary main background mesh block containing tower and nacelle, and three moving sub-blocks used for each individual blade. The computational domain is mostly filled with tetrahedral elements, except on the solid surface where prismatic cells are packed to better capture the boundary layer. The first prism layer thickness is set to $7.3 \times 10^{-5}$ of the 75% span chord length, such that the $y^+$ value is maintained less than one on the blade surface. The total number of cells used was approximately 14.1M, while the number of nodes was about 4.3M. For the CSD calculations, 49 finite elements were used along the span to model the structure of the blade. The elastic axis was assumed to be located at 1/4-chord as reported by NREL [3].

The coupled CFD-CSD calculations were conducted until the difference of the BEM aerodynamic loads between the subsequent iterations was reduced below 0.5% based on the $L^2$ relative error norm. A converged set of the periodic blade response and the CFD-based blade aerodynamic loads was obtained after eight coupled iterations for both yaw angle cases. In figure 5, the predicted blade tip deformations are compared with those of un-yawed freestream case [8]. The results show that as the yaw angle is increased, the overall magnitude of blade deformations is reduced. This is because the blade aerodynamic loads are decreased due to the reduction of the axial wind velocity component perpendicular to the rotor disk plane ($V_x \cos \beta / \cos \alpha$, see figure 3). However, due to the presence of the
tangential wind component ($V_\infty \sin \beta$), the unsteady deviation from the mean value becomes larger, particularly in the flapwise direction. The deflection becomes larger in the azimuthal range from 90º and 270º where the blade is advancing toward the tangential wind component, and decreases in the remaining blade retreating side. The variations of edge-wise bending deflection are all very similar, since this degree of freedom is dominated by the gravitational force [8]. In the case of torsion, the nose-down deflection is predicted for all azimuthal positions. The maximum negative torsion deflection is observed near the azimuth angle of 90º for the un-yawed case, whereas the location is delayed to around 150º azimuth angle for yawed freestream cases. The unsteady behaviours of the flapwise and torsional deformations contain higher frequency contents larger than 1/rev for all cases, which is caused by the aerodynamic interference with tower when the blades pass by the tower near 180º azimuth angle [8].

Figure 5. Comparison of azimuthal variations of blade tip deformations between the cases with and without yaw misalignment (R: blade length).

In figure 6, the tower clearance and the rotor wake structure are compared between the cases with and without yaw misalignment when the reference blade is located at the azimuth angle of 180º. As shown for the flap-wise bending deflection behaviour in figure 5, the blade tip-to-tower clearance becomes larger as the yaw angle is increased. Also, due to the reduced axial freestream velocity component, the rotor wake, skewed in accordance with yaw, remains closer to the rotor disk plane. This implies that the turbine may operate under an undesirable interaction with its own wake.

In figure 7, the azimuthal variations of stagnation pressure, normal force coefficient, and centre of pressure at the 0.93R blade section are compared between the CFD-alone rigid blade and coupled CFD-CSD calculations at 60º yaw angle. In the figure, the results for axial freestream without yaw [8] are also presented for comparison. To examine the effect of the aerodynamic model, the results of the BEM-based calculations for the rotor-alone configuration are also presented. It is shown that in general the effect of yaw appears as larger unsteady variations of the aerodynamic quantities, caused by the tangential wind velocity component. Also, because of the reduced axial wind velocity, the normal force coefficient is significantly reduced. By examining the CFD-alone results for the rigid blade, it is shown that the unsteady aerodynamics at yaw can be characterized by the higher stagnation (dynamic) pressure and the lower normal force coefficient (angle of attack) at the advancing blade side and an opposite behaviour at the retreating side. The centre of pressure is located after the quarter
chord, and the location moves further downstream at the advancing blade side. This results from the reduction of the leading-edge suction pressure peak caused by the reduced angle of attack. In the case of elastic blades, due to the nose-down torsional deformation, the normal force coefficient is significantly reduced, particularly at the advancing side where the negative maximum torsion occurs as indicated in figure 5. A very similar behaviour is also observed for the centre of pressure. In contrast, the effect of blade deformation on the stagnation pressure is not very significant. It is also shown that, due to the tower interference, the normal force coefficient and the location of centre of pressure are abruptly changed near 180º azimuth angle. The overall unsteady behaviour and blade deformation effect for 30º yaw angle are very similar to those of the 60º yaw angle case. It was observed that when the BEM-based aerodynamic model is used, the overall behaviour of the dynamic pressure and the normal force coefficient are similar to those of the CFD-based calculations, even though the detailed unsteady pattern is not captured as well.

In figure 8, the predicted normal and tangential forces and the 1/4-chord pitching moment at the 0.93R blade section are compared between the rigid blade CFD-alone and coupled CFD-CSD calculations. The calculations were also made using the BEM-based aerodynamic model for the rotor-alone configuration. The results for the two yaw misalignment cases show that although the magnitudes of the blade aerodynamic loads are quite different between the two yaw angles, the overall
unsteady behaviours are quite similar. In the case of the rigid blade, the normal force is higher at the advancing blade side, indicating that the effect of dynamic pressure is dominant. In contrast, the tangential force is affected more by the angle-of-attack change. Because the pressure centre is located aft of the quarter chord, negative pitching moments are predicted at all azimuthal positions. This behaviour is also consistent with the normal force change. Due to the nose-down torsion deformation for this wind turbine, the magnitudes of the normal and tangential forces for the flexible blades are much smaller than those of the rigid blades. As shown for the normal force coefficient in figure 7, this effect is larger at the advancing side, especially for the normal force, resulting in an unsteady pattern different from that of the rigid blade. Since the pressure centre is moved further downstream when the normal force is reduced, the pitching moments are almost identical between the rigid and flexible blades. It is shown that at this nominal wind speed, since the angle of attack of the blade is moderate, and the flow remains mostly attached to the blade surface, the low-order BEM-based calculations also provide comparable results. However, due to the limitation of the model, the detailed unsteady pattern, such as the oscillatory load behaviour due to tower, is not predicted as well.

In figure 9, the blade root flap-wise bending moment predicted by the coupled CFD-CSD is compared between the cases with and without yaw misalignment. It shows that under the yaw misalignment, the amplitude of the predominant frequency of 1/rev is increased, compared to that of the un-yawed case. The overall unsteady behaviours are very similar between the two yaw angles, except near the 180° azimuth angle where the tower exists. At 60° yaw angle, the effect of tower is further manifested as larger amplitude for high frequency components.

3.2. Non-uniform Sheared Wind

Next, the aeroelastic behaviour of the rotor blades at a vertically sheared wind was investigated. The wind shear velocity profile was prescribed based on a power law relation as shown in figure 10. The wind speed at the hub (V_{hub}) was set to 8 m/sec, and a power exponent (α) of 0.55 was used. This results in a maximum wind speed of about 11 m/sec at the outermost blade top position and a minimum of about 4 m/sec at the bottom position. For this sheared wind case, a rotor angular velocity of 9.2 RPM was used, similar to the study by Zahle and Sørensen [6].
At first, the unsteady blade aerodynamic loads were investigated by the CFD-alone rigid blade calculations. In figure 11, the spanwise distributions of thrust and torque forces are presented at four azimuthal positions of 0º, 90º, 180º, and 270º. The results are also compared with other CFD-alone predictions [6] for a rotor-alone configuration without the rotor shaft tilt. As expected, the blade aerodynamic loads are high at the top position where the blades are exposed to higher wind velocity, whereas the magnitude is reduced to the lowest level at the bottom position. The blade loads at 90º azimuth angle are slightly higher than those at the 270º azimuth angle, although the wind speeds at the two positions are identical. This is presumably because the effect of induced downwash flow is relatively smaller at 90º azimuth angle caused by the lower loading of the preceding blade. Compared with the other prediction [6], the present results show slightly lower values, particularly for the torque force. This difference may be attributed to the effect of rotor shaft tilt and tower.

In figure 12, the azimuthal variations of blade tip deformations predicted by the coupled CFD-CSD calculation are presented. The flap-wise bending deflection and the nose-down torsion are larger at the top position because of the higher blade loads. The edge-wise bending deflection is not affected much by the wind shear as it is dominated by the gravitational force.

In figure 13, the predicted normal and tangential forces and the 1/4-chord pitching moment are compared between the CFD-alone and coupled CFD-CSD calculations. Due to the nose-down torsion, the overall values of blade aerodynamic loads are reduced. This effect is slightly higher at the top position.

Finally, the rotor wake structures are compared between the rigid and flexible blades in figure 14. The results are presented when the reference blade is located at the bottom with the azimuth angle of 180º. The results clearly show the difference in the downstream convection speeds of the roll-up vortices trailed from the blade tip between the top-most and down-most positions of the blade. In the case of flexible blades, because of the flap-wise bending deflection, the overall position of the tip vortex is located further downstream, compared to the CFD-alone rigid-blade calculation.
Figure 12. Azimuthal variations of blade tip deformations at the sheared wind condition.

Figure 13. Comparison of azimuthal variations of normal and tangential forces and 1/4-chord pitching moment at 0.93R blade span between the CFD-alone and coupled CFD-CSD calculations.

4. Conclusion

In the present study, coupled CFD-CSD aeroelastic simulations of horizontal-axis wind turbine rotor blades were conducted to investigate the unsteady blade loads and the dynamic response due to yaw misalignment and non-uniform sheared wind. The coupling of the CFD and CSD solvers was accomplished in a loosely coupled manner by exchanging the data after each rotor revolution on a periodic basis. The applications were made for the NREL 5MW wind turbine rotor blades.

It was found that yaw misalignment magnifies the unsteady variations of the blade aerodynamic loads, and causes larger blade deformation than that observed in the non-yawed case. Mainly due to the nose-down torsion deformation for the wind turbine considered in the present study, the blade aerodynamic loads are significantly reduced, particularly at the advancing blade side. The BEM-based results compare well with the CFD-based ones, except for missing the oscillatory load behaviour due to the tower interference.

When the turbine rotor is exposed to vertically sheared winds, the blade deformation becomes larger at the top position where the blade aerodynamic loads are higher. The large deformation at the same time leads to a reduction of the aerodynamic loads, particularly due to torsion.

It was concluded that the present coupled CFD-CSD method is well established for analysing the aeroelastic behaviour of horizontal-axis wind turbine blades, when they are exposed to yaw misalignment and non-uniform sheared wind. The methodology can be effectively used for designing advanced turbine rotors in the future.

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