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Numerical investigation of optimal yaw misalignment and collective pitch angle for load imbalance reduction of rigid and flexible HAWT blades under sheared inflow

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ABSTRACT

Wind shear can strongly influence the cyclic loading on horizontal axis wind turbine blades. These load fluctuation causes a variation of power output and introduces fatigue load. Thus, individual pitch controllers have been developed that are focused on the load alleviations, however, comes at a price of actuator requirements for control. Moreover, these controllers are unable to apply to already existing wind turbines with active yaw and collective pitch control system. Therefore, the investigations for minimizing load imbalance through the adjustments of yaw misalignment and collective pitch angle are implemented for the rigid and flexible blades under the sheared inflow. By applying the optimization process based on a sequential quadratic programming approach, the optimal yaw and pitch angle can be estimated. Then, the numerical simulations for predicting the performance are performed. The results showed that the fluctuation range of the root flapwise bending moment for the rigid blades can be reduced by 84.5%, whereas the vibratory bending moment for the flexible blades can be reduced by up to approximately 82.4% in the best case. Therefore, the magnitudes of load imbalance can be minimized by the adjustment of the optimal yaw misalignment and collective pitch angle without any power loss.

1. Introduction

With the increasing size of horizontal axis wind turbine rotor diameters and hub-height, the variations of the mean wind speed over the rotor height due to vertical wind shear are considerable [1]. In sheared inflow, the wind speed at the top of the wind turbine is different from that at the bottom of the wind turbine, which can strongly influence the cyclic loading on the turbine blades [1]. This azimuthal fluctuation of load results in a variation of power production and introduces fatigue loads. Fatigue loads determine a fatigue life of the wind turbines, directly concerning the cost problems for maintenance [2], and can lead to damage of wind turbine components, and are crucial factors for the design of wind turbine blades. The wind turbines have to operate on the loading environment over a design life of 20 years or longer so it is important to understand the unfavorable load variations of wind turbine under sheared inflow condition [3].

To deal with the increasing load variations on the turbines, some active or passive controllers have been designed that are focused on reducing the load imbalance [4]. Control systems for horizontal axis wind turbines have conventionally been based on sensors for measuring the wind speed and direction, rotor speed and power output or torque, actuators for regulating generator torque, and yaw misalignment angle and collective pitch angle [4]. Many studies [5–10] related to the IPC (individual pitch control) schemes for large scale wind turbines have been investigated to compensate for the asymmetric loads caused by the wind field. This control system can attenuate the impacts of asymmetric wind loads [8,9]; however, it comes at a price of actuator requirement [4]. Also, the IPC system for load alleviations is unable to be applied to already existing wind turbine systems. Therefore, investigation of other means of load alleviation that can be applied without the additional actuator requirements is needed [4].

Abbreviations: BEM, blade element momentum; CFD, computational fluid dynamics; FSI, fluid-structure interaction; HAWT, horizontal axis wind turbine; IPC, individual pitch control; RFBM, root flapwise bending moment; SQP, sequential quadratic programming.

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Wind directions changes frequently with respect to the rotor axis of horizontal axis wind turbines in field operating conditions. Thus, wind turbines should be adjusted individually with the rotor plane against the wind in order to maximize power production [11]. Large scaled wind turbines commonly employ active yaw control capabilities to keep the turbines facing into the wind, but sudden changes in the wind direction can cause the turbines to operate with yaw misalignment. For this reason, almost previous studies related to yawing control have primarily been focused on increasing the power capture through improved yaw misalignment at below wind speeds [4,12–16]. On the other hand, Kragh et al. [4] demonstrated that only the optimal yaw misalignment angle for minimizing the load variations of the rigid turbine blades can be identified for both deterministic and turbulent inflows at above rated wind speeds. Because the yawed flow conditions lead to a cyclic pitch angle of attack at the rotor blades [11], the positive sign of yaw misalignment can produce about the higher (lower) load in the lower (upper) half part of the rotor plane. Whereas the vertical sheared inflow due to the wind speed variation with the blade elevation [2] causes the lower (higher) load in the upper (lower) half part of the rotor plane. Thus, through adjustments of the yaw misalignment and pitch control system, load imbalance reduction has the potential of decreasing the load variations without any power loss for large scale wind turbines, even already existing wind turbines. In other words, the combined impact of positive sign of the yaw misalignment and wind shear can partially cancel each component, thus resulting in load alleviation of the wind turbine blades. Murata et al. [2] described details of a numerical method for calculating the aerodynamic loads of rigid turbine blades in combined yaw and wind shear inflows. From the numerical results of Murata et al. [2], we can identify the potential of reducing the fatigue load by the combined inflow effects.

The objective of this research is to estimate the optimal yaw misalignment and pitch angle through optimization process for minimizing load imbalance and stabilizing the designed power production of the rigid and flexible horizontal axis wind turbine blades. For the calculations of the performance and vibratory bending moment of the turbine blades, an aerodynamic model based on BEM (blade element momentum) theory is adopted and this method is coupled with the ABAQUS/standard tool, which takes into account the blade elastic deformations. Then, the optimal conditions of the yaw and pitch angles for minimizing the vibratory bending moment are finally estimated through the optimization module based on a SQP (sequential quadratic programming) approach.

2. Modeling

2.1. Estimation of performance and blade deformation of horizontal axis wind turbine

2.1.1. Blade element momentum method

Power law model, which is an empirical relationship, is the most commonly used methods for predicting the wind profile of sheared inflow. The equation of the power law is defined as follows:

$$V_{wind}(z) = V_{hub} \cdot \left(\frac{z}{z_r} \right)^{\alpha}, \tag{1}$$

where V_{wind}, V_{hub}, z, and z_r stand for the target height wind speed, hub height wind speed, target height, and hub height, respectively, and α denotes the wind shear exponent. Many studies have investigated the empirical relationships for the wind shear exponent as parameter functions for the speed of wind, ground's surface roughness and its roughness variation, and the nature of the terrain [17,18]. Evaluating the azimuthal angle of the blade from blade vertical upward position, the incoming wind speed for blade radial positions in an axial flow is given by Ref. [3].

$$V_{wind}(r,\psi) = V_{hub} \cdot \left(\frac{z_r + r\cos\psi}{z_r} \right)^{\alpha}, \tag{2}$$

where r is the blade radial position, and ψ is the azimuthal position of the blade. The fundamental concept of the BEM (blade element momentum) theory is to equalize the linear and angular momentum variations of the air masses flowing through the rotor plane with the axial load on the horizontal axis wind turbine blades. This equilibrium is achieved by taking into account the flow through annular strips and the airloads on the blade elements. In reality, the wind turbines experience the inherent unsteadiness of the wind due to the presence of the sheared and yawed flow. For this reason, a modified Pitt-Peters dynamic inflow model, which can account for the wake effects, was used for the aerodynamic simulations [19]. The induced factors are assumed to remain to their stationary values instantly under the assumption of a quasi-steady wake [20,21]. In other words, the induced velocities can be expressed as follows [22]:

$$\begin{aligned} v_{normal} &= \frac{-BL\cos\theta_{flow}}{4\pi\rho r F_{tip-loss}\left|V_{wind}(r,\psi) + n(n\cdot W)\right|} = a_{q-s}(r,\psi)\cdot V_{rel} \\ v_{tangential} &= \frac{-BL\sin\theta_{flow}}{4\pi\rho r F_{tip-loss}\left|V_{wind}(r,\psi) + n(n\cdot W)\right|} = a'_{q-s}(r,\psi)\cdot(\Omega\cdot r) \end{aligned}, \tag{3}$$

where v_{normal} and $v_{tangential,}$ are the induced velocities in normal and tangential directions, respectively; B, the number of turbine blades; L, the lift force; θ_{flow}, the flow angle between the rotor plane and the relative velocity; n, the unit vector in the direction of thrust; W, the induced velocity; $F_{tip-loss}$, the Prandtl's tip-loss correction factor. This tip-loss correction factor should be introduced into the analysis process to consider the three-dimensional aerodynamic effects, because the tip vortices have a substantial impact on the distribution of the induced velocity [22]. The terms a_{q-s} and a'_{q-s} are the axial and tangential induction factors under the assumption of a quasi-steady wake, respectively; Ω, the rotational speed of the blade. Since the horizontal axis wind turbines under yawed inflow conditions produce a skewed wake behind the rotor plane, the BEM method also requires correction to account for the effect of the skewed wake [23,24]. In addition, it is accomplished by the Du-Selig dynamic stall model for correcting the viscous effects. The rotational augmentation correction for three-dimensional delayed stall, which employs the Selig and Eggers methods to modify the aerodynamic coefficients, is applied by using AirfoilPrep [25]. Using the predicted wind profile and induction factors, the effective angle of attack at the each blade section under cases of sheared inflow can be estimated as follows:

$$\begin{aligned} \alpha_{effective}(r,\psi) &= \theta_{flow} - \theta_{total} \\ &= \tan^{-1}\left\{ \frac{(V_{rel})_{axial}}{(V_{rel})_{tangential}} \right\} - \Big(\theta_{twist} + \theta_{pitch} \\ &\quad + \theta_{FSI}(r,\psi) \Big), \end{aligned} \tag{4}$$

where $(V_{rel})_{axial}$ and $(V_{rel})_{tangential}$ are the relative wind velocity in the axial and tangential directions, respectively; θ_{twist}, the structural twist angle; θ_{pitch}, the collective pitch angle; and θ_{FSI}, the torsionally deformed angle calculated by fluid–structure interaction analysis. By introducing the terms of the wind velocity in axial and tangential directions, Equation (4) can be rewritten, as given in Equation (5):