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Lift correction model for local shear flow effect on wind turbine airfoils

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ABSTRACT

Wind turbines operate under various wind conditions in which turbulence virtually always exists. Therefore, unsteady wind turbine simulation methods to estimate wind loading in turbulent inflow conditions are very important for developing optimally designed wind turbines. Several methods have been developed for this purpose and are usually based on the blade element momentum theory (BEMT), which is used for calculation of the wind loading on turbine blades. The local shear flow effect induced by turbulence, however, is not explicitly considered in the popular BEMT-based simulations. Extreme situations can occur in a large-scale wind farm where the inflow field of a wind turbine may contain strong tip vortices generated from upstream turbines. In this study, the effects of idealized local shear flows around a two-dimensional airfoil, S809, on its aerodynamic characteristics were analyzed by CFD simulations. Various parameters including reference inflow velocity, shear rate, angle of attack, and cord length of the airfoil were examined. From the simulation results, several important characteristics were found. The shear rate in a flow causes some changes in the lift coefficient depending on its sign and magnitude, while the angle of attack does not have a distinguishable influence. The chord length and reference inflow also cause proportional and inversely proportional changes in the lift coefficient, respectively. Based on these observations, we adopted an analytic expression for the lift coefficient from the thin airfoil theory and proposed a lift correction model, which is easily applicable to the traditional load analysis procedure based on the BEMT.

1. Introduction

Wind energy is considered to be one of the most feasible renewable energy sources to compete with traditional ones, even in an economic sense. The underlying assumption enabling this competitiveness is the low maintenance cost of a wind energy conversion system (i.e., a wind turbine, during its expected life time under various environmental stresses). In general, the expected life time of a wind turbine is over 20 years and continuous maintenance efforts are required to guarantee stable operation. Thus lowering the maintenance cost improves commercial competitiveness. Designing an excessively robust system, however, can require an unacceptable initial investment. Therefore, an optimal design compromising both robustness and low maintenance cost is inevitable for a commercially successful wind turbine (Fig. 1).

One of the most important processes for wind turbine design is the wind load analysis. An accurate and efficient wind load analysis is crucial in the optimal wind turbine design because a wind turbine operates in various wind conditions for a long time. The load analysis is usually carried out by the software based on the blade element momentum theory (BEMT) [1] such as Bladed [2] and FAST [3]. In BEMT, the net aerodynamic forces on a blade are calculated by the total sum of partial forces exerted on small segments of the blade. The partial forces are calculated by table searches from a data set of aerodynamic coefficients, thus this process can be very simple and fast. Though the overall accuracy is limited due to underlying assumptions, BEMT has served as the major research tool in initial conceptual design requiring iterative load analysis by virtue of its computational efficiency. On the other hand, computational fluid dynamics (CFD) is gaining in popularity with recent outstanding advancements in computer technology and numerical algorithms. Aerodynamic load analysis by CFD can be used for more detailed and physically reliable calculations of the flow field around a wind turbine because CFD is based on directly solving the

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Nomenclature

L_c	chord length
C_D	drag coefficient
U	inflow velocity
C_L	lift coefficient
L_c^0	lift coefficient in uniform inflow
C_M	moment coefficient
U_0	reference velocity
K	shear rate
η	shear rate sensitivity
f_t	thickness distribution
γ	vortex distribution

governing equations of the flow field (i.e., Navier–Stokes equations), but it is a very time consuming method compared to BEMT.

Recently, a hybrid method, the actuator line method (ALM), which combines the advantages of both methods, was introduced [4]. In ALM, the flow field is calculated by CFD while the interaction between the flow and turbine blades is based on the BEMT. From this point of view, BEMT, though a rather classical method, can be considered still very important. Therefore, improving the accuracy of BEMT is crucial for the successful load analysis of wind turbines. For this purpose several modifications to the basic BEMT have been proposed, which include various models for wake effects, tip loss, dynamic stall, tower shadow, etc. [1].

The table used for aerodynamic coefficients in BEMT-based methods is basically correct only in uniform inflow conditions. However wind typically contains turbulent velocity components induced by various sources like complex terrains. Thus it is highly plausible that wind turbine blades can experience localized shearing wind conditions. Much severer situations can occur in modern wind farms where a highly turbulent wake stream containing strong tip vortices generated at the tips of large turbine blades can directly affect loading conditions on the neighboring wind turbines. In this situation, the accuracy of the classical BEMT can deteriorate to some extent because the shear flow effects are neglected, which can make a classical optimal design process unsuccessful in such an environment. Therefore, developing a suitable correction method for the classical BEMT accounting for the local shear flow is a very urgent issue.

In the present paper, the aerodynamic effects, especially to the lift, caused by the shear flow conditions with various relevant parameters are examined by numerical simulations and an efficient correction model describing these effects for the classical BEMT is proposed.

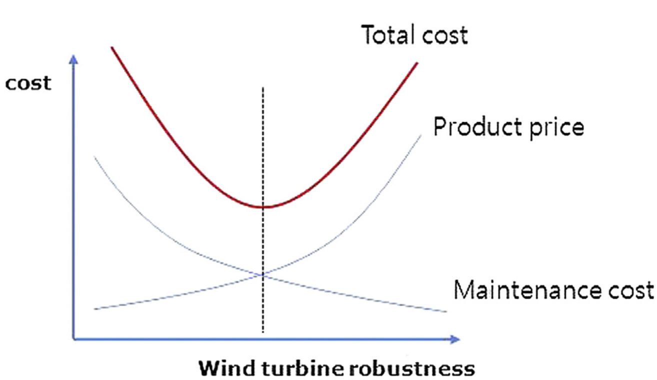

Fig. 1. Optimal design of wind turbine.

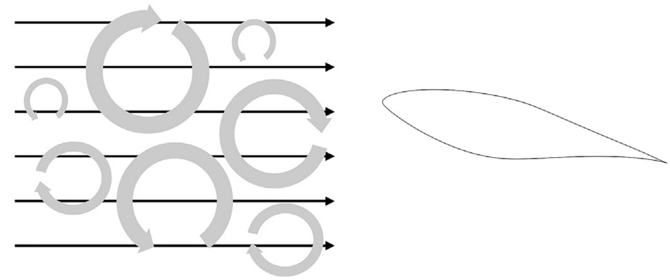

Fig. 2. Turbulent inflow around an airfoil.

2. Numerical methods

2.1. Shearing inflow condition

Turbulence is a dissipative process in which the flow structure consists of various sizes of length scales. The kinetic energy of large-scale motions is cascaded down to a smaller size in the flow structure. In this energy cascade concept, a turbulent flow is regarded as a mixture of vortices of various length scales (Fig. 2). Therefore, vortices with various sizes and strengths are common in turbulent flows. A sufficiently strong vortex has a rigid body rotating core as shown in Fig. 3, which can be generated in a turbulent flow around a complex terrain region or from the tip of a rotating wind turbine blade. The local flow around a blade in this flow field can be "locally" idealized as a simple shear flow with a constant and homogeneous vorticity, at least, instantaneously. In this study, in order to simplify the local shear flow in a turbulent flow or uniform flow coupled with a strong vortex, a simple shear flow is assumed and the aerodynamic properties of an airfoil in this field with several configurations are examined (Fig. 4).

2.2. Airfoil

In this study, S809, an airfoil dedicated to horizontal-axis wind turbine applications, is used as a test airfoil model. S809 is a laminar airfoil that was designed to achieve a restrained maximum lift coefficient and low profile drag coefficient for a Reynolds number 2×10^6. As shown in Fig. 5, S809 has a 21 percent in thickness-to-chord length ratio, and thus is rather a thick airfoil compared to airplane wings and has a negligible camber [5].

2.3. Numerical methods

Two-dimensional simulations of an airfoil are conducted with the commercial CFD software, FLUENT. In order to resolve the transition on the surface of the airfoil, the transitional SST k-w model is adopted. The second order upwind interpolation method is used for all flow variables. The residual level 1×10^{-4} is used as the criterion for solution convergence, with the additional condition that no significant variation in aerodynamic properties exists

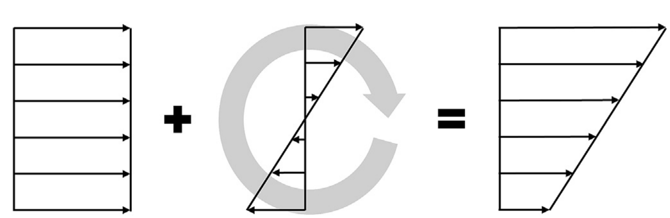

Fig. 3. Simple shear flow assumption of a uniform inflow with a nested ideal vortex.