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Improved actuator surface method for wind turbine application

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ABSTRACT

The purpose of this study was to develop an improved actuator surface model for wind turbine analyses. A new actuator surface model based on the lifting line theory has been suggested to eliminate the unexpected induced velocity due to the circulation, as well as to estimate the span-wise and chord-wise variation of the circulation of the blade. In addition, the method developed overcomes the need for tip-loss correction. A fixed wing case was used to validate the proposed method according to the reference line position and the number of chord-wise panels. Additionally, the present method has been validated against other computational results of various wind turbine cases. In this study, the over-prediction of the thrust and power coefficients at the hub and tip regions, previously observed in the existing unsteady actuator model, has been eliminated. The ambiguity concerning the location of the reference line has also been eliminated and the ad hoc tip-loss correction widely used in the legacy actuator line/surface model is no longer necessary in this method.

1. Introduction

Two major numerical techniques are used for the wind-turbine performance analysis: (1) the simple blade element method (BEM), and (2) the CFD method. The BEM is used widely for conceptual design and preliminary performance analyses of wind turbines because of its theoretical simplicity and ease of use. However, BEM has inherent limitations associated with rotor wake effects, the unsteady effect arising from the dynamic motion of the rotor blades, and viscous/flow-separation effects. More importantly, the BEM does not provide physical information for the overall flow fields [1]. However, the CFD method offers overall information of the entire flow fields, but is computationally expensive for the routine design of wind turbine blades. The actuator disk or actuator surface methods are hybridized methods for the advantages of both the BEM and the CFD methods. These methods do not require the calculation of the aerodynamic effects induced by the rotor blades in a direct manner, as required by the full CFD method. Rather, the effects of the rotor blades are replaced by a pressure discontinuity across the rotor disk in terms of the boundary conditions on the virtual rotor disk plane, or by adding source terms in the momentum equation. The actuator disk method (ADM) considers the rotor effects by setting the averaged pressure jump at the rotor disk, whereas the actuator line method (ALM) and the actuator surface method (ASM) impose the pressure jump on the exact location of the virtual rotor blades at a given azimuthal angle.

In more detail, ADM considers the rotor effects by imposing the time-averaged pressure jumps or the source terms across the rotor disk of an infinitesimal thickness in the flow domain. Recently, the ADM, coupled with the BEM, has been widely used for predicting wind turbine performance. Wu [2], Conway [3,4], Sørensen and Myken [5], Sørensen and Kock [6], and Sørensen et al. [7] have shown that ADM can be used for wind turbine analysis. Mikkelsen [8] introduced various types of ADMs, and analyzed the performance of wind turbine blades with different coning angles, adopting the source-type in a generalized ADM. Réthoré et al. [9] suggested an actuator shape model in which the rotor disk cells of the computational domain do not need to coincide with the real rotor disk area. This study employed the pressure-jump type method for handling rotor force.

In ALM and ASM, the aerodynamic effects of a rotor blade are imposed on the computational cells at the exact location of the rotor blade at a given azimuth angle. In ALM, a rotor blade is replaced with a line at which the aerodynamic effects are imposed using a Gaussian function. Unlike ADM, in both the ALM and ASM, one can readily observe the formation and propagation of the blade tip vortices, and the wake behavior is similar to that obtained from the CFD calculation. These two methods are useful in studying the wake effects of wind turbines.

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The ALM was introduced to the wind turbine community by Sørensen and Shen [10] and Mikkelsen [8]. Troldborg [11] also provided useful information on the blade wake behavior for various inflow conditions using ALM. In ALM, the reference line is usually chosen to coincide with the actuator line, because the circulation itself does not affect the velocity at the center of the circulation. Thus, the velocity obtained at the circulation center does not include a bound circulation effect. Dobrev et al. [12] introduced the concept of ASM, such that the source terms imposed on the virtual rotor-blade surface, are distributed unevenly using a simple relationship, which replicates the surface distribution of the pressure coefficient along the chord-wise direction. In his study, the flow fields around the rotor blades were divided into the global and local inflow such that the velocity components induced by the existence of the rotor blade were excluded from calculating the effective angle of attack. Shives and Crawford [13] performed a parameter study on the actuator line model using an infinite span wing, a constant circulation wing, and an elliptically loaded wing. In their study, they argued that the parametric ε in Gaussian function should be chosen from a physical turbine length, that is, the chord length, because the velocity induced along the actuator line is not zero. For this method, the reference line should be set sufficiently far apart from the rotor blade. Shen et al. [14] attempted to improve the modeling of the surface pressure coefficient. However, he still used a reference line at 1–2 chord-lengths away from the blade leading edge, as in previous studies. Masson and Watters [15] calculated the effective angle of attack based on the relationship between the circulation and velocities on the blade surface. However, this technique has a shortcoming, in that, the relationship derived for the velocity change on the blade surface is rather arbitrary. It also has the disadvantage that the calculations of the flow field and the induced velocities from CFD have to be conducted simultaneously. Recently, Kim and Park [16] performed a thorough numerical analysis of the helicopter rotor problem using ASM. In this study, the induced velocities were obtained by averaging the velocities on the surface of the virtual blades. To avoid any effects induced by the existence of the rotor blade, the velocities in the specific region around the blade leading edge were excluded in calculation of average velocity.

As found in previous studies, one of the most ambiguous steps in ASM is to set the location of the reference line, for obtaining the induced velocities. It should be noted that the velocity components obtained from CFD calculations include not only the induced velocities due to the trailed and shed vortices but also the velocity components induced by the bound circulation on the rotor blades. When the reference line is too far away from the blade, it tends to yield relatively low induced velocities. On the other hand, when it is too close, it is difficult to separate the induced velocities due to the tip vortex from that of the bound circulation on the blade. There have been various attempts to eliminate the arbitrariness in setting the location of the reference line, but there is still some ambiguity on this issue.

Similar technical difficulties exist in ALM. As observed by Troldborg et al. [17], the sectional forces of the wind turbine blades – both normal and tangential – tend to be overestimated at both the rotor hub and tip regions, and the reason remains unclear. Accordingly, the aerodynamic performance capability of ALM is considered less reliable compared to the full CFD method.

In the present study, a novel method is suggested to eliminate the arbitrariness of setting the location of the reference line in ASM, and to eliminate the effects due to the bound circulation on the blades for calculating the induced velocities. This study also provides a method to avoid the overestimation of the normal/tangential forces at the hub and tip based on the assumption that the overprediction of the forces might arise from ignoring the span-wise variation of the circulation. This assumption was adopted in the work of Kim and Park [16], where the span-wise velocity variation on the wing surface induced by the source terms was taken into account, yielding a good agreement with the experimental results. This study also suggests the ASM that does not require tip-loss correction.

For this purpose, a novel ASM, based on the lifting line theory has been developed so that the new method eliminates the undesirable velocity induced by the bound circulation and allows estimation of the span-wise variation of the circulation. As it will be shown, the present method eliminates the need for a tip-loss correction because the tip-loss effect is already considered in the lifting line theory.

The present method has been validated using a performance analysis of a fixed wing and 5 MW/10 MW wind turbines. This process showed that the present method can successfully eliminate the need for the tip-loss correction and can solve the problem of overestimation of normal/horizontal forces at the root and tip regions. More importantly, the verification cases are performed to demonstrate that the technical ambiguity in setting the location of the reference line in ASM is eliminated, manifested by the coincidence of the induced velocities at different reference line locations.

An improved actuator surface model based on the BEM that accounts for the aerodynamic effects of the wind turbine is presented in the following sections. The OpenFOAM CFD code for the platform to integrate the actuator surface model adopted, and introduced in Section 2.1. Moreover, the existing solver has been modified to handle the rotor effects. Section 2.2 explains the actuator surface model integrated with the CFD code, and Section 2.3 introduces the BEM. Section 2.4 explains how the improved method obtains the relatively velocities of ASM.

2. Materials and methods

2.1. Numerical analysis algorithm of OpenFOAM

The merged PISO-SIMPLE (PIMPLE) algorithm was used for transient simulations. The Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) algorithm was used to calculate the pressure on a staggered grid from velocity components by applying an iterative procedure coupled with the Navier–Stokes equations [18]. The PIMPLE algorithm, which is combined with the SIMPLE algorithm, uses the Pressure Implicit with Splitting the Operators (PISO) algorithm to rectify the second pressure correction, and corrects both the velocities and the pressure explicitly [18,19]. The incompressible solver in OpenFOAM was developed by Jasak [20].

2.2. Extension to handle rotor force

To incorporate the effects of the rotor in the CFD analysis, the grid should be generated to match the shape of the rotor blades and should be rotated in the computational domain to calculate the thrust. However, this CFD calculation requires a considerable amount of computational resources to process the numerous nodes in the grid system and to rotate the grid. One practical solution to overcome such difficulties in the CFD analysis is the use of the actuator surface model. This imports the aerodynamic effects of the rotor in a simpler way, through the import of the blade element model to the CFD algorithm, instead of directly calculating the rotor in the same CFD analysis.

This research provides the local aerodynamic coefficients using the blade element model, calculates the time-marching thrust on the blade cell, and embeds the thrust value as a source term into the momentum equation to account for the rotor effects in the CFD analysis. Fig. 1 illustrates the two methods that handle the boundary conditions and the additional source terms that have