Implementation and Testing of Actuator surface Modelling in OpenFoam

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Abstract

Actuator Line Model (ALM) is mainly used for modelling wind turbines in a wind park. However, the ALM is unable to resolve the detailed geometrical features of turbine blades on a mesh. To alleviate this problem, Actuator Surface Models (ASM) for turbine blades, which take into account more geometrical details, have been proposed. In the present paper, the method developed by Yang and Sotiropoulos (Journal of Fluid Mechanics 744 (2014): 376-403) has been implemented in PisoFoam. An unsteady PisoFoam solver is modified to account for wind turbines, where each turbine is modelled as a sink term in the momentum equation. The modelling of the turbine is based on an actuator surface concept, where the turbine blades are represented as a surface. The loads on each surface of the turbine are estimated using the Blade Element Method (BEM). The inputs for the solver include tabulated airfoil aerodynamic data, wind turbine dimensions, wind magnitude, turbulence intensity, and direction. Preliminary results are presented and discussed. The model will be validated with available literature data.

Introduction:

A full CFD method (resolving wind turbines on the grid scales), compared to the widely used approach based on Blade Element Method (BEM), are much more advanced and provide more detailed information of the entire flow fields. However, these advanced CFD methods are computationally demanding and almost impossible to apply in the design and optimization of wind farms and park control. To overcome these challenges, a method based on combing CFD and BEM have been developed [1–4]. In this coupled method, the wind turbines are not resolved on the grid, but the effect of turbines on the flow field is modelled. This effect is modelled either using actuator disk method (ADM) or actuator line method (ALM). In ADM, each turbine is assumed to be a porous disk and the forces acting on the wind turbine are estimated from thrust coefficients and incoming wind velocities. In ALM, the forces acting on a turbine is calculated assuming each blade as a line and the forces are calculated using BEM approach in which both drag and lift coefficients of the foils are used. The actuator line model can incorporate rotational effects, tip loses, 3D stall effects, and the effect of non-uniform force distribution in the azimuthal direction. Despite these advantages, there are two major limitations with the standard ALM: i) The lack of an effective nacelle model, and ii) A finer mesh (i.e. Large Eddy Simulation) cannot resolve more geometrical features of the turbine blade. Yang et al. [7] have shown that grid-independent results cannot be obtained when the mesh is refined in the ALM simulations. To overcome these challenges, Actuator Surface Model (ASM) has been developed by many previous researchers [1–4]. In the proposed work, ASM has been implemented. The theory and implementation strategy are described in next sections.

Implementation of approach:

The turbines are modelled as a sink term in momentum equation and this is described by following generalized N-S equation.

$$\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{p}_i}{\partial x_i} + \frac{\partial \tau_i}{\partial x_j} + S \quad (1)$$

Where ρ is the density, u is the flow velocity, $\boldsymbol{\tau}$ is the shear stress, x_i, x_j are the directions, and p is the pressure. The source term (S) in the momentum equation can be estimated either by ADM, ALM or ASM. Here we will estimate source term based on ASM. The method implemented in OpenFoam is based on the approach developed by Yang and Sotiropoulos [2]. They assumed that the blade geometry can be represented by a surface formed by the chord lines at different radial locations of a blade as shown in Figure 1. The forces are calculated on each chord line using BEM. In the present paper, a brief description of the approach is discussed. For more details please refer to the paper by Yang and Sotiropoulos [2]

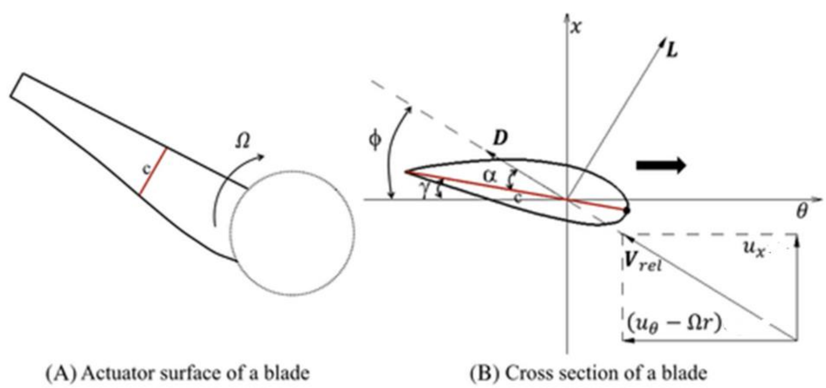

Figure 1: Schematic representation of a turbine blade cross-sectional view of the blade airfoil (image based on Yang and Sotiropoulos [2])

The local angle of attack (α) shown in Figure 1B is computed at each radial location from the u_x, u_t and twist angle ($\boldsymbol{\gamma}$).

$$\alpha = tan^{-1}\left(\frac{u_x}{u_t}\right) - \gamma \quad (2)$$

Based on the local angle of attack and relative velocity, the lift (L) and drag (D) forces per unit span are calculated.

$$\boldsymbol{L = \frac{1}{2} C_l(\alpha)\rho V_{rel}^2 c} \quad 3$$

$$\boldsymbol{D = \frac{1}{2} C_D(\alpha)\rho V_{rel}^2 c} \quad 4$$

where C_L and C_D are the lift and drag coefficients, and c is the chord length. The C_L and C_D are functions of the Reynolds number and the angle of attack. The fluid velocity relative to the blade, $V_{rel} = \sqrt{u_x^2 + u_t^2}$ is decomposed into a axial $u_x$component and a tangential component $u_t = u_\theta - \Omega r$. These velocity components (u_x and u_t) are averaged over the chord for every radial locations, which are computed using

$$u_x = \frac{1}{c}\int_c u(X)ds \quad 5$$

$$u_\theta = \frac{1}{c}\int_c u(X)ds \quad 6$$

where **X** denotes the coordinates of the grid points on the actuator surfaces. Since the grid on the actuator surfaces (X) does not coincide with the computational domain grid (x), therefore following model is used for calculating the velocity.

$$u(X) = \sum_{x\in gx} u(x)\delta_h(x - X)V(x) \quad 7$$

where x is the coordinates of background nodes, gx is grid points associated with the turbine blades. A smoothed discrete delta function (δ_h) proposed by Yang et al [5] is employed to estimated velocities at actuator surface from the values on the background grid nodes as follows.

Stall delay phenomena of the blade increase the lift coefficients and decrease the drag coefficients as compared with the corresponding two-dimensional airfoil data. To account for such three-dimensional effect, the stall delay model developed by Du and Selig[6] have been implemented. For a detailed description please refer to the original publication. Tip-loss corrections have also been implemented. The blade forces($\boldsymbol{f_i^B}(X)$) acting on the blade surfaces is calculated using velocities and corrected airfoil data. These blade forces are transferred on the background mesh as a source term ($\boldsymbol{S(x)}$) using the following function as described earlier.

$$S(x) = \sum_{X\in gX} f_i^B(X)\delta_h(x - X)A(x) \quad 8$$

where gX is the set of the actuator surface grid cells and A is the area of the actuator surface grid cell. An earlier developed solver, OffWindSolver[7], based on ALM was modified to account for ASM.

Results and discussions:

The approach is verified by comparing the present ASM results with SOWFA result [8]. SOWFA (Simulator fOr Wind Farm Applications) is a set of computational fluid dynamics (CFD) solvers, boundary conditions, and turbine models based on the OpenFOAM CFD toolbox. A CFD simulation of single NREL 5MW turbine was performed. The inlet velocity was set to 8 m/s with 6% turbulence intensity. The axial deficit velocity profiles calculated using ASM approach is compared with the SOWFA results and shown in Figure 2. It is to be noted that SOWFA is based on LES and ALM approach. The current approach is based on RANS and ASM. These are preliminary results and the work is under progress. Detailed results and comparison will be discussed later.

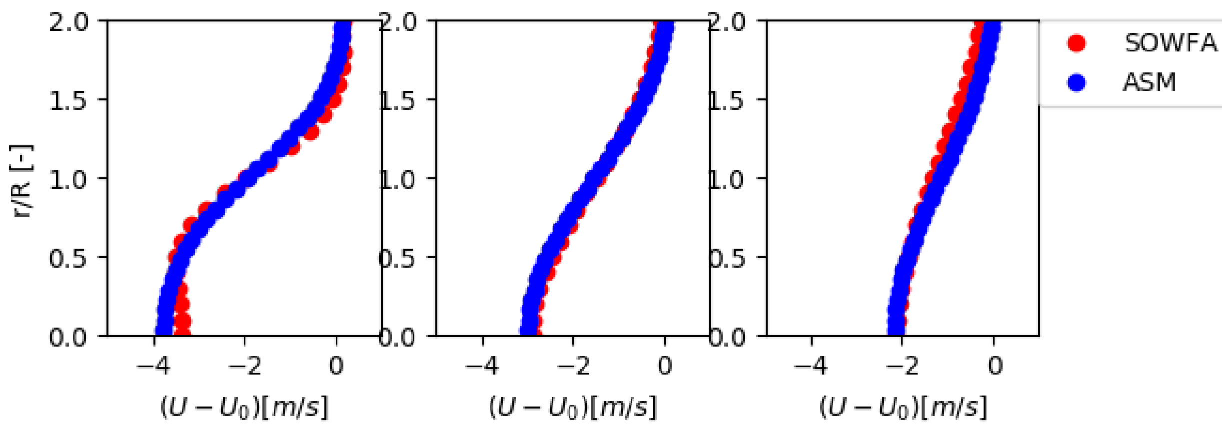

Figure 2: Radial profiles of axial velocity deficits at 2D, 4D and 6D downstream of the wind turbine for the wind velocity of 8m/s and turbulence intensity of 6%

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