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WIND FIELD SIMULATION IN A WIND FARM USING OPENFOAM AND ACTUATOR LINE MODEL

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Abstract. In this study, a horizontal axis wind turbine (HAWT) is modeled using so called *Actuator Line Model* (ALM), where full resolution of boundary layer over turbine blades is not needed and hence computation is cheaper. Results are validated against other numerical and experimental studies as well as panel method (XFOIL) and Blade Element Momentum Theory (BEMT) results which are still widely employed in today's wind energy industry. Important simulation and operation parameters and their effects on accuracy are discussed. It is concluded that within a certain range of tip speed ratios, ALM gives acceptable results and is a promising model for full-scale wind farm simulations to estimate energy production.

1 INTRODUCTION

Market share of renewable energy grows at ever highest rates and wind turbine and wind farm design processes becomes more sophisticated with the advancements in computation technologies. There are two main design problems in wind energy:

- Design of an individual wind turbine at its ideal operation conditions, where classical methods like 2D airfoil theory, potential flow theory and Blade Element Momentum Theory (BEMT) are still widely used,
- Design of a complete wind farm, in which statistical meteorological data is used for macro-siting and simple analytical or empirical methods are used for micro-siting.

Accurate air flow-turbine blade interaction is important for a good estimation of turbine performance and wake simulation. On the other hand, optimal positioning of turbines on the field depends on the proper wake calculation, since wake deficit is the primary cause of power loss even in ideal operation conditions. Considering length scales of blade boundary layer and wake propagation are $10^{-3}m$ and $10^{3}m$ respectively, wind farm design becomes a challenging numerical problem where those wide range of length (and hence time) scales need to be resolved. Actuator Line Model (ALM) adopts a computationally cheaper approach, where boundary layer resolution (hence dramatic increase in grid size) is avoided. Blades are introduced into the flow domain as virtual lines, consisting of a predefined number of ‘blade elements‘, which acts as moving body force sources. In this study, ALM's trade-off between inexpensiveness and loss of accuracy is examined by comparing its results to other numerical and experimental data, as well as results proposed by other researchers.

2 METHODOLOGY

`OpenFOAM` **:** `OpenFOAM` is an open source CFD code which has various customizable flow solvers as well as preprocessing (`blockMesh` and `snappyHexMesh` are used for mesh generation) and postprocessing (`paraFoam - ParaView` are used for visualization) utilities. It employs finite volume approach in spatial discretization and is capable of running in parallel. Incompressible and unsteady flow solver `pimpleFoam` is used, which is a combination of PISO (*Pressure Implicit with Splitting of Operator*) and SIMPLE (*Semi-Implicit Method for Pressure-Linked Equations*) algorithms [4]. In this study, transient, incompressible Navier-Stokes equations are solved with Large Eddy Simulation (Smagorinsky SGS) turbulence model:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot (\nu \nabla \mathbf{u}) + \mathbf{f} \tag{2}$$

where $\mathbf{u}$: velocity vector, p: pressure per density, ν: kinematic viscosity and f is the body force per density per volume. `OpenFOAM` is used for mesh generation and solution. Actuator Line Model (ALM) is implemented by use of `turbinesfoam` library. NREL's 5MW horizontal axis wind turbine (HAWT) has been chosen as the sample turbine.

Actuator Line Model and `turbinesfoam` : In ALM, wind turbine blades are introduced into the flow field not as solid boundaries in the classical sense, but as virtual lines which has calculated lift-drag forces distributed along them [1]. Blades are divided into a number of elements of constant sections. Each element has its airfoil section, chord, span and twist. A local 2D Lift-Drag calculation is done on each element by use of relative velocity and angle of attack at the quarter chord position, which are calculated iteratively at each time step. Resultant force calculated at the mid-span is then distributed among the cell centers in the vicinity, via $\mathbf{f}$ term in (2). Distribution is in the form of a normal distribution to prevent singular unstable behavior. This functionality is implemented by `turbinesfoam` , which is an ALM extension library for `OpenFOAM` [2].

Blade Element Momentum Theory: BEMT is a widely used wind turbine performance assesment method in industry. An open source software *QBlade*, which employs XFOIL [3] for 2D airfoil calculations. It is used for performance comparisons.

3 RESULTS and DISCUSSION

The mesh consists of a single block, where domain span is $(-15D, 5D)$ in x-direction and $(-5D, 5D)$ in y and z-directions. Free stream conditions are applied at outer boundaries. Grid size varies from case to case; for instance, cell size is refined through 5 levels (halved at each one) from $36m$ at farfield to $1.125m$ at turbine rotor (corresponding to 56 cells within turbine radius) for $TSR = 8$ case (Figure 1).

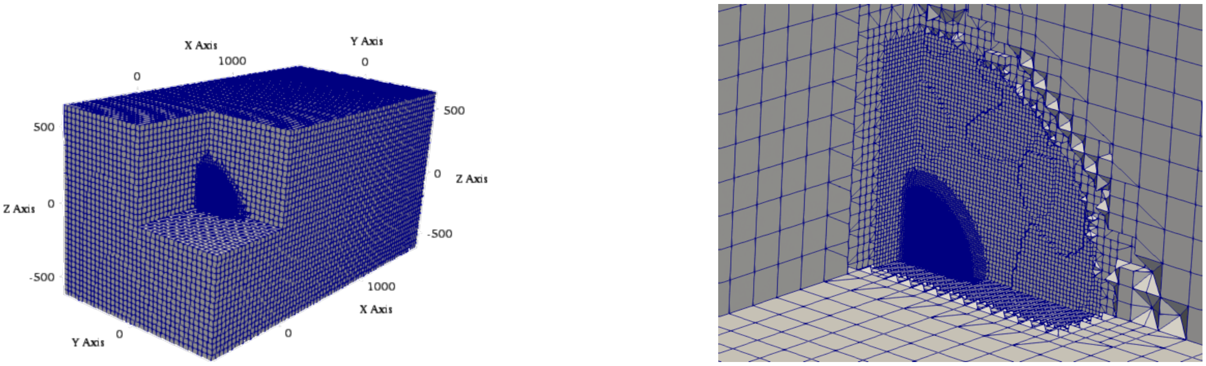

Figure 1: Mesh, clipped (left) and rotor region zoomed (right)

The NREL 5MW HAWT is $126m$ in diameter, has 3 blades and rated at $U_\infty = 11.4m/s$ and $TSR = 7$. Power and thrust coefficients, given as $C_P = P/(0.5\rho U_\infty^3 A_d)$ and $C_T = T/(0.5\rho U_\infty^2 A_d)$ respectively (where A_d is the area swept by blades), are calculated for tip speed ratio ($TSR = U_{tip}/U_\infty$) values from 1 to 10.

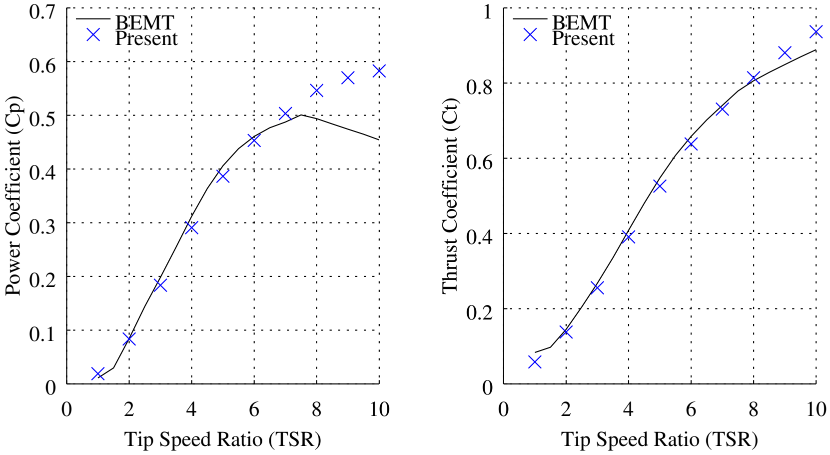

Figure 2: Calculated power and thrust coefficients compared against BEMT results

For TSR values up to 7, C_P and C_T calculated by ALM is in close agreement with BEMT, whereas ALM fails to capture peak C_P at $TSR = 7$ and overestimates at larger TSRs. Blade loading is also plotted and compared to BEMT results.

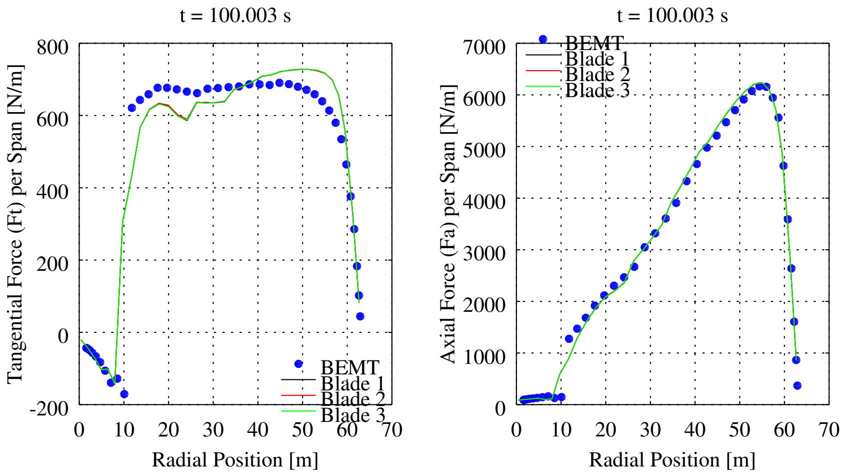

Figure 3: Forces exerted on blades, compared to BEMT results

Tangential (in rotor plane) and axial (normal to rotor plane) force distributions along blade span shows close agreement with BEMT results. However, tangential force is overestimated towards the blade tip in ALM. This might be a result of tip vortices not being resolved by solid boundaries but instead modeled with tip loss functions.

4 CONCLUSIONS

- Turbine performance (power and thrust) estimation by ALM is acceptable for small to mid range TSR values.
- Tip loss functions play a critical role in ALM.

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