A Large Eddy Simulation framework for Industrial Wind Farm Aerodynamics

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ABSTRACT EWEA 2015

Aim

This abstract describes a new Large Eddy Simulation (LES) framework for industrial applications, called the Energy-Conserving Navier-Stokes (ECNS)-LES solver. The Energy research Centre of the Netherlands (ECN) is developing the ECNS-LES to help improve its existing and known Engineering model (EM), FARMFLOW.

Introduction

Wind farm aerodynamics (WFA) is the study of how wind turbine wakes interact with the atmospheric boundary layer (ABL), downstream turbines and possibly with each other, as they develop over the length of a wind farm. The velocity field provides insight into the power that is available, how much the turbines extract and to what extent do their wakes recover. Nowadays, WFA could also help predict the effect of wind farms on local weather. It is important to note that WFA does not concern how the turbines extract energy from the wind as that is a different area called rotor aerodynamics. However, WFA does rely a on simple and sensible representation of the wind turbines in a manner that is accurate enough to predict the large scale effects of the turbines and particularly, in a region that is beyond the near wake of the turbine, where the wake begins to recover.

Approach

WFA essentially involves processing aerodynamic data that can simply be gathered from existing wind farms. However, in this manner, it cannot be used for a pre-deployment analysis of a new wind farm. Therefore, numerical studies are the obvious solution. Currently, the industry relies of simple EMs based on basic principles of physics and tuned using experimental observations for WFA. Although speed and accuracy with regards to predicting statistics averaged over a long duration and an array of wind directions is a benefit, the simplicity precludes any analysis of phenomena like wake-meandering, effects of gusts etc., and also the prediction of local flow variables with high accuracy. Given the importance of wind power in the future, it is wise to switch to numerical models that encompass first-principle physics to a greater extent than EMs.

A first-principle physics-based model that over the last few decades has been very contributory to the understanding of WFA, is LES. Numerical frameworks for WFA include the JHU-LES code of the Johns Hopkins University, the KULeuven code of the University of Leuven, the EllipSys3D code of the

Technical University of Denmark, to name a few. Although studies with these codes have been fruitful, they are yet to find their way into industrial applications due to factors like computational requirements and the highly detailed modelling involved. In short, LES is the other end of the spectrum of which, EMs are the simplest models.

However, as is the case with every numerical method, certain modifications to the practice of LES can adapt if for industrial WFA. Although one cannot expect an LES code to be as quick as an EM, it can certainly help propose modifications and reduced-order models to complement EMs.

Main body

LES by design, is most relevant to WFA because it resolves only the large energy-containing scales of a flow field. These large scales in an ABL are comparable to in size to a wind turbine's rotor and bigger than the same, setting a limit on the spatial resolution actually required. Predicting the behaviour of these scales correctly is hence, sufficient. One can divide an LES framework for WFA into four components,

- A numerical scheme for spatial discretisation that should have very low numerical dissipation even on relatively coarse grids, which could lead to spurious and quicker recovery of wakes.
- A time integration scheme that is stable and accurate even with large time steps and does not introduce numerical dissipation through time advancement, which is also known to have a significant effect on the flow's development.
- A subgrid scale (SGS) model that correctly reproduces the interactions between the large scales being resolved and the small scales that are being modelled and missing from the actual computations.
- A model for the wind turbines capable of predicting the macroscopic effect of the turbines' presence in terms of the correct velocity deficit and turbulence intensity beyond the turbine's near wake. The possible options are the actuator disk (AD), actuator disk with rotation (ADR) and the actuator line (AL), in increasing order of accuracy. The AL requires a finer time step to account for the blades' movement and hence, is computationally demanding. Existing literature suggests using the simpler AD models for the LES of WFA.

With regards to numerical schemes, the ECNS uses a Finite Volume Method (FVM) based on a uniform and staggered Cartesian grid called an energy-conserving (EC) discretisation. For an inviscid and incompressible flow within periodic boundaries and in the absence of body forces, an EC discretisation leads to no change in the flow's kinetic energy (KE), which is an invariant property of such flows. This in the context of a real flow ensures the absence of numerical dissipation. Although the pseudo-spectral (PS) that are common in academic, are more accurate, the FVMs can be adapted for complex geometries and permit grid refinement around important areas. Also, the ECNS is designed for industrial applications that may include analyses on wind farms placed on and near hills, wherein the ability to account for surface inhomogeneities is a must.

In terms of time integration, we noticed that statistics such as turbulence intensity require a fairly high sampling rate for accuracy. Thus, the time step for simulations is low and quite conservative with regards to numerical dissipation through time integration. In such a situation, an explicit but non-EC time method is also capable of producing accurate results and especially with very little computational effort. However, is one wishes to simulate a larger time step, one could use the implicit EC methods that are stable and highly accurate but as a drawback, demand excessive computational effort even with large time steps therefore, nullifying the advantage an implicit method offers in general.

In terms of SGS modelling, the possible options include the Smagorinsky model (SM) or the Modulated Gradient model (MG) and their dynamic or scale-dependent dynamic formulations. For FVM methods, the SM seems to be the best option due to its simplicity, flexibility with tuning and adaptability in terms of advanced dynamic and scale-dependent dynamic SGS modelling. Further, it does not require explicit filtering, which is more suitable and easily done with PS methods. With suitable modification, the SM can also account for the presence of the ground. After tuning the SM through a series of test cases, the ECNS-LES was able to predict the decay of isotropic turbulence, the statistics of a neutral ABL and fares well in a test involving the comparison with other LES codes against data from a wind tunnel experiment.

Conclusion

A comparative analysis with other LES codes revealed that the ECNS-LES-AD framework is suitable for WFA. Although not as accurate as a PS scheme, the EC discretisation helps minimise numerical dissipation and appears to be a fine alternative. Further, an EC implicit time integration scheme offers an advantage in terms of stability and accuracy, when computational costs are not the limiting factor. Tuning the SM to correctly model a neutral-ABL while relying on a wall model for the ground can serve as an alternative to more advanced SGS models used in academia. However, one must also explore the modulated gradient model as it is suitable for FVMs due to the absence of explicit filtering. Finally, one can use the AD and ADR methods that are simple and accurate, but should one require detailed near wake statistics, the AL is a fine approach but again with added computational costs.

Learning Objectives

This study was centred around using the collective knowledge from academia and industry, to develop an advanced computational tool for the industry. On the one hand, it revealed how simple models and schemes can be combined and tuned for industrial applications and yet be accurate enough in terms of averaged statistics. On the other, it provides ample opportunities for using the ECNS to develop reduced-order models for EMs, modifying the ECNS to account for changes in surface topology, atmospheric stability etc.

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