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Large eddy simulation of turbine loading and performance in a wind farm

R.C. Storey [a], J.E. Cater [a], S.E. Norris [b], *

[a] Department of Engineering Science, University of Auckland, 70 Symonds St, Auckland 1010, New Zealand
[b] Department of Mechanical Engineering, University of Auckland, 20 Symonds St, Auckland 1010, New Zealand

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ABSTRACT

We investigate multiple wind turbines operating in a small turbine array using a coupled LES/aero-elastic method. Wake interaction effects are assessed for multiple wind-speeds, with performance of the wind farm quantified, including measurement of efficiency, controller utilisation and loading effects. Power losses are shown to peak at over 40% for the full-wake case, with increased power fluctuation and control actuator usage noted at downwind turbine locations. Spectral analysis of the wake indicates a broad peak meandering frequency. Dynamic yaw control has also been included in the simulations – a first for LES simulation of wind farms – with significant yaw actuation observed due to local wind direction changes despite a constant global wind direction.

1. Introduction

With cost a central factor in the development of wind power projects, accurate predictions of wind farm performance are required to secure site locations and funding [1]. The aerodynamic considerations of a single turbine involve not only the prediction of local fluid forces, but also the onset flow conditions. This is especially important for locations where the free-stream flow upwind of a turbine is affected by neighbouring turbine wakes [2]. This scenario is common where groups of turbines are arranged to utilise available land and regions with high wind resources [3]. Regular arrays of turbines are particularly common in offshore installations, leading to turbine wake interaction regardless of wind direction.

Turbine wake regions are characterised by a velocity deficit and increased turbulence intensities, and can have a significant effect on turbine farm operation with decreased power output, and increased fatigue loading of machines [4]. Observations by Neustadter [5] and Barthelmie et al. [6] suggest that wake related losses can reduce a wind farm's average power output by 10%. Numerical studies by Porté-Agel et al. [7], and the observations of Hansen et al. [8] indicate that these losses can peak at over 40% for a single wind direction. Increased fluctuations in power output and turbine loads can be significant in some conditions, which has also been observed in measured data [6]. Accurate prediction of wind farm performance and turbine loading therefore requires wake effects to be taken into account.

Numerical modelling of wind farms has become a viable tool with the development of modelling techniques and increasing computational power. Large eddy simulation (LES) has shown the potential to accurately model atmospheric flows, and has been successfully implemented in conjunction with actuator models of wind turbines for modelling wakes [9–11]. Despite LES offering unsteady flow solutions, previous implementations have focused on turbine rotors in a pre-determined, steady operating state. This often limits current methods to turbines operating in below-rated conditions where pitch control is not required [12]. As turbine loads are often observed to peak at the turbine's rated wind-speed [13], this can prevent the use of these models to examine peak loads.

Actuator methods have also demonstrated the ability to model time-dependent loading on turbine rotors. In the work of Masson et al. [14], an actuator disc method was demonstrated to correctly predict trends in both power output and bending moment, of a blade undergoing step changes in pitch angle. Sørensen and Kock [15] also presented results with good agreement to experimental data of unsteady loads.

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* Corresponding author.
E-mail address: s.norris@auckland.ac.nz (S.E. Norris).

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Other transient processes, such as wake meandering, have been cited as an important feature of turbine wake flows, where large oscillations of a turbines wake region can occur in certain conditions [16]. Meandering has been studied using field measurements and modelling techniques by Larsen et al. [17], where the model uses a passive tracer analogy to represent the movement of the wake region [18]. These low frequency fluctuations are expected to influence the recovery of velocity deficits in the wake, as well as downstream wind conditions incident on other turbines. Shortcomings in the comparison of steady state wake models with measured data are often attributed to this phenomena not being modelled.

This research aims to utilise a coupled, multi-physics wind turbine modelling methodology to study the transient performance of a wind turbines operating in a wind farm environment. The coupled model will allow for the detailed analysis of the wind turbine state as well as the wind environment and wake over a range of wind conditions including above-rated wind speeds. We aim to study wake interaction effects, quantify loads, and study overall farm performance. Insight into the flow through a turbine array will allow for the investigation of complex interaction effects which are not able to be studied using field measurements.

2. Methodology

2.1. Flow solver

The SnS CFD code was originally developed at the University of Sydney and the University of Auckland [19,20] for modelling convective and channel flows, and offers a suitable basis for the development of efficient simulation tools. The code uses a structured, Cartesian, non-staggered mesh and a fractional step method being used to solve the transient, filtered Navier-Stokes and continuity equations given by,

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j^2} + f_i, \quad \text{and} \quad \frac{\partial \tilde{u}_i}{\partial x_i} = 0. \tag{1}$$

In this method, the advective components are discretised in time using the Adams-Bashforth scheme and the diffusive components are discretised using the Crank-Nicolson scheme. Both the advective and diffusive components of the momentum equations are discretised in space using second-order central differencing, resulting in second-order temporal and spatial accuracy. A Jacobi method is used to solve the velocity equation, while pressure is solved for using a bi-conjugate gradient stabilised (BiCGSTAB) method [21] with the strongly implicit procedure (SIP) of Stone [22] being used as a preconditioner. Both velocity and pressure systems are solved with a tolerance of 10^{-6} for all simulations.

Rhie-Chow interpolation is used to prevent decoupling of the pressure and momentum equation [23]. Turbulence is simulated using LES in conjunction with the Smagorinsky sub-grid scale (SGS) model [24], with a model coefficient of 0.18. Wall effects are included with the near wall damping model of Mason and Thompson [25] and a rough wall function [26].

The code has been parallelised using the message passing interface (MPI) for efficient scalable operation on distributed memory systems. This is important for simulation of large computational domains with multiple turbines by allowing the use of the large computing cluster facility available at the University of Auckland [27].

2.2. Wind turbine modelling

The turbines are modelled using an optimised actuator line method, or the 'actuator sector method', detailed by Storey et al. [28]. The actuator method is coupled to an aero-elastic wind-turbine modelling code, FAST, for the prediction of wind turbine performance, loading and control response. FAST (fatigue, aerodynamics, structures and turbulence) is an aero-elastic simulation code developed at the National Renewable Energy Laboratory (NREL) to model horizontal axis wind turbines [29,30]. The code combines aerodynamic and structural analyses in conjunction with control models to simulate turbine performance. The aerodynamic section of the FAST code, AeroDyn, uses tabulated aerofoil data in conjunction with the turbine state and local angle of attack to determine lift and drag, and subsequently thrust and torque values at radial blade locations.

FAST models the dynamic operation of the wind turbine, where the rotor speed is calculated using the rotor torque, generator torque and rotor moment of inertia. A control system is also modelled, which can execute control actions such as blade pitching, rotor yaw and the variation of generator torque. A dynamic stall model [31] is also used to model unsteady effects on blade aerodynamics. The turbine is modelled as a rigid structure as the actuator model does not account for blade deflection. In the coupled configuration, the LES solves for the induced velocities at the turbine rotor as well as the turbine wake. The resulting coupled system thus models both the induced wind velocities, the wind turbine wake, as well as the turbine performance such as power output, control parameters, loading and structural response.

Fig. 1 illustrates the basic coupling interaction between the LES code and FAST, with further detail of the FAST code and the coupling implementation are given in a previous publication [32]. The information shared between the systems (illustrated in red in Fig. 1) includes wind velocities sampled from the CFD domain at the blade locations and an array of blade element forces from FAST. The system was designed to interface with multiple concurrent, independently controlled wind turbines within one CFD domain. This requires a separate FAST process and associated communication infrastructure for each turbine simulated. This creates a flexible system with the capability of multiple turbines even when executed on multiple computational nodes on distributed computing platforms.

Using an actuator model to represent the wind turbine, the sectional aerodynamic loads generated at the turbine blades, $\vec{\ell}_b(r)$, are included in the momentum equations solved in the rotor region. The loads, expressed as a force per unit length, can be defined in a turbine based coordinate system as,

$$t_b(r) = \vec{\ell}_b(r)\cdot\vec{e}_x \quad \text{and} \quad q_b(r) = \vec{\ell}_b(r)\cdot\vec{e}_\theta, \tag{2}$$

where $t_b(r)$ are the thrust loads and $q_b(r)$ are the tangential loads on a particular turbine blade, b, as a function radius, r. $\vec{e}_x$ is the unit vector defined as normal to the rotor plane in the flow direction, and $\vec{e}_\theta$ is the unit vector, lying on the rotor plane, that is normal to the blade azimuth angle in the direction of blade rotation.

The actuator sector method builds on the methodology of an actuator line method (see e.g. Sorensen and Shen [33] and Troldborg [34]), however, rather than forces being mapped into a line, the actuation region is based on the swept area of a blade. This is related to the speed of the blade and the simulation time-step. This removes the restrictive time-stepping condition of the actuator line method where a Courant number limit, based on the rotor tip speed, requires a small time-step for the accurate representation of the rotor, therefore reducing the computational expense of the simulation [28].

The total thrust on the rotor is therefore given by,