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A fast reduced order method for assessment of wind farm layouts

Yngve Heggelund[a,*], Chad Jarvis[a], Marwan Khalil[b]

[a]*Christian Michelsen Reseach AS, NO-5892 Bergen, Norway*
[b]*GexCon AS, NO-5892 Bergen, Norway*

Abstract

Due to wake losses, the power production of wind farms depend on the positioning of turbines in relation to each other, i.e. the wind farm layout. Computational Fluid Dynamics (CFD) can be used for solving the complex flow in a wind farm since wake effects are inherently simulated. However, it is too slow for interactively assessing the power production for variations of wind farm layouts. Therefore, there is a need for an accurate and fast model based on CFD for computing the flow field and the wake losses in a wind farm for a range of wind speeds and wind directions. In this paper, we adapt model reduction methodology to wind farm flow. The governing equations are formulated in a reduced finite dimensional space spanned by a set of orthogonal modes created from CFD simulations. The accuracy of the reduced model is assessed on a set of test cases. In the reduced model, new solutions for different turbine layouts and wind speeds are produced in a matter of seconds, as opposed to hours for full CFD simulations.

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1. Introduction

Offshore wind power is increasingly becoming more important as a renewable energy source and large investments in offshore wind farm projects are expected in near future.

Power losses from wakes in wind farms are difficult to predict, and the impact on power production from underestimation of the wake effect has been estimated to be in the region of 5-10% [1]. There is a need for fast and

* Corresponding author. Tel.: +47 917 97 224; fax: +47 55 57 40 41.
E-mail address: yngve@cmr.no

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accurate methods for evaluation of power production to enable interactive design and optimization of wind farm layouts.

This study uses the power production as the layout design parameter, where layout refers to the number and positioning of turbines within the wind farm area. There are clearly other parameters to consider such as fatigue loads, sea bed conditions and the electrical system, but the power production is considered the dominant layout design parameter [2].

The current state-of-the-art is to use simplified models for the turbine wakes since they are computationally fast. Many different wake models exist and are in use in commercial wind resource software such as WaSP (www.wasp.dk), WindPro (www.emd.dk/WindPRO) and GH WindFarmer (www.gl-garradhassan.com). The Jensen model [3] is probably the first wake model proposed. The model is based on a linear expansion of the wake region, and mass conservation. Since then, several other simplified models have been introduced. For example, the Frandsen model [4] and the Ainslie model [5]. Studies have been performed comparing many of these wake models in an offshore setting (see for example [6]). From these studies, no particular model seems to outperform the other models. In large wind farms, these wake models appear to under-predict wake losses [7].

Computational Fluid Dynamics (CFD) is a powerful tool, which can be used for solving the complex flow in a wind farm since wake effects are inherently simulated. CFD is, however, computationally expensive, which makes it unsuitable in an interactive design tool where the user expects fast response. This leads to the investigation of alternative CFD based techniques for solving the wind farm flow. Fuga [8] is a promising linearized CFD model for offshore wind farms. The model performs several orders of magnitude faster than the standard CFD simulation. However, since it is linearized it is not clear that it captures all the necessary physics of the flow in a wind farm.

The approach investigated here is a CFD based approach using a model reduction technique of the steady state Reynolds Averaged Navier-Stokes (RANS) equations. This approach rather than simplifying the RANS equations simplifies the solution space and still includes the nonlinear effects. Model reduction is a technique which has successfully been applied to CFD models within other areas of application, e.g. study of flow past a rectangular cavity [9], compressible flows [10], optimal rotary control of cylinder wake [11], and computer graphics [12], [13]. Other examples include weather forecasting, image processing, signal analysis and data compression [14]. To our knowledge model reduction has not yet been applied to wind farm flow using steady state RANS.

2. Theoretical framework

The idea of model reduction is to formulate the governing equations in a reduced finite dimensional solution space spanned by a set of orthogonal basis modes. For three-dimensional grids, the modes are cell values arranged in one-dimensional vectors by some pre-determined ordering.

2.1. Reduced order model

The governing equations considered here are the steady state RANS equations with the k-ε turbulence closure scheme. Using Einstein notation the momentum equations are given by

$$\rho \frac{\partial}{\partial x_j}\left(u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\sigma_{ij}\right), \tag{1}$$

where the stress tensor σ_{ij} is given by

$$\sigma_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\rho k. \tag{2}$$

The density ρ is assumed constant, and the flow is incompressible and divergence free.