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Flow Modelling for Wind Farm Control: 2D vs. 3D

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Abstract. Control-oriented models provide a basis for wind farm control to improve power production and reduce structural loading. Wake steering is considered to be one of the most promising techniques to achieve this. Wind turbine wakes under yaw misalignment are deflected downstream and have been shown to produce a curled or kidney-shaped structure. A Navier-Stokes based code called FRED was developed to model wind farm flow in 2D to perform yaw control. To tackle the differences between 2D and 3D flow, this work introduces a generalised continuity correction and wind turbine force scaling terms to the FRED framework. The effectiveness of approximating 3D results is tested by comparison with 3D simulations in the same framework. The continuity correction is now applicable to general wind directions and effective in reducing wake width and speed-up effects. The magnitude of wake deflection can be tuned using a force scaling term. However, we show that there remains a qualitative difference in the deflection profile downstream, as well as a difference in the propagation of yaw effects over time. From this study we can conclude that there is a fundamental difference between 2D and 3D flow physics in spatial and temporal dynamics which makes the 2D modelling approach challenging for control without further empirical adjustments. The necessary corrections are likely to be complex and non-physical, leading to a departure from the first principles foundation that FRED is developed from.

1. Introduction

Reducing the cost of wind energy is essential to make it competitive with fossil fuel alternatives. Wind turbines are placed offshore because of the higher wind speeds and lower turbulence levels over sea than above land. To make the most of limited offshore parcels, wind turbines are placed in wind farms to increase the energy density and to reduce the necessary infrastructure.

Wind turbines produce wakes with lower wind speed and higher turbulence intensity, dependent on turbine orientation and/or rotational speed. Downstream turbines affected by wakes produce less power and experience higher fatigue loading. The wind farm topology is optimised with respect to the annual distribution of wind direction and speeds at the site to reduce negative aerodynamic interactions between wind turbines, with turbines generally spaced about 7-10 times the rotor diameters from each other [1].

The aerodynamic interaction between turbines remain significant even at this coarse spacing. Several studies have shown that yaw misalignment with the wind direction can redirect the wake and minimise the interaction between different turbines for existing wind farms under quasi-steady conditions.

However, for realistic inflow conditions a challenging time-varying control problem has to be solved [2]. A dynamic, model-predictive control strategy may realise these gains in real-world wind farm scenarios, where they have not been achieved with current control approaches based on steady-state models [3, 4].

The basis for this new control strategy is a wind farm flow modelling tool suitable for adjoint optimisation of controls that simulates two-dimensional (2D) flow for computational efficiency [5, 6] which was inspired by control optimisation using a high-fidelity adjoint LES simulation [7]. It has been incorporated in FRED - Framework for wind farm flow Regulation and Estimation with Dynamics [8].

Wake steering relies on the downstream deflection of wind turbine wakes due to yaw misalignment with the inflow wind direction. The wake of a misaligned actuator disk has been shown to produce curled wakes with counter-rotating vortex pairs [9]. This kidney-shaped wake has also been demonstrated in free-vortex wake code [10]. These 3D dynamics have been incorporated in the curled wake model in FLORIS through an engineering approach for steady-state results [11].

These fundamental differences between 2D and 3D flow exist due to the degrees of freedom in the flow, which may limit use of a 2D flow model for wind farm control optimisation. WFSim, a physics-based, control-oriented wind farm model, approaches some of these physical differences by modifying the Navier-Stokes continuity equation to reduce speed-up effects and implementing a variable mixing length eddy viscosity to improve wake recovery [12]. These adjustments are limited because they are only valid for flow along the pre-defined streamwise axis of the simulated domain.

The main contribution of this work is twofold. First, we extend the dynamic 2D wind farm model in FRED [5, 8] with two correction factors:

- a novel generalised relaxation of the continuity condition,
- scaling factors to tune wake deflection.

These contributions are compared with 3D results within the same simulation framework for both steady and time-varying conditions. Second, we show that it is fundamentally challenging to accurately represent key features necessary for wind farm flow control with yaw misalignment in a dynamic physics-based 2D model.

The remainder of this paper is organised as follows. Section 2 introduces the two flow adjustments that extend the control-oriented model, after which Section 3 describes the framework for the simulations and experiments run. The results of steady and dynamic tests are presented in Section 4, followed by the discussion in Section 5. Finally, Section 6 draws the conclusions from the presented results.

2. Model Extensions

2.1. Continuity Adjustment

Due to the incompressible continuity condition in the Navier-Stokes equations, 2D wakes become wider and have a larger speed-up effect around the wake than 3D wakes. WFSim implements a continuity adjustment based on an assumption of axial symmetry to reduce these effects [12]. The adjustment is limited to flow along the pre-defined streamwise axis of the domain, limiting its use to simulations with a largely constant wind direction. We generalise the continuity adjustment for all wind directions by expressing the incompressible Navier-Stokes continuity equation in a flow-aligned coordinate system, where the continuity is relaxed orthogonal to the inflow direction. The novel relaxation of the continuity condition is defined as

$$\frac{\partial u_{\mathrm{s}}}{\partial s} + 2\frac{\partial u_{\mathrm{n}}}{\partial n} = 0\,, \tag{1}$$

where u_s is the velocity component aligned with the inflow direction, u_n is the velocity component orthogonal to the inflow, and s and n are the aligned and orthogonal axes of the flow-aligned coordinate system. The condition is then expressed in Cartesian coordinates for implementation in the flow model.

2.2. Forcing Adjustment

In our simulations, we observe a lower deflection of the wake centre in 2D flow than in 3D flow. To correct for this effect, we introduce two scaling factors to the force $\mathbf{f}$ that the turbine imposes on the flow as

$$\mathbf{f} = s_{\|}\mathbf{f}_{\|} + s_{\perp}\mathbf{f}_{\perp} , \tag{2}$$

where $s_{\|}$ scales the force $\mathbf{f}_{\|}$ parallel to the inflow and $s_{\perp}$ scales the orthogonal component $\mathbf{f}_{\perp}$. These scaling factors are parameters for tuning the wake properties.

3. Simulation Framework

3.1. Simulation

The simulations for this study are performed with FRED [8]. The flow model has been extended to be able to perform both 2D and 3D simulations with an actuator disk turbine model to enable a clean comparison of the three proposed correction factors. The wind turbine is modelled after the DTU 10MW reference turbine using an actuator disk model [13].

The 2D model is simulated with a uniform inflow given as a Dirichlet boundary condition. The sides of the domain and outflow boundary are given no-stress conditions.

The 3D simulations are run with a horizontally uniform inflow. The vertical variation of velocity in the boundary layer is specified according to the power law. The bottom boundary is given a no-slip condition and the top boundary is given a no-stress boundary condition. The other boundaries are the same as for 2D.

The domain of the simulations is illustrated in Figure 1, where the 3D domain is the same size in the $x - y$ plane. The numerical properties are listed in Table 1. The 3D domain is $2\,\mathrm{km} \times 1\,\mathrm{km} \times 0.5\,\mathrm{km}$ with $80\,\mathrm{cells} \times 40\,\mathrm{cells} \times 20\,\mathrm{cells}$, whereas the 2D domain is $2\,\mathrm{km} \times 1\,\mathrm{km}$ with $80\,\mathrm{cells} \times 40\,\mathrm{cells}$. Both simulations are performed with a time-step $\Delta t = 0.5\,\mathrm{s}$.

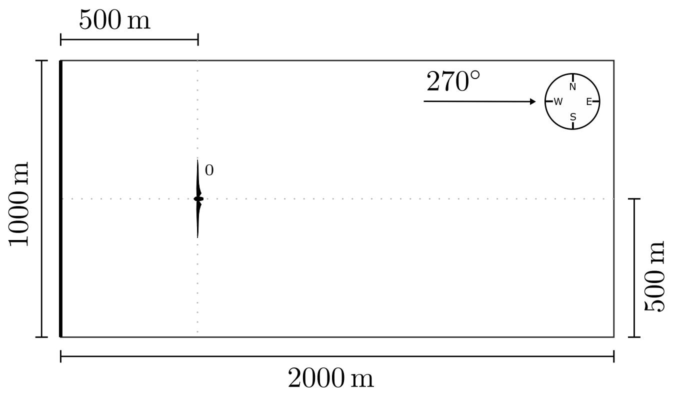

Figure 1: 2D view of the simulation domain.

Table 1: Numerical properties for simulation

	2D	3D
Domain	2 km × 1 km	2 km × 1 km × 0.5 km
Cells	80 cells × 40 cells	80 cells × 40 cells × 20 cells
Time-step	0.5 s	0.5 s

3.2. Experiments

The simulation is run with a $9\,\mathrm{m\,s^{-1}}$ inflow and a constant 20° yaw misalignment to observe the steady-state difference between 3D flow and 2D flow with correction factors. The flow slices are taken after 600 s of simulation with a 0.5 s time-step.

The output measure to assess performance of the numerical modelling approach for wake redirection control is wake deflection. It is chosen as a proxy for the effectiveness of attenuation downstream wake interaction. The wake deflection is calculated as weighted average of the velocity deficit below the free-stream velocity.

The dynamic behaviour of wake deflection changes in response to yaw angle changes is studied with the same single-turbine case. The steady inflow is maintained but the yaw angle reference of the turbine ψ is varied over time in a series of steps as

$$\psi = \begin{cases} 270^\circ & \text{for } t < 200.0\,\mathrm{s}\,, \\ 300^\circ & \text{for } 200.0\,\mathrm{s} \le t < 500.0\,\mathrm{s}\,, \\ 285^\circ & \text{for } 500.0\,\mathrm{s} \le t < 700.0\,\mathrm{s}\,, \\ 270^\circ & \text{for } t \ge 700.0\,\mathrm{s}. \end{cases} \tag{3}$$

4. Results

4.1. Kidney-Shaped Wake and the Hub-Height Slice

Figure 2 shows a downstream slice of a wake from a misaligned turbine. It clearly illustrates the 3D structure of the wake. The counter-rotating vortex pair forms a kidney-shaped wake.

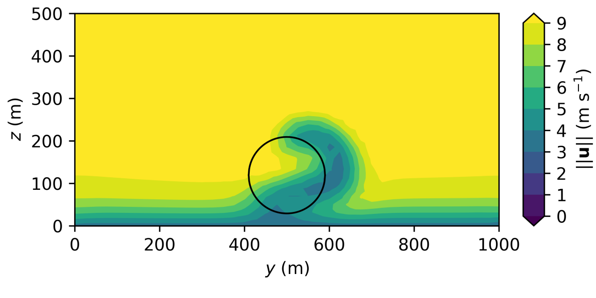

Figure 2: Vertical slice of the 3D flow for a turbine with a 20° yaw misalignment illustrates the kidney-shaped wake forming with the counter-rotating vortex pair.

This 3D structure of the wake is also reflected in Figure 3 where the hub-height slice is compared to the average velocity over the rotor diameter. The difference in structure is apparent. We believe the averaged velocity to be more relevant to downstream turbine performance, therefore that will be used for the comparisons in the remainder of this study.

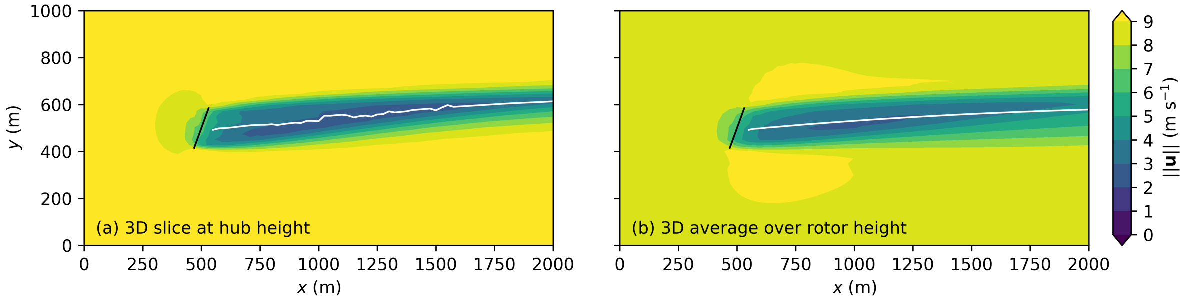

Figure 3: 3D flow simulation for a $9\,\mathrm{m\,s^{-1}}$ inflow at hub height with a 20° yaw misalignment. Compare (a) the slice at hub height and (b) the weighted average of the velocity field over the rotor height.

4.2. Flow Fields Comparison

A comparison of the simulated turbine wakes after 600 s of simulation is shown in Figure 4 for a 20° yaw misalignment with respect to the inflow of $9\,\mathrm{m\,s^{-1}}$ at hub height.

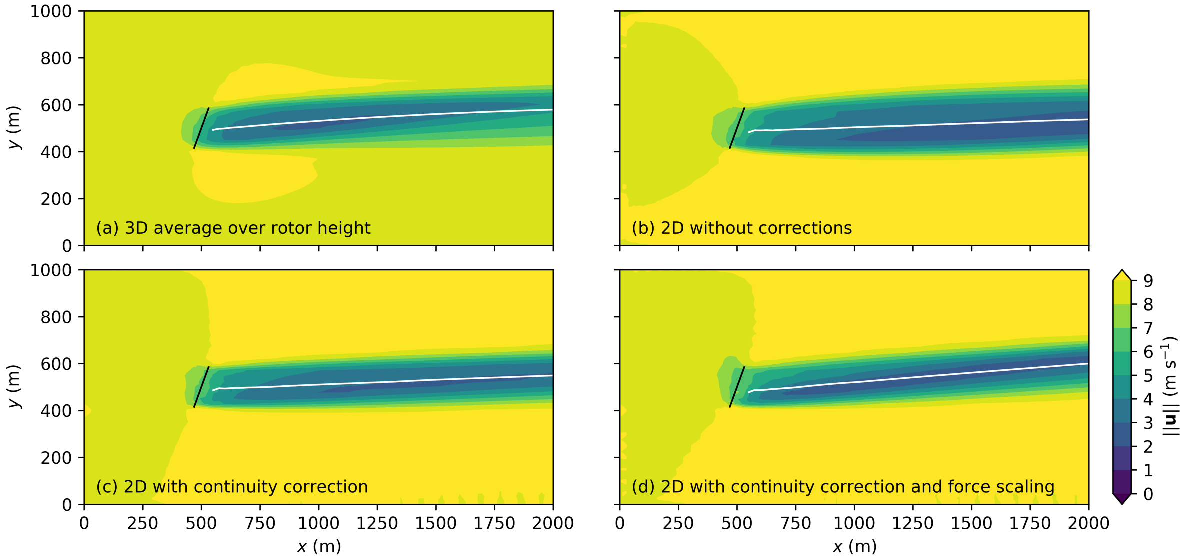

Figure 4: Wind turbine wakes for a $9\,\mathrm{m\,s^{-1}}$ inflow along the x-axis and a 20° yaw misalignment. Wake centres marked in white. (a) Hub height slice of a 3D simulation and (b) a 2D flow simulation without adjustments, (c) with the modified continuity correction, and (d) with additional scaling of the turbine force orthogonal to the inflow ($s_\perp = 2$).

Figure 4(a) shows a hub height slice of a 3D simulated wake. The unmodified 2D wake in Figure 4(b) is visibly wider than the 3D wake as is expected. It also shows less deflection and lower recovery to the free-stream flow.

The effect of the continuity correction in Figure 4(c) is a clearly smaller level of wake expansion than for the unmodified flow. Additionally, implementing a scaling factor on the turbine forcing orthogonal to the inflow, whilst not scaling the force parallel to the flow, in Figure 4(d) leads to a larger wake deflection but does introduce disturbances in the near-wake flow. These disturbances are likely to be irrelevant to wind farm control optimisation because downstream wind turbines will be spaced as to only interact with the far wake.

4.3. Wake Centrelines

The deflection of the wake centrelines from the streamwise axis are gathered in Figure 5 for the flow fields presented in Figure 4. The continuity correction shows only minor effect on the deflection of the wake. The scaling of the force perpendicular to the flow does lead to a larger deflection. However, the wake deflects along an almost linear path, whereas the 3D wake follows a curve that realigns with the direction of the free stream.

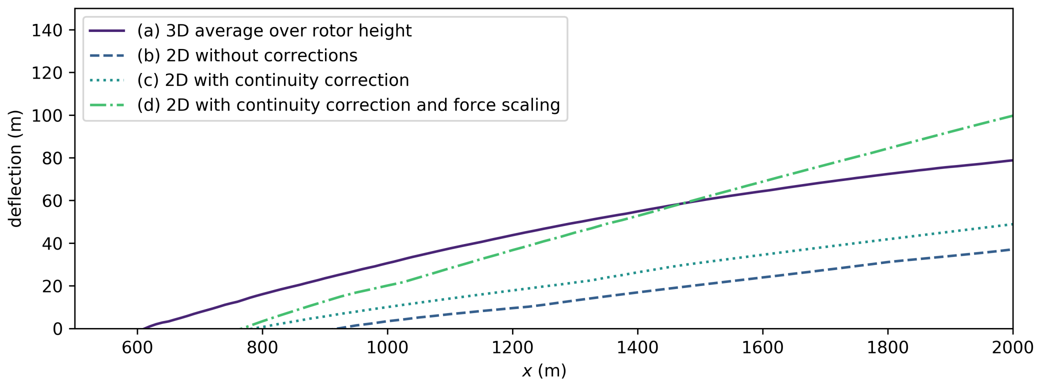

Figure 5: Comparison of the deflection of the wake centre line for a $9\,\mathrm{m\,s^{-1}}$ inflow along the x-axis and a 20° yaw misalignment. (a) Hub height slice of a 3D simulation and (b) a 2D flow simulation without adjustments, (c) with the modified continuity correction, and (d) with additional scaling of the turbine force orthogonal to the inflow ($s_\perp = 2$).

4.4. Wake Deflection Dynamics

The time-varying, stepped, yaw reference signal is applied to a turbine under steady inflow conditions. The wake deflection over time in 3D is calculated with the velocity field averaged over rotor height and shown in Figure 6. The 2D case shown in the same figure is run with the continuity correction and a scaling factor $s_\perp = 2$ on the forcing term introduced by the turbine into the flow. There is a difference in the magnitude of the wake deflection between 2D and 3D as previously observed with steady yaw misalignment. Additionally, the propagation of the effects from yaw angle changes downstream happens faster for 2D than for 3D flow.

5. Discussion

5.1. Effectiveness of the Correction Terms

The continuity correction is effective in reducing speed-up effects and wake width in 2D flow simulation. The assumption of axisymmetry that motivated the adjustment is invalid under yaw misalignment because of the kidney-shaped curled wake that forms. However, even though the underlying assumption is invalid, the continuity correction is still effective and useful for modification of 2D flow towards 3D results. The generalisation in terms of flow direction presented here means that it may be used for simulations that are not necessarily aligned with the axis of the domain.

A force scaling term may be used to tune deflection in 2D wakes to match 3D results or experimental measurements. However, the 3D wake aligns with the free flow vector, whereas

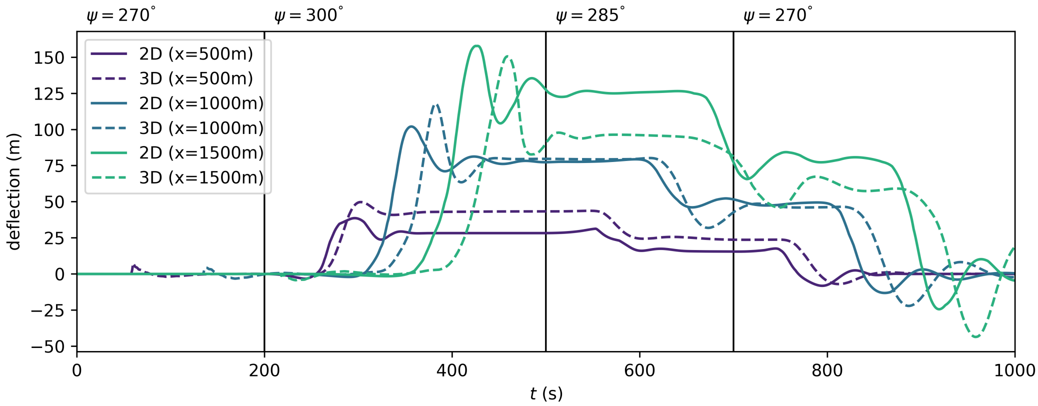

Figure 6: Dynamics of wake deflection at different downstream positions for a turbine under steady inflow conditions with a time-varying yaw angle reference. Comparison of the wake centre of a height-averaged flow in 3D and the 2D flow modified with the continuity correction and force scaling $s_{\|} = 1$ and $s_{\perp} = 2$.

the 2D flow simulation follows an almost linear trajectory that continues deflecting further downstream. This has a significant impact especially for modelling of the interaction between wake effects and downstream turbines.

We observe a difference in downstream propagation of the effects of yaw angle changes. The 2D flow appears to propagate the effects of yaw angle changes at a higher speed than the 3D simulation. The difference in time constant poses a challenge for dynamic control which will be hard to tackle using simple or physical correction terms.

5.2. Fundamental Differences in Flow Physics

The physics of wake deflection under yaw misalignment appear to be a fundamentally 3D effect from the pair of counter-rotating vortices that are generated. The unmodified 2D flow simulation shows very little deflection. Even thought the deflection magnitude may be adjusted with a force scaling term, the spatial dynamics of the wake remain different from the 3D flow. Furthermore, the temporal dynamics of yaw angle changes propagating downstream differs between 2D and 3D. These physical differences are hard to capture in 2D flow simulations and may be corrected for with more complex corrections. This added complexity would mean a departure from the first principles modelling to naturally include the wake dynamics that motivated the development of FRED.

6. Conclusion

This work introduces two correction factors to adjust 2D flow simulation of wind turbine wakes to more closely represent 3D flow for the purpose of dynamic wake redirection control. 3D flow is reduced to 2D by a weighted average over the rotor height because the 3D shape of the wake means a hub height slice is not representative.

The generalised continuity correction may be applied for all flow directions to adjust wake width and reduce speed-up effects, even though the assumption of axisymmetry that it was based on is invalid for wakes under yaw misalignment. A force scaling term can increase the deflection magnitude of wakes in 2D flow to approximate the 3D deflection magnitude but the spatial dynamics remain different. Under time-varying conditions, it appears that the temporal dynamics of the propagation of yaw angle changes downstream are also different between 2D and 3D.

The fundamental qualitative difference in the wake deflection profile over downstream distance and the disparity in time constant for downstream yaw effects make the 2D modelling approach unsuitable for control without further corrections. The necessary corrections are likely to be complex and non-physical, leading to a departure from the first principles modelling that inspired the development of FRED.

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