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Development of a dynamic wake model accounting for wake advection delays and mesoscale wind transients

B Foloppe[a], **S Buckingham**[a], **W Munters**[a], **L Vandevelde**[b], **J van Beeck**[a]

[a] Environmental and Applied fluid dynamics Department, von Karman Institute, Belgium
[b] Electromechanical, Systems and Metal Engineering Department, Ghent University, Belgium

E-mail: benoit.foloppe@vki.ac.be

Abstract. Over the last decade, the size and the number of offshore wind turbines and wind farms are constantly increasing and ongoing projects show that this will continue. With tip height often above 200 meters, currently installed wind turbines are interacting and impacting massively the atmospheric boundary layer. Therefore, the research intends to develop a new dynamic wake model that considers weather transient inputs. The Flow Redirection and Induction in Steady State (FLORIS) framework has been proven to be an easy to use, easy to tune, computationally inexpensive and powerful wake modelling tool even though lacking dynamical effects. Therefore, an extension of the FLORIS framework is presented in order to include wake advection delays between wind turbines, time-varying and spatially heterogeneous wind conditions. The new dynamical model is inspired by the FLORIDyn model presented in 2014. The so-called Observation Points (OPs) are generated at the rotor centre location. Following a Lagrangian approach, the OPs are convected downstream, along the wake of the wind turbine, defining the wake centreline. It is during this process that the dynamics of wind turbine wake and background flow field unsteadiness are included. Finally, using the same approach currently implemented for yaw-misalignment wake deflection, the wake is shifted to match the unsteady wake centreline. The developed model is validated against Large Eddy Simulation using the SOWFA tool. The validation is done for unsteady inflow, with both wind speed and direction changes, variable wind turbine control and wake interactions. The new model is applied to a simulation of the Horns Rev wind farm with a sinusoidally time-varying wind inflow direction to show an hysteresis in the wind farm power extraction curve.

Keywords: FLORIS, dynamic wake model, wake advection delays, unsteady flow field, SOWFA

1 Introduction

Over the last decade, the size and the number of offshore Wind Turbines (WTs) and wind farms are constantly increasing and this growth is expected to continue in the future. With tip height often above 200 meters, currently installed WTs are interacting and impacting massively the atmospheric boundary layer. In the future, wind farms will become even more important contributors to the electrical power system and will require additional flexibility in terms of farm control, ancillary services and response to weather transients as explained in [1]. It is crucial for fast control-oriented models to be informed of weather inputs but current models are almost always quasi-steady, hence internal wind farm dynamics are not accounted.

2 Objectives

The wind farm model should account for the unsteadiness of the background flow field. Two different main usages of this new model can be distinguished. The first one can be called “operational” usage where the flow field is obtained from a single measurement location. The model can inform wind-farm control algorithms and increase fidelity. Another usage can be done by coupling the model with a weather prediction model in order to estimate wind-power resources accounting for the influence of synoptic phenomena or to improve current wind farm parametrizations that are commonly used at mesoscale level by informing on sub-grid scale effects. Currently available wake models are only steady state models and thus not suitable for a coupling with time-varying mesoscale simulations. The objective is to develop a new dynamical wake model accounting for wake advection delays and mesoscale wind transients.

3 Methodology

The Flow Redirection and Induction in Steady State (FLORIS) framework has been proven to be an easy to use, easy to tune, computationally inexpensive and powerful wake modelling tool even though lacking dynamical effects. Therefore, an extension of the FLORIS framework is presented in order to include wake advection delays between wind turbines, time-varying and spatially heterogeneous wind conditions. The new dynamical model is inspired by the FLORIDyn model presented in [2]. The so-called Observation Points (OPs) are generated at the rotor centre location. Following a Lagrangian approach, the OPs are convected downstream, along the wake of the wind turbine, defining the wake centreline.

In the current paper, we consider cases where the vertical OP displacement is much smaller than the horizontal displacements (computed in following Large Eddy Simulation (LES) and also shown in [3]), justifying the use of a two-dimensional dynamical model at hub height z_t. The first point of the centreline ($p = 1$), of turbine t at time step k, is located at the WT rotor centre, $\boldsymbol{x_C}(t) = (x_C(t), y_C(t), z_C(t))$, which gives:

$$\boldsymbol{x_{t,p=1,k}} = \boldsymbol{x_C}(t)$$

The downstream convection of $\boldsymbol{x_{t,p,k}}$ to $\boldsymbol{x_{t,p+1,k+1}}$ is defined as follows:

$$\boldsymbol{x_{t,p+1,k+1}} = \boldsymbol{x_{t,p,k}} + \boldsymbol{U}_{t,p,k} \Delta \mathrm{K}$$

where ΔK is the time step. Thus, the previous expression can be simplified to:

$$\begin{pmatrix} x_{t,p+1,k+1} \\ y_{t,p+1,k+1} \end{pmatrix} = \begin{pmatrix} x_{t,p,k} \\ y_{t,p,k} \end{pmatrix} + \begin{pmatrix} u_{t,p,k} \\ v_{t,p,k} \end{pmatrix} \Delta \mathrm{K}$$

Using matrix notation, the time update laws of OPs are:

$$\begin{bmatrix} x_{t,1,k+1} & y_{t,1,k+1} \\ x_{t,2,k+1} & y_{t,2,k+1} \\ \vdots & \vdots \\ x_{t,N_p,k+1} & y_{t,N_p,k+1} \end{bmatrix} = [A] \begin{bmatrix} x_{t,1,k} & y_{t,1,k} \\ x_{t,2,k} & y_{t,2,k} \\ \vdots & \vdots \\ x_{t,N_p,k} & y_{t,N_p,k} \end{bmatrix} + [B][x_C(t) \quad y_C(t)] + [A] \begin{bmatrix} u_{t,1,k} & v_{t,1,k} \\ u_{t,2,k} & v_{t,2,k} \\ \vdots & \vdots \\ u_{t,N_p,k} & v_{t,N_p,k} \end{bmatrix} \Delta K$$

where $[A] = \begin{bmatrix} 0 & & & \emptyset \\ 1 & 0 & & \\ & \ddots & \ddots & \\ \emptyset & & 1 & 0 \end{bmatrix}$, $[B] = \begin{bmatrix} 1 \\ 0 \\ \cdots \\ 0 \end{bmatrix}$ and N_p is the number of OPs.

The local velocity vector $U_{t,p,k} = (u_{t,p,k} \; v_{t,p,k})$ is obtained with a steady FLORIS evaluation that reflects the background input velocities and turbine settings at time index k. It is important to note that N_p is increasing at the beginning of the simulation and thus the computational time is expected to increase during the first part of the simulation and then reach a plateau.

It is during this process that the dynamics of WT wake advection delays and background flow field unsteadiness are included. Finally, using the same approach currently implemented for yaw-misalignment wake deflection, the wake is shifted to match the unsteady wake centreline. This implementation differentiates from [2] in the fact that the original FLORIS modules (wake velocity, wake turbulence and wake combination modules) are kept and a new module accounting for the wake unsteady centreline deflection is added. The new tool is hereafter called Unsteady FLORIS (UFLORIS).

4 Results

4.1 Validation

The developed model is validated against LES using the SOWFA tool [4]. The validation was conducted for steady inflow and unsteady turbulent inflow conditions, with both wind speed and direction changes, variable WT control and wake interactions. The simulation shown in Figure 1 is done using a NREL 5MW WT represented by an actuator line model. The precursor domain has dimensions of 3 x 3 kms in the horizontal direction and 1 km in the vertical direction with a uniform resolution of 20 meters. The main simulation has a refinement region around the WT and the near wake so as to reach a resolution of 5 meters. The wind is coming from bottom left at a magnitude of 8 m/s at hub height and around 6% of turbulence intensity. In the main simulation, the time step is 0.125s. The same simulation is run with and without the wind turbine in order to obtain the background flow field to be inserted into UFLORIS. This can be considered as a one-way coupling between SOWFA and UFLORIS updated every 50s. In this simulation, the WT starts with a 30° yaw angle and at $T = 800s$ the turbine is rotating at a rate of 0.1°/s in order to retrieve a nominal position without yaw angle. For the UFLORIS simulation, the time step is 10s and the output flow field figure has a resolution of 15m. The wake deficit is computed using a gaussian wake model [5].

The centreline from SOWFA (in green in Figure 1 top left) is extracted by using the methodology from [6] and compared to the UFLORIS centreline presented in the previous section (in black). The figure on the top right corresponds to data extracted at the dashed black line position. It shows a value that is proportional to the amount of wind energy that is lost due to the upstream WT. A good agreement is found between the new model and LES. The small difference between the location of the two centrelines can also be observed on this figure. Finally, the bottom figure is showing the power generated by the wind turbine. The agreement is good considering the fact that there is a 50s updating lag which corresponds to these plateaus.

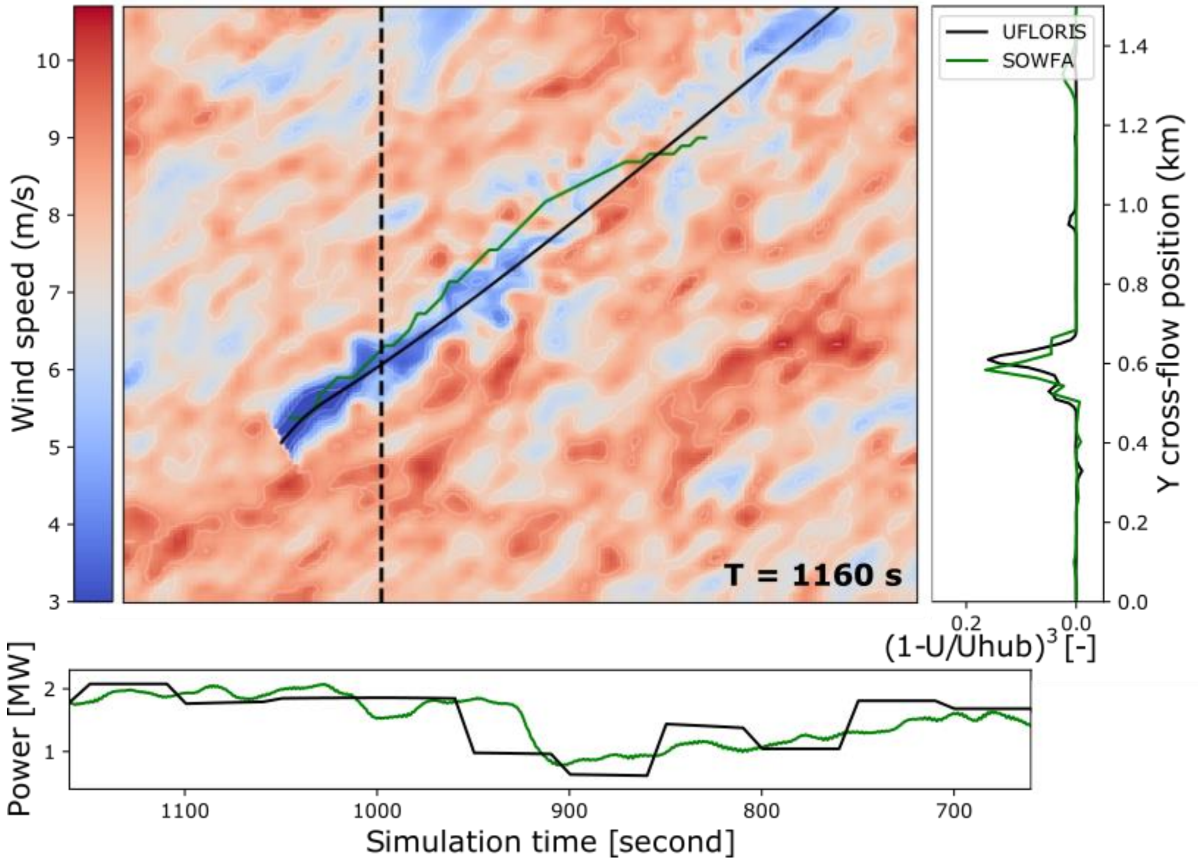

Figure 1 Instantaneous snapshot of wake centrelines from UFLORIS (black) and SOWFA (green) together with contours of background flow field from LES and model comparison of predicted power (bottom) and centreline cross-flow positions (right) at the dashed-black line position.

4.2 Application

The UFLORIS model is applied to a simulation of the Horns Rev wind farm with a sinusoidally time-varying wind inflow direction ($\theta(t) = 270° - 30° sin(2\pi t/T_\theta)$; $T_\theta = 1h$) as detailed in [7]. It is an ideal test-case to assess this new dynamical wake model because it involves dynamics of wake advection delays in wind farms and dynamical hysteresis effects in power production. Results are shown in Figure 2 where the normalized Horns Rev wind farm power is plotted as a function of the incoming wind direction. The UFLORIS simulation is capturing the dynamical effects despite not featuring lower power than the steady case as shown in [7].

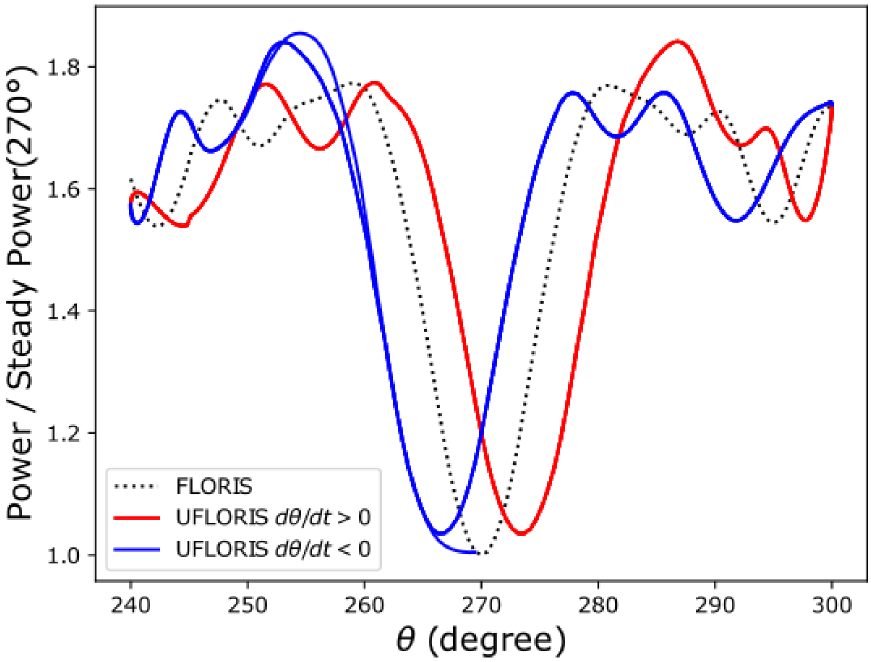

Figure 2 Normalized Horns Rev wind farm power as a function of the incoming wind direction.

5 Conclusions

In this abstract, the development of a dynamic wake model accounting for wake advection delays and mesoscale wind transients is presented. The new Unsteady version of the original FLORIS consists in the addition of a new module. It is computing the unsteady wake centreline position and shifting the wake. The implementation has been validated against LES and is applied to the Horns Rev wind farm subjected to sinusoidal wind direction changes in order to reproduce an hysteresis in the wind farm power extraction curve.

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