

Incorporating Atmospheric Stability Effects into the FLORIS Engineering Model of Wakes in Wind Farms

P. M. O. Gebraad, M. J. Churchfield, and P. A. Fleming

National Renewable Energy Laboratory, Golden, Colorado, 80401. USA

E-mail: Matt.Churchfield@nrel.gov

Abstract. Atmospheric stability conditions have an effect on wind turbine wakes. This is an important factor in wind farms in which the wake properties affect the performance of downstream turbines. In the stable atmosphere, wind direction shear has a lateral skewing effect on the wakes. In this paper, we describe changes to the FLOW Redirection and Induction in Steady-state (FLORIS) wake engineering model to incorporate and parameterize this effect.

1. Introduction

Atmospheric stability is a measure of the atmosphere's tendency to promote or resist vertical mixing. This stability depends on thermal buoyancy effects and thus on the rate of change of temperature with height above the surface. An example of an unstable condition is when the air closer to the ground is warmer than the higher layers of air, and the warm air will rise and mix with the higher layers. An example of a stable atmosphere is when there is a colder layer of air near the ground that is covered by a warmer layer at a higher altitude, in which case there is a limited amount of turbulent mixing between the layers.

Atmospheric stability affects the level of turbulent mixing in the atmosphere, and thereby the magnitude to which the differences in wind velocity and direction with height are able to persist. These differences in direction (also known as wind direction shear or wind backing and veer) and velocity (wind velocity shear) can be higher in a stable atmosphere because of the limited mixing between the air layers. Wind direction shear is predominantly driven by the interaction of the Coriolis force induced by the Earth's rotation and large-scale pressure gradients associated with weather patterns over the Earth's surface. It can also be influenced by the collapse of the atmospheric boundary layer that occurs over land at night as the land cools through radiative heat transfer.

The turbulence and shear levels affect the properties of wind turbine wakes. In references [1], [2], and [3], computational fluid dynamics (CFD) studies were performed that show that wind direction shear occurring in a stable atmosphere will laterally skew the wake. The cross-stream component of the inflow is in an opposite direction in the lower part of the wake as compared to the upper part, skewing the wake laterally with downstream distance. In an unstable atmosphere, vertical mixing makes wind direction shear nearly nonexistent, so this wake skewing effect is not present. Wake skewing is important in that it affects how wakes interact with downstream turbines and other wakes.

In model-based control approaches for wind plant control and wind plant layout optimization, computationally efficient parametric engineering models of the wake effects in a wind plant are



useful for quickly finding optimized settings, whereas more high-fidelity wind plant models that tend to be more computationally expensive are better suited for verifying or studying a few particular cases in detail.

High-fidelity wind models based on CFD can include stability effects by including thermal buoyancy effects in the underlying equations. In existing simplified wake engineering models, effects of stability on the average recovery of the wake velocity to the free-stream wind speed through turbulent mixing can be described by adjusting the parameters related to wake recovery and expansion, as in [4], for example. To our knowledge, however, the effect of wind direction shear on the skewing of the wake has not been included in parametric engineering models described in literature. In this paper, we extend the FLOW Redirection and Induction in Steady-state (FLORIS) wake engineering model with the ability to laterally skew the wake to model the effect of wind direction shear in a stable atmospheric boundary layer (ABL) in a simplified, computationally efficient manner.

The FLORIS model is a parametric model for which the input parameters are tuned based on measured data or high-fidelity simulation data. The description of the original FLORIS model in [5] includes an example of tuning FLORIS based on high-fidelity simulation data generated by the Simulator fOr Wind Farm Applications (SOWFA). In this paper, we also use data generated by SOWFA to tune the parameters of the model.

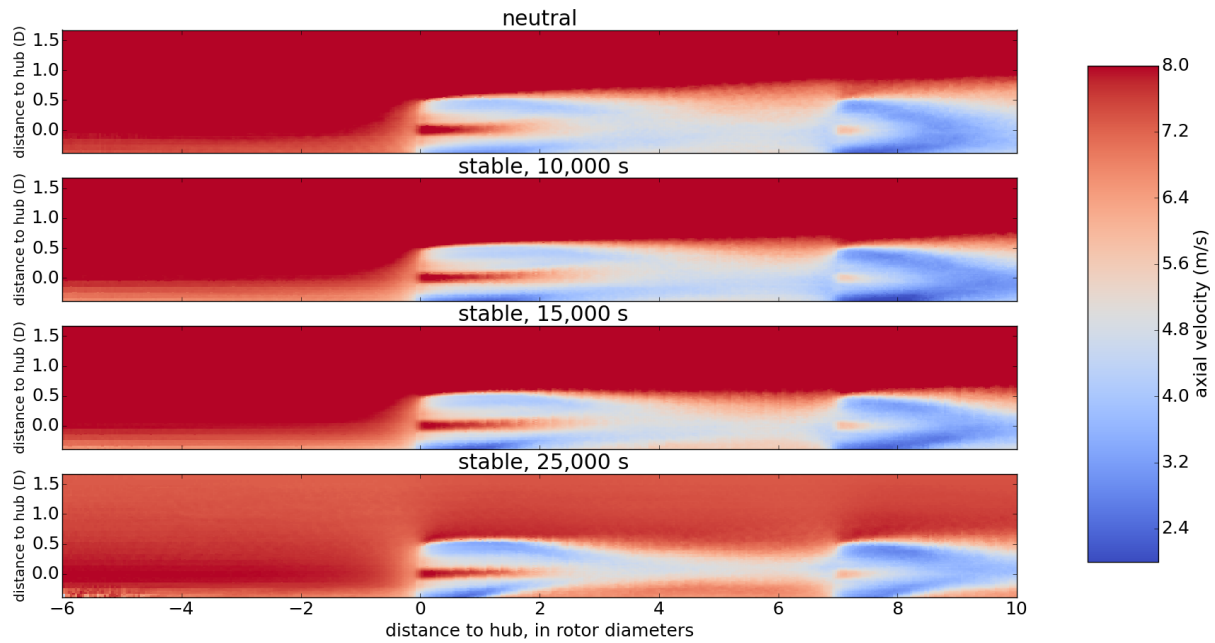
In Section 2, more information is provided on how different stability conditions are simulated in SOWFA. In Section 3, the extensions to the FLORIS engineering model are described, and Section 4 provides detail on the methodology that was used to tune the parameters of the FLORIS model based on different stability conditions simulated in SOWFA.

2. CFD simulations of atmospheric stability conditions in wind farms in SOWFA

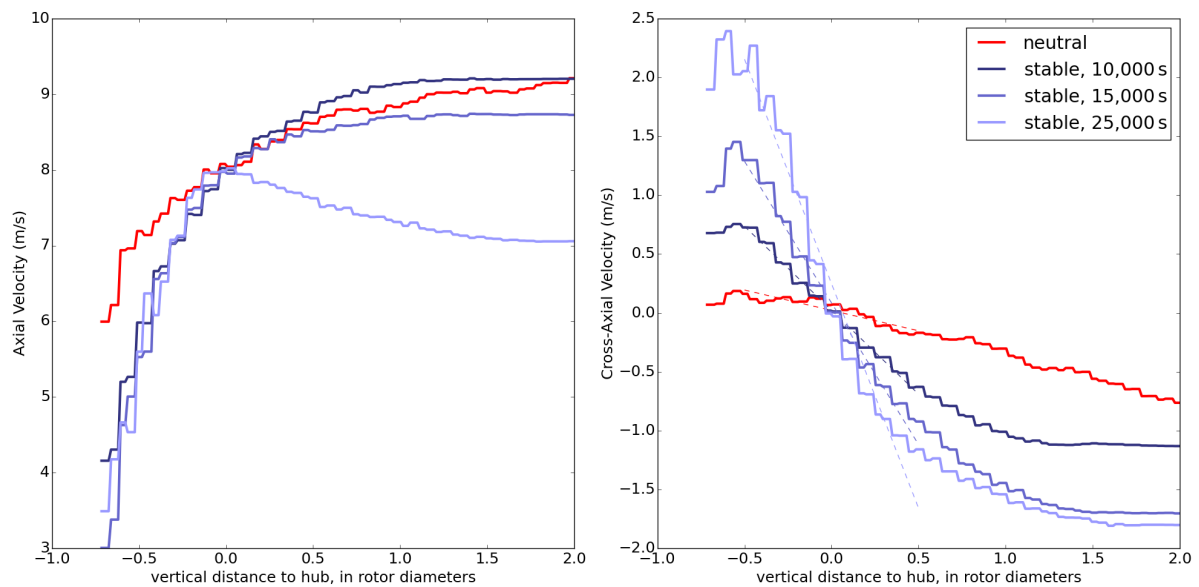
SOWFA is a high-fidelity CFD simulation tool for wind farms [6, 7]. SOWFA simulates the ABL around the wind turbines in a wind farm using large-eddy simulation (LES) to solve the three-dimensional incompressible Navier-Stokes equations and transport of potential temperature equations, which take into account the thermal buoyancy and Earth rotation (Coriolis) effects in the ABL. Turbine rotors are simulated by putting rotating actuator lines in the ABL, which represent the rotor blades (as proposed in [8]). The forces applied by the blades on the flow are calculated from the velocities sampled along the actuator lines. This calculation is done by a coupled simulation of the wind turbine dynamics in FAST [9]. FAST also calculates the loads and power production of each wind turbine.

Prerequisites for a typical SOWFA simulation of a wind farm are a predefined, developed turbulent flow in the initial field and in the inflow to the simulated domain. These should represent the ambient atmospheric conditions that a researcher is interested in testing in the simulation. They are generated by running a precursor simulation of the ABL in which there are no turbines present in the simulated domain. In this precursor simulation, the boundary conditions are set such that the flow is cycling repeatedly through the domain. A pressure gradient is applied to control the mean velocity and direction of the flow at hub height to a predefined set point. At the ground surface, a roughness is set and a heating rate is applied using a predefined temperature flux. The simulation is started with an initial uniform velocity, pressure, and temperature field and as the simulation progresses, a certain shear profile and turbulence develop. Once the turbulence reaches a quasi-steady state, the developed flow is sampled and used as initial and boundary conditions for a following simulation with turbines placed in the domain.

In this paper, we focus on simulation cases with stable and neutral conditions, each with an average hub-height wind speed of 8 m/s and a surface roughness of 0.0002 m, characteristic of offshore conditions. The domain size is 3 km (length) by 3 km (width) by 1 km (height). To simulate a stable atmosphere, the ground surface temperature is cooled at a constant rate, and



(a) Vertical-streamwise contour plane of time-averaged streamwise velocity.



(b) Variation of time-averaged wind speed components with height at inflow of the first turbine (5 rotor diameters upstream of the turbine). Shown as solid lines are the cell-centered velocities, explaining the step-like behavior. The level of wind direction shear is quantified as the slope of a linear fit of the cross-stream velocity variation across the rotor. These linear fits are displayed as dashed lines.

Figure 1: Time-averaged velocity data from SOWFA simulations with two turbines. Turbine simulations were performed in a fully developed neutral atmosphere, or in a stable atmosphere allowed to develop in a precursor simulation for 10,000, 15,000, or 25,000 s. The turbine wakes are allowed to develop for 700 s, and then the velocity field is averaged over the subsequent 300 s to generate these profiles.

a zero cooling rate results in a neutral ABL. In the precursor simulations for the stable ABL cases we apply a ground cooling rate of 1 K/hr. Higher levels of wind direction and velocity shear develop as time progresses in the precursor simulation, as can be seen in Figure 1b for 10,000, 15,000, and 25,000 s after initialization of the precursor simulation. For the 25,000-s case, a low-level jet forms. SOWFA simulation cases with two National Renewable Energy Laboratory 5-MW turbines aligned in the flow with a spacing of 7 rotor diameters (7 D) are then performed in the stable ABL in these different stages of the progression of the shear development, and in the developed neutral atmosphere, resulting in several “stability cases.”

3. Incorporating atmospheric stability effects in the FLORIS wind plant engineering model

The FLORIS engineering model describes the steady-state properties of wakes in wind farms and was developed to optimize wind turbine control settings and turbine positions, taking into account the effect of wakes on downstream turbines. To optimize the control settings, the model includes the influence of pitch, rotor speed, and yaw settings on the wake’s steady-state speed and direction. It was first presented in [5], and later extended with a more advanced rotor model in [10]. It is an extension of the Jensen model [11]. The Jensen model assumes a uniform velocity deficit with a top-hat profile that decays and widens with downstream distance. In FLORIS, this model was extended to better model situations with partial wake overlap by including three concentric circular wake deficit areas (“wake zones”) that each have their own expansion and recovery properties. With increasing downstream distance from the rotor, the velocity in the outer wake zone 3 recovers faster than the velocity in the inner wake zone 1 (the recovery rates are set individually for each zone by coefficients $m_{U,1}$, $m_{U,2}$, and $m_{U,3}$). The effective wind velocities at downstream turbines in the wind farm are then predicted by applying a reduction factor to the free-stream velocity, where the reduction factor is a function of the weighted sum of the overlap areas of each circular wake zone with the downstream turbine’s rotor. From the effective wind speeds, the power production and thrust levels at downstream turbines are calculated.

The FLORIS engineering model extension for atmospheric stability effects, called the FLORIS Ellipsoid model, provides the ability to apply a lateral skew (transvection) to the circular shape of the wake deficit areas to introduce the veer effect, as illustrated in Figure 2. When applying skew factor s to a circular area with radius R , the resulting area $(x + sy)^2 + y^2 < R^2$ forms a tilted elliptical shape. The tilt rotation angle, and the width and length of the ellipsoid, can be analytically derived from the skew factor s applied to the circle.

Similar to the work in [1], the tilted elliptical shapes of the wake velocity deficit areas in the FLORIS model were fitted to the SOWFA-simulated wake profiles of wind turbines in a stable atmosphere. We extend the approach by finding the parameterized relations that adjust the skew factor s to the distance from the rotor and to the level of wind direction shear in the atmosphere (see Section 4 for further details).

The definition of the elliptical shape of the wake zones is also coupled to the wind farm power prediction model; similar to the previous “circular” FLORIS model, in the new FLORIS Ellipsoid model, the weighted sum of the overlap areas of each ellipsoid wake zone with the rotor area of downstream turbines is used to predict the effective velocity and power production at downstream turbines. For calculating the overlap of the ellipsoid wake zones with the downstream rotors, we use an efficient method based on an analytic solution for calculating the overlap area of ellipsoids, presented in [12].

A source code for the FLORIS Ellipsoid model is available in [13]. Note that a skewing method similar to the one described above can also be applied in other engineering wake models, such as the often-used Jensen model [11] for wakes or the Dynamic Wake Meandering model [14].

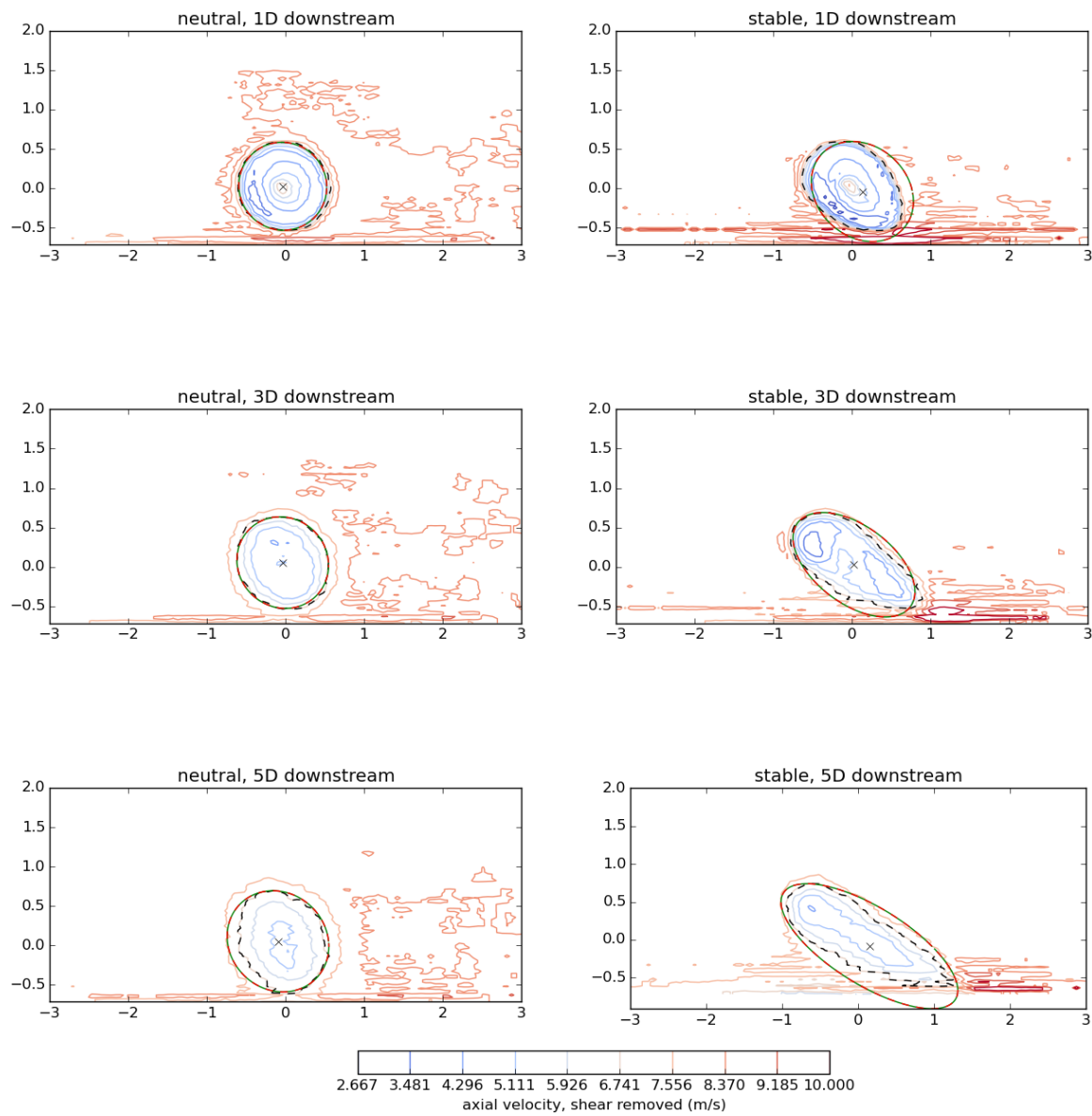


Figure 2: Contour plots of time-averaged wake velocity at 1D, 3D, and 5D downstream of a turbine. Both the x-axis and y-axis have units of rotor diameters with respect to hub. Profiles are shown for a neutral ABL with low levels of wind direction shear (left) and for one of the stable atmosphere cases with higher levels of wind direction shear (right), as simulated with SOWFA. To make the wake profiles more clear, the velocity shear was removed by applying a correction factor based on inverting the free-stream velocity shear profile normalized with the hub-height velocity. One of the outer contours is highlighted with a dashed black line, which shows that the wake is skewed laterally as a result of the wind direction shear. Both skew and expansion of the wake increase with downstream distance. The solid black line is an illustration of the concept of fitting elliptical profiles to approximate the wake profile in engineering models.

4. Fitting the FLORIS Ellipsoid model with SOWFA simulation results

A case study for the data fitting procedure for the FLORIS Ellipsoid model was performed using data from the SOWFA simulation cases with two aligned turbines in a neutral or stable ABL with different levels of wind veer (described in Section 2). For each of the stability cases, the wakes and the coupled turbine dynamics simulations are allowed to develop for a time period of 700 s, after which the power production of both turbines reach a quasi-steady state. Both the flow velocity profiles and the power output of the turbines are then averaged over the subsequent 300 s to provide the tuning data for the FLORIS Ellipsoid model. This averaging period is sufficient to yield smooth velocity profiles for the wake.

The parameters of the FLORIS Ellipsoid model were then found such that both the velocity profile of the wake and the power production of the downstream turbines as predicted by FLORIS fit to the time-averaged SOWFA simulation results for the different stability cases (see Figures 4 and 5). Figure 3 gives an overview of the parameterization. Further downstream of a turbine in the stable ABL, the lateral skew of the turbine's wake consistently increases under the influence of the wind direction shear. Therefore, in FLORIS we let the wake profile skew factor s increase linearly with the downstream distance from the rotor (see Figure 4). Further, the rate at which the skew increases with the downstream distance is modeled to depend linearly on the level of wind direction shear in the inflow to the upstream turbine. This level of wind direction shear in the inflow is determined by finding the slope of the variation of the cross-stream velocity over the rotor plane height at a point 5D upstream of the first turbine (see dotted-line fits in Figure 1b).

In addition to the wake skew parameterization, the wake zone expansion coefficient k_e (see Figure 3) and the wake velocity recovery rates $m_{U,1}$, $m_{U,2}$, and $m_{U,3}$ in the FLORIS model are adjusted to the different stability cases. An overview of the parameter values used for fitting the FLORIS model to the SOWFA cases is given in Table 1.

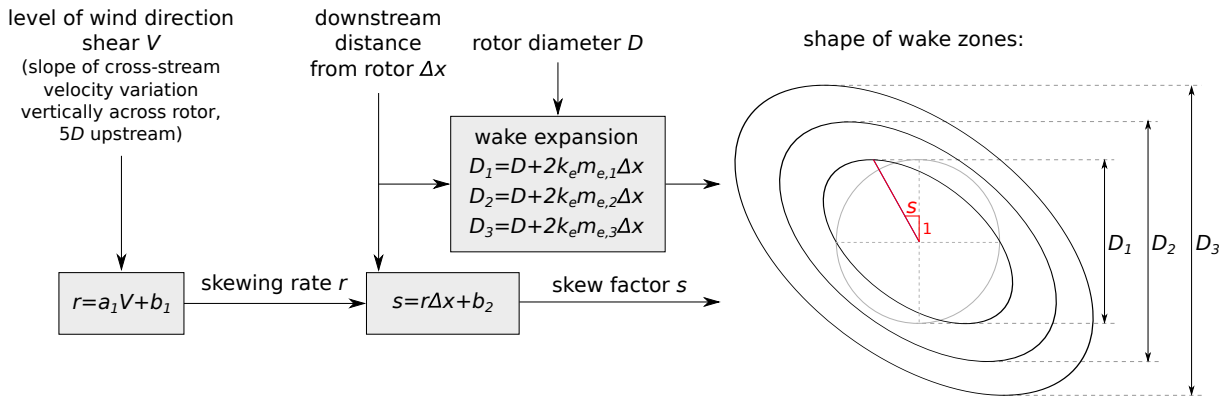


Figure 3: Parameterization of the wake shape with respect to downstream distance x and the level of wind direction shear V .

Table 1: Parameter values for the FLORIS Ellipsoid model, related to expansion, velocity recovery, and skew. Different expansion and recovery parameters are set for the neutral case than for the stable cases. FLORIS parameters not given here are set the same as in [10].

	k_e	$m_{e,1}$	$m_{e,2}$	$m_{e,3}$	$m_{U,1}$	$m_{U,2}$	$m_{U,3}$	a_1	b_1	b_2
neutral case	0.055				0.8	1.0	5.5			
stable cases	0.105	-0.5	0.25	1.0	0.25	0.4	5.5	-0.088	-0.000123	0

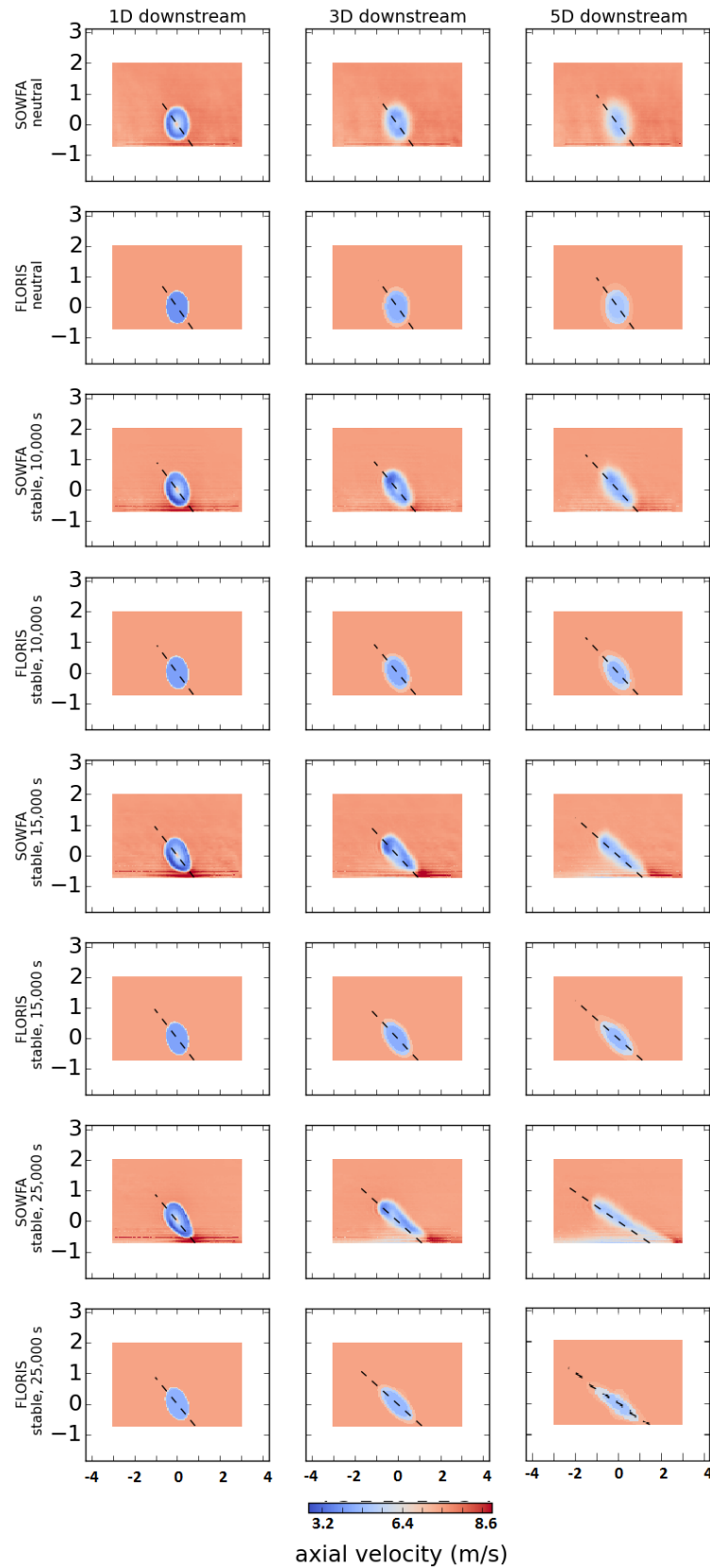
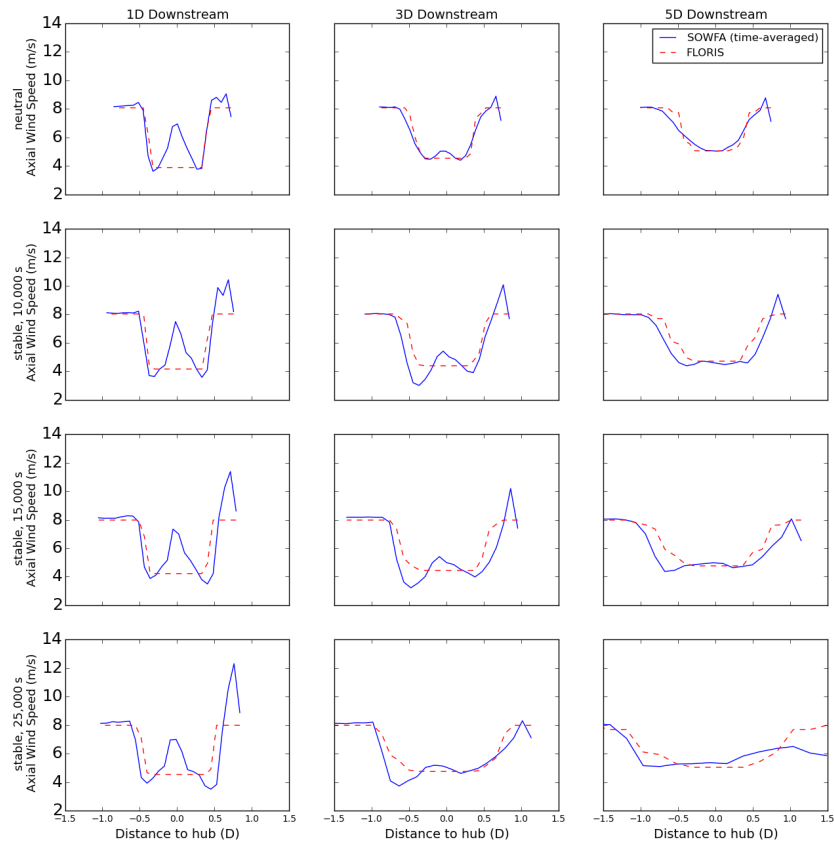
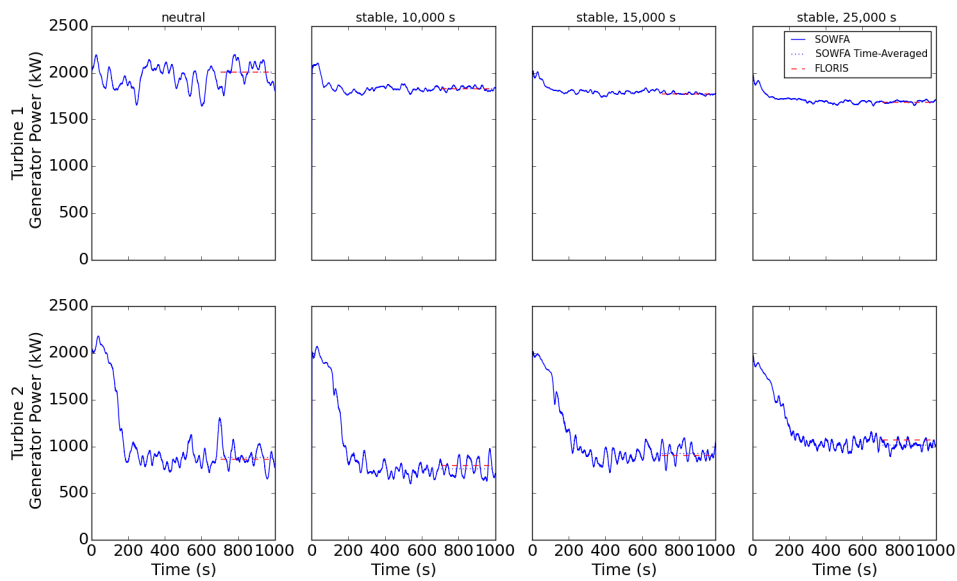


Figure 4: Vertical cross-stream contour planes of time-averaged streamwise velocity (velocity shear removed). Both the x-axis and y-axis have units of rotor diameters with respect to hub.



(a) Wake velocity profiles along diagonal shown as black dashed line in Figure 4 (blue = SOWFA, red dashed = FLORIS).



(b) Turbine power production.

Figure 5: FLORIS and time-averaged SOWFA results compared for a stable and neutral case. The SOWFA results are averaged over the last 300 s of the turbine simulation, where the generated power of Turbine 2 has reached a quasi-steady state.

5. Conclusion and future work

This paper presented a method to incorporate atmospheric stability effects on the wake into FLORIS, an engineering wake model that is an extension of the Jensen model. By allowing the wake to have a tilted elliptical shape, the effects of wind direction shear in the stable atmosphere could be incorporated. It was shown that this allowed a fit of the engineering model with high-fidelity CFD simulation results for a two-turbine setup in the stable atmosphere.

In the context of wake modeling with the aim of wind farm wake control, relevant future work would be to improve the modeling of the effects of control offsets on the wake in different atmospheric stability conditions. Relevant related work is the LES study of yaw-based wake deflection in stable and unstable atmospheres, presented in [15]. Once atmospheric stability effects are fully incorporated in the engineering models, researchers can evaluate how stability conditions impact optimized wake control methods for wind farms, and possibly the design of the wind farm layout.

Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding for the work was provided by the DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office.

The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

References

- [1] Abkar M and Porté-Agel F 2015 *Physics of Fluids* **27** 035104 URL <http://dx.doi.org/10.1063/1.4913695>
- [2] Churchfield M J, Lundquist J K, Quon E, Lee S and Clifton A 2014 Large-eddy simulations of wind turbine wakes subject to different atmospheric stabilities *American Geophysical Union Fall Meeting*
- [3] Bromm M, Vollmer L and Kühn M 2016 *Wind Energy*
- [4] Peña A, Réthoré P E and Rathmann O 2013 Modeling large offshore wind farms under different atmospheric stability regimes with the Park wake model *Proceedings of the 2013 International Conference on aerodynamics of Offshore Wind Energy Systems and wakes (ICOWES2013)*
- [5] Gebraad P M O, Teeuwisse F W, van Wingerden J W, Fleming P A, Ruben S D, Marden J R and Pao L Y 2014 *Wind Energy* URL <http://dx.doi.org/10.1002/we.1993>
- [6] Churchfield M and Lee S 2014 NWTC information portal (SOWFA) <https://nwtc.nrel.gov/SOWFA>
- [7] Churchfield M J, Lee S, Michalakes J and Moriarty P J 2012 *Journal of Turbulence* URL <http://dx.doi.org/10.1080/14685248.2012.668191>
- [8] Sørensen J N and Shen W Z 2002 *Journal of fluids engineering* **124** 393–399
- [9] Jonkman J 2014 NWTC information portal (FAST) <https://nwtc.nrel.gov/FAST>
- [10] Gebraad P, Thomas J J, Ning A, Fleming P and Dykes K 2016 *Wind Energy* URL <http://dx.doi.org/10.1002/we.1993>
- [11] Jensen N O 1984 A note on wind generator interaction Tech. Rep. Risø-M-2411 Risø National Laboratory
- [12] Hughes G B and Chraïbi M 2012 *Computing and Visualization in Science* **15** 291–301 ISSN 1432-9360 URL <http://dx.doi.org/10.1007/s00791-013-0214-3>
- [13] National Renewable Energy Laboratory 2016 FLORISSE ELLIPSE GitHub repository <https://github.com/WISDEM/FLORISSE/tree/ellipse>
- [14] Larsen G C, Madsen Aagaard H, Bingöl F, Mann J, Ott S, Sørensen J N, Okulov V, Troldborg N, Nielsen N M, Thomsen K *et al.* 2007 Dynamic wake meandering modeling Tech. rep. Risø National Laboratory
- [15] Vollmer L J, Steinfeld G, Heinemann D and Kühn M 2016 Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: An LES study *Wind Energy Science Discussions*