Overview of FLORIS updates

Paul Fleming, Jennifer King, Christopher J. Bay, Eric Simley, Rafael Mudafort, Nicholas Hamilton, Alayna Farrell, and Luis Martinez-Tossas
National Wind Technology Center, National Renewable Energy Laboratory, Golden, CO 80401 USA
E-mail: paul.fleming@nrel.gov

Abstract. In this paper, we review updates made to the FLORIS (FLOw Redirection and Induction in Steady State) open-source framework for wind farm control modeling, design and analysis. The updates are focused on improvements for large arrays of turbines - including heterogenous inflows and incorporating second-order wake steering effects - design, and analysis tools for practical application of wind farm control, and improvements to the software architecture for best practices in modularization and cooperative development.

1. Introduction
FLORIS [1] (FLOw Redirection and Induction in Steady State) is an open-source framework, developed originally by the National Renewable Energy Laboratory (NREL) and TU Delft, which includes both control-oriented wake models as well as tools used for the design and analysis of wind farm control strategies. FLORIS was first developed to provide a model of wake control methods, such as axial control, and especially wake steering [2]. Since its initial development, it has continually been improved and updated, and has been used for an expanding number of use cases. FLORIS is open-source and shared freely on github.com at https://github.com/NREL/floris.

Over the past year, a number of important improvements and advances to FLORIS have been incorporated. These improvements cover a range of areas within FLORIS and are typically the subject of separate individual journal papers. In this paper, we holistically cover these updates and how they cooperatively work together to improve wind farm control modeling, design, and analysis.

There are three central themes of the updates. The first theme is improvements focused on applying wind farm control on large arrays of turbines. These updates include modeling heterogeneous inflows and modeling how wake control affects large arrays of turbines. A second theme is the practical implementation and validation of wind farm control. A central consideration of practical implementation is accommodating the uncertainty inherent in field application of wind farm control. Implementation of uncertain optimization, in addition to static optimization strategies, are now included within FLORIS. Further, several field validation studies of FLORIS have now either been accomplished or are under way; these will be reviewed in this paper.

A third theme is increasing international collaboration. The FLORIS framework has again been revised to more easily accommodate models of wakes developed internally and externally to
NREL. These updates include further modularization and improvements to the software design to better support open-source collaboration.

The central goals of this paper are to demonstrate the updates present in FLORIS since the initial public release, v1.0.0, as well as to document how researchers can make use of the growing tool base in their work. By sharing the research code openly and encouraging collaboration across institutions, we hope to broaden the impact of research in wind farm controls, make results more accessible and reliably transferable to industrial practice.

2. Large array updates

Originally, FLORIS was developed and calibrated against large-eddy simulations using the NREL tool Simulator fOr Wind Farm Applications (SOWFA) ([3]) consisting of pairs of turbines interacting through their wake ([4]). This work led to the initial implementation of FLORIS as an expanded multizone version of the Jensen wake deficit model, coupled to the Jimenez model of wake deflection ([2], [5]). In ([6]) it was shown that one issue with this model is that wake expansion was not affected by changes in control or turbulence, which made assessing strategies, such as axial control, difficult. Implementing versions of the Gaussian wake deficit and velocity models of ([7], [8], [9]) as options within FLORIS provided thrust and turbulence dependence, and this Gaussian model became the default wake model used within FLORIS. The Gaussian model was, for example, used in the first phase study of a field validation campaign of wake steering in ([10]).

Recent studies have demonstrated a need for further refinement of the models to capture effects important to modeling larger arrays of turbines operating in realistic conditions and layouts. These modifications will be covered in this first section.

2.1. Counter-rotating vortices in wake steering

As described earlier, FLORIS was originally constructed to model and predict the changes in power production for wake control implemented for two-turbine layouts. In ([11]), LES were used to show that for wake steering applied to larger arrays of turbines, the counter-rotating vortices generated in wake steering affect an interaction of steered wakes not included in the state-of-the-art engineering models. These vortices, noted in earlier papers ([12], [13]), generate additional effects, termed secondary steering, wherein the wake of a nonsteered turbine is laterally deflected, influenced by steered wakes of upstream turbines.

In ([14]), an engineering model of wake steering, including these counter-rotating vortices, the so called curl model, is designed. It is then implemented into FLORIS in ([15]). The curled wake model is solved in a marching fashion and thus requires a full flow-field grid, which increases the computation time over other engineering models. However, the additional physics that are modeled capture the deformation of the wake from the generated counter-rotating vortices, as shown in Fig. [1]. The center of the wake is also displaced from directly downstream of the turbine. Examples are included in FLORIS that demonstrate how to execute the curled wake model.

Although very useful for exploring and understanding the key physical phenomena of wake control, as a gridded model, the curled wake model is more computationally expensive than analytical models, such as the Gaussian model of ([7]). Fast analytical models with low computational costs, which can be computed in fractions of a second, are very important for the suite of engineering processes in wind plant analysis, the design of wake control strategies, and layout optimization such as ([16]).

To implement the flow physics observed in secondary steering without increasing the computational costs of wake modeling, a new Gauss-Curl Hybrid (GCH) model was implemented and defined in ([17]). The model combines aspects of the Gaussian model of ([7], [8], [9]) with an analytical approximation of the curl model in ([14]). The GCH model is now implemented in FLORIS as a pair of possible modifications to Gaussian models of wake deficit and wake
deflection. The first modification, called *yaw-added recovery*, modifies the wake recovery based on the effects of the yaw-induced vortices. The second modification is *secondary steering* caused by the modeled vortices’ impact on downstream turbines. In [17], it was shown that the two effects improve both FLORIS’ ability to determine optimal yaw angles for larger arrays of turbines and to better predict impact on power in LE simulations. Further, the optimal yaw angles fit a pattern of decreasing yaw angles which accord with the result found in wind tunnel studies in [18]. In [19], the GCH model of wake control in FLORIS is compared positively to results of a field campaign of wake steering in predicting changes in energy production.

2.2. Heterogeneous inflows

Previously, all models within FLORIS assumed a single (hub-height) wind speed, direction, and turbulence intensity (however, shear and veer could be included in the inflow). This is a reasonable assumption for pairs of turbines, however, for larger, wind-farm-sized arrays, this limitation can lead to errors in modeling because the actual inflow can be spatially heterogeneous.

Researchers in [20] present an update to FLORIS that models the atmospheric inflow as a heterogeneous field with spatially varying wind speed, direction, and turbulence intensity. In the paper, this is shown to lead to an 18% reduction in error of forecasting the total power of a commercial wind farm. This improvement is now included by default, with homogeneous inflows being a special case of general heterogeneously defined inflows.

2.3. Demonstration of GCH and Spatial Heterogeneity

In this section, we take a case study of an LES of a 38-turbine wind farm (adapted from [17]). Both GCH and heterogeneity would be expected to improve FLORIS’ prediction of power given the size of the farm and the presence of arrays of turbines aligned to the flow. The simulation is run in LES for one inflow case of 8 m/s and 9% turbulence intensity (TI) in two conditions: all turbines aligned and turbines yawed to expected optimal values. The results are then compared to two FLORIS implementations: One assuming homogeneous inflow conditions and without GCH enabled, and a second using heterogeneous inflow and the yaw-added recovery and secondary steering physics in the GCH model. The homogeneous inflow speed is calculated as that which provides the least error to the power of unwaked freestream turbines, while the heterogeneous is defined similarly but allowed to vary across the front row of turbines (but assumed in this case to be unchanging along the wind direction). The wind direction and ambient turbulence intensity are assumed to be homogeneous in all cases. The results of each case are visualized in Fig. 2.

Starting by considering the all-aligned condition, switching from homogeneous to
Figure 2: Comparison of average flow across simulations for all turbines aligned (left column) or in wake steering mode (right column). A central row where the turbines are well-aligned to the flow is highlighted to call attention to the presence or lack of secondary steering.
heterogeneous lowers the error in total power production by 15% (from 5.3% to 4.4%). Note this simulation is not expected to have much heterogeneity, the impact (as shown in [20]) can be more substantial for farms with terrain, inducing a more substantial effect.

Then considering the expected benefit from wake steering, SOWFA reports a gain in power production in baseline of 3.1%. The homogenous case without GCH predicts a gain of only 0.6%, while the heterogenous GCH case predicts 2.6%. For a good explanation of why the gain increases, it’s useful to consider the well-aligned row highlighted in Fig.2. The powers of those six turbines are visualized in Fig.3. In the left pane, the powers of the yaw-aligned case for the row are in better agreement using the heterogenous inflow. Then in the right pane, the gains in power from yawing the turbines is much better matched with the inclusion of secondary steering from GCH (note the largest misses are in the rear of the row, where modeling secondary steering is most important).

Figure 3: Comparison of the turbine powers in the highlighted row of turbines in Fig. 2

2.4. Near-Wake and Alternative Gaussian Models
A final update to wake models in FLORIS is the modification of the Gaussian model already implemented (based on [7, 8, 9]) with methods proposed for improving the near-wake power prediction.

The paper [21] describes a super-Gaussian formulation of the wake deficit model that produces a near-wake profile that better conforms to LES and wind tunnel results. The previous Gaussian model in FLORIS uses the model of [7, 8, 9] to model the far wake, and a linear interpolation is used to model the near wake.

A version of this super-Gaussian model is now implemented in FLORIS. The FLORIS implementation adapts the method of [21] slightly to ensure that at around 5-6 diameters behind the rotor, the results are nearly identical to the previous Gaussian model implementation. This was done to ensure consistency with previous results which were mostly beyond the near wake. Fig. 4 compares the new Gaussian model, including the suggested formulation of Blondel compared with the previous Gaussian model, and newly run LES results. The results show much improved agreement in the near wake, while maintaining very similar results past 5 diameters downstream.

An alternative Gaussian wake model with an explicit near-wake formulation was introduced in [22]. As opposed to the super-Gaussian approach of [21], the model proposed by Ishihara and Qian introduces an additional term in the amplitude of the velocity deficit that only makes a significant impact in the near-wake region, and thus does not introduce significant deviations from other Gaussian wake models in the far wake. In addition, the work by [22] refra...
the model parameters such that they are all similarly defined as a combination of the thrust coefficient and the TI incident on a given wind turbine. This effectively expands the parameter space, enabling more options to tune the model to match training data. The velocity deficit model of Ishihara and Qian is implemented in FLORIS but has not yet been tuned to mirror previous FLORIS modeling results.

3. Practical application updates

Recent research emphasis in wind farm control has increasingly moved toward investigation into the practical application of control methods such as wake steering. This can include investigations into the impact of uncertainty (cf. [23, 24]), or the design of closed-loop controllers ([25, 26]), or the methods for design and analysis of wind farm control experiments.

3.1. Optimization

The FLORIS framework includes methods for design of wind farm control strategies as well as analysis. Previously, design of wake steering controllers was performed through an optimization of the farm model for a fixed wind direction, yielding the static optimum. However, in the current update to FLORIS, robust methods for computing the dynamic optimum, by assuming uncertainty in measurements, as well as accounting for the dynamics of the yaw controller, can now be performed.

Robust optimization methods are implemented in FLORIS according to the methods described in [27]. Because yaw controller dynamics are typically slow to help mitigate loads, a turbine’s yaw position may remain fixed for several minutes before the turbine yaws again, while the wind direction varies significantly. Additionally, the yaw controller may settle on a different yaw offset than was originally intended, depending on the dynamics and hysteresis of the controller. Finally, uncertainty may exist in the wind direction and yaw position measurements used by the controller. Consequently, optimum yaw offsets assuming known, fixed wind directions might be suboptimal in a dynamic wind environment. The effects of wind direction and yaw position uncertainty resulting from dynamic wind conditions are modeled in FLORIS by including a distribution of wind directions and yaw offsets centered on the intended wind direction/yaw offset combination when calculating wind farm power [27]. Examples are provided
in FLORIS illustrating how to find robust optimum yaw offsets, assuming wind direction and yaw uncertainty. As explained in [27], robust yaw offsets are typically smaller than the static optimum offsets, but result in larger power gains in the presence of uncertainty. FLORIS users can provide their own probability distributions for wind direction and yaw uncertainty or rely on the default Gaussian distributions.

3.2. Field Validation
There are several ongoing validation projects to compare FLORIS either to historical supervisory control and data acquisition (SCADA) of wind farm behavior or to the results of FLORIS designed wake steering field validation campaigns.

![Figure 5: Example of energy ratio calculation included in FLORIS. In (a) the layout of three turbines is shown, a control turbine, test turbine downstream, and an unaffected reference turbine. The control turbine is aligned to the flow in the baseline case, and has a fixed yaw offset in the controlled case. The energy ratio shown in (b) represents the energy production of the test turbine relative to that of the reference turbine as a function of wind direction.]

Often, FLORIS and field results are compared using a method called the energy ratio. The energy ratio function is included in FLORIS to facilitate open collaboration on analysis in a similar way as the open wake models. In addition, FLORIS includes example scripts to demonstrate the method of implementation of energy ratio analysis; an example is visualized in Fig. 5. In the example, the energy ratio of a waked test turbine over a freestream reference turbine is computed by wind direction. The test turbine is in the wake of a controlled turbine, which, in the baseline case, operates normally and in the controlled case implements a fixed yaw offset.

Several important validation studies of the models in FLORIS have been undertaken recently. In [10], a wake steering controller designed using FLORIS’ implementation of the Gaussian model is described. The controller is derived through a static optimization and implemented using a look-up table based on the turbine’s measurement of wind speed and direction. In [19], the phase 2 results were presented. In the second phase, the controller was redesigned using the uncertain optimization approach of [27]. The Gaussian model was again used in design, but in the analysis the results were compared against the GCH model of [17]. The effect of wake steering on a downstream turbine is shown in Fig. 6. The results are expressed as the energy ratio of the waked turbine to a reference unwaked turbine.

Other ongoing field campaigns afford the opportunity to compare the latest wake models to field data for larger arrays of turbines operating normally (not yawed). Fig. 7 shows the energy ratio results for the second, third, and fourth turbines of a four-turbine array within a commercial wind farm during normal operation.
Figure 6: Energy ratio of the downstream turbine from [19]. The result compares the energy ratio measured in the field campaign, with the controller off (Baseline) or on (Controlled), and compares these results with those predicted by FLORIS using the GCH model. Note the shaded regions indicate the areas where wake steering is applied.

Figure 7: Comparing the results of latest FLORIS model (red) against the energy ratios collected from an array of four turbines at a commercial site (blue), where the energy ratio of the second, third and fourth turbines are compared with the first. Note the third turbine is on a hill, accounting for the increased power production relative to the upstream turbine.

4. Software updates
A final set of updates to FLORIS is to further enable community collaboration and provide a framework for developing and testing new wake models. In that regard, FLORIS as an open source software has undergone procedural and organizational changes that enable a more sustainable workflow for further development.

4.1. Framework Modularization
To establish a more consistent and flexible framework, modularization has been improved and expanded in the code structure. In addition to the existing modular hierarchy for velocity deficit, wake deflection, and wake combination models, the turbulence intensity models have been fully abstracted. A further level of abstraction has been added where a class of model exists and derivatives warrant a standalone model. Fig 8 describes the current modular organization and classes of wake model components, where they exist in the software, and how they are implemented in an instance of FLORIS.
Ongoing work in this regard will lead to more modularization among the functions that couple the wake models and perform the wake calculation throughout the wind farm. Specifically, NREL is targeting a fully generic, user-specified solver scheme along with fully interchangeable models that would allow researchers to modify existing models or add entirely new models easily. For a more detailed description of the software architecture see https://floris.readthedocs.io/en/master/source/code.html.

4.2. Sustainability in open source software

The workflow for general collaboration among developers of FLORIS has been slightly modified and become well established. The expectation is that all work in progress will take place on the developer’s fork of the FLORIS repository. Active development should follow the git-flow model where the master branch is the release branch, develop contains generally stable but unreleased updates, and feature/branch-name contains partially completed work that should carry no expectation of stability and correctness. The feature/* branches are frequently merged into develop, and develop is infrequently merged into master. Interaction between forks should generally happen through GitHub Pull Requests. Following this model, FLORIS has successfully merged a number of pull requests over the past year from developers external to NREL.

In addition to code collaboration, FLORIS has established a more effective support process for handling bugs and issues. For programming, syntactic, and usage questions, a tag has been created on StackOverflow that aggregates all FLORIS-related questions and alerts followers of the tag of new questions. The tag is simply floris. For all other questions, the GitHub Issues page has become the primary mechanism for identifying bugs, collaborating on work assignments, and tracking the status of fixes. Both the StackOverflow tag and the GitHub Issues have had organic community traffic throughout the year.

Finally, several improvements to the general infrastructure have been incorporated. The test suite has been expanded to incorporate more unit tests and improved regression tests, and a code coverage tracker was added to quantify the amount of coverage in the tests. A more complete continuous integration pipeline has been developed that runs all tests for every commit and automatically deploys releases to the PyPi and Conda repositories. The documentation and a rich series of examples have continuously been expanded and improved. Logging has been formally introduced, enabling a consistent format for displaying various levels of data to the users.
user and allowing users to request more or less verbose output.

Through these improvements, we hope to foster an environment of open collaboration in wind farm control, where models and methods can be compared in an open framework, encouraging collaboration and repeatability of results.

5. Summary
FLORIS is a software framework that provides wake models and wind farm control design and analysis methods. Recent updates to FLORIS improve FLORIS’ modeling, design and analysis capabilities, as well as improve functionality toward open collaboration. FLORIS is a living code, and we will continue to incorporate new research and welcome open collaboration with others interested in contributing new models, design or analysis tools, or validation.

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