LITERATURE REVIEW

BP Wind Sim Team

Bert Yan, Penn State University

David Rohrbaugh, Penn State University

Marissa Stecko, Penn State University

Nelloe Anonyuo, Penn State University

Scott Carroll, Penn State University

Seilayo Olagbami, Penn State University

Shuaipeng Dong, Penn State University

Work Distribution | MechE, CMPSC subgroups

Mechanical Engineering | Members

Marissa Stecko, Scott Carroll

Outline

I. Basics of a Wind Turbine (Stecko and Carroll)
II. Wake Modeling Strategies (Stecko and Carroll)

Computer Science | Members

Bert Yan, David Rohrbaugh, Nelloe Anonyuo, Seilayo Olagbami, Shuaipeng Dong

Outline

III. Software Investigation
  a. SCADA International by Bert Yan
  b. OpenFAST by Bert Yan
  c. FLORIS by David Rorhbaugh
  d. Ashes by Seyilayo Olagbami and Nelloe Anonyuo
  e. PyWake by Shuaipeng Dong
  f. QBlade by Bert Yan, David Rorhbaugh, and Shuaipeng Dong

Mechanics | Basics of a Wind Turbine

Most wind turbines consist of 3 blades, varying greatly in size depending in location. These blades act as large airfoils, creating a pressure gradient across the blade that causes motion of the turbine, generation energy (U.S. Office of Energy Efficiency & Renewable Energy, n.d.). The taller that a wind turbine is, the faster winds it will experience, thus having a higher potential for energy generation. Winds at elevation around and above 30 meters (100 ft) are optimal for operation as winds are consistently faster and less turbulent (U.S. Office of Energy Efficiency & Renewable Energy, n.d.). Safe operation of wind turbines is between 7-65 mph; speeds any lower will not generate net positive energy, and speeds any higher will likely damage the mechanics of the turbine (U.S. Office of Energy Efficiency & Renewable Energy, n.d.).

Wind turbines are designed to operate optimally when facing directly into the wind. Yaw misalignment describes an orientation of the rotor where it is rotated at an angle with respect to the oncoming wind. Turbines were not designed to be operation this way, so operating turbines in yaw misalignment can place damaging stressors on the turbines, as well as negatively impacting the efficiency of energy generation (WindESCo, 2020). Yaw misalignment can be measured by sensors on the wind turbines, such as wind vanes and accelerometers. Yaw alignments can be changed can corrected by yaw motors in the turbines designed to rotate the nacelle back to the desired position (WindESCo, 2020).

Wind turbines create a wake behind them that can affect the efficiency of the other turbines in the wind field. Once proposed solution to increasing the efficiency of a wind field is applying intentional yaw misalignment to steer wakes away from downstream turbines (Nash, 2021). Referenced work done previously and documented in literature regarding the optimal positioning for yaw misalignment will be a helpful step in applying intentional yaw misalignment strategies to 3D-modeling software.

Mechanics | Wake Modeling Strategies

Free vortex wake (FVW) and low-fidelity blade-element momentum (BEM) simulation models are used to provide estimated outcomes for the wakes of turbines in a wake field (Harrison, 2018). Efficacy of each modeling method will need to be compared since the difference in computation processes between the two methods will yield different results. In a study conducted by Kelsey Shaler out of the National Renewable Energy Laboratory in Colorado, USA, the differences between these free vortex wake (FVW) and blade-element momentum (BEM) results were discussed in depth (Shaler, 2022). Differences in simulation output were evaluated for various parameters (inflow, shear and yaw misalignment), and compared to high-fidelity SOWFA results. For steady inflow with no yaw misalignment present, both FVW and BEM methods gave comparable results. However, when yaw misalignment was factored into the simulation FVW methods produced much more accurate results when the BEM method did when compared to the SOWFA standard. FVW yielded approximately 1.2% error consistently, whereas BEM methods were up to 48%, particularly during turbulent inflow conditions coupled with yaw misalignment. In conclusion, FVW models produce results that are more computationally accurate that BEM models when being compared to SOWFA standards, thus FVW models would be best to use when simulating wake of turbines in a wind field.

References

Harrison, M. (2018). Aerodynamic modelling of wind turbine blade loads during extreme deflection events. *Journal of Physics: Conference Series, 1037*(6). Retrieved from IOP Science: https://iopscience.iop.org/article/10.1088/1742-6596/1037/6/062022

Nash, R. (2021, August 12). Wind turbine wake control strategies: A review and concept proposal. *Energy Conversion and Management, 245*. Retrieved from https://doi.org/10.1016/j.enconman.2021.114581

Shaler, K. (2022, January 12). Comparison of Free Vortex Wake and BEM Structural Results Against Large Eddy Simulations Results for Highly Flexible Turbines Under Challenging Inflow Conditions.

European Academy of Wind Energy. Retrieved from https://wes.copernicus.org/preprints/wes-2021-130/wes-2021-130.pdf

U.S. Office of Energy Efficiency & Renewable Energy. (n.d.). *How a Wind Turbine Works*. Retrieved from Energy.gov: https://www.energy.gov/eere/wind/how-wind-turbine-works-text-version

WindESCo. (2020, June 16). *What is Yaw Misalignment?* . Retrieved from WindESCo: https://www.windesco.com/blog/what-is-yaw-misalignment#:~:text=Any%20measured%20difference%20between%20the,is%20known%20as%20yaw%20misalignment.

SCADA International | Researched by Bert Yan

Software Solution | Name of the Product

- SCADA International's One View SCADA
  - Utility Constrained Maintenance Based Optimization
  - SCADA monitoring for Vestas wind turbines
- SCADA International's OneView Universal Park Controller
  - Intermediate Historian

Description | Work Summarization

- OneView® Park SCADA solution allows for asset management at all levels.
  - As a mature product that had been developed for years, working with the industry, we can learn many things from their software.
- Provides extensive feedback data to customers.
  - The eventual simulation we will develop will likely allow for providing quite a bit of outputs that can be beneficial to subsequent studies, we can also learn what typical data they output are looked at most.
- Enables customers to run the system on own hardware or explore hosted solution
  - The project will likely be run locally at this stage, BP's Azure services will likely be introduced to next semester's team.
- Get a flexible pricing module and choose the way you pay
  - Not relevant to the project.

Project Relevance | How the Software Relates to The Project

SCALA's products are focused on end-users, providing detailed control over all levels of the wind farms, and providing necessary information via the extensive GUI the company had developed. This product can be a useful resource providing insights to top-level interfacing GUI design. As the current project is asking for wake steering manipulation simulation, one of the deliverables could be developing such a GUI to work with the steering simulation for simulated end-user controlling. For this purpose, we can develop such interface using React.JS for this application.

Legal & Financial | Why This Items May or May Not Cause Legal/Financial Issues

Currently, BP company uses the SCADA International software products to maintain the wind farm parks, in-land and off-shore. The attempt in researching in the SCADA International software is to understand how BP uses SCADA OneView in their systems of control, SCALA as itself is an extensive learning subject for this 12-week project. BP has included examples of how they have utilized this software as potential resources for the team.

Utilization | Whether or Not the Software Will Be Used in The Project

As the sponsors at BP intends to have our final deliverable to have the ability to be further developed into a training tool, then as the primary control software BP uses, there is a lot to learn from the product. Given that the nature of this project is an academic study, we will not be using the product, but we can ask the sponsors of what features they interact most with the software that they would like to see on our simulation GUI.

References | Links

https://scada-international.com/?utm_medium=cpc&utm_source=google.com&utm_campaign=home+page&gclid=Cj0KCQjwpeaYBhDXARIsAEzItbFvsI5ztz7BiRujqE_88xZequo52sbLUkeJxHPJC_vkNH4ImFiXSFEaAmYMEALw_wcB

OpenFAST | Researched by Bert Yan

Software Solution | Name of the Product

OpenFAST V8

Documentation: https://openfast.readthedocs.io/en/main/source/this_doc.html

Description | Work Summarization

OpenFAST is an open-source wind turbine simulation tool that was established with the FAST v8 code as its starting point.

- As pointed out by Marissa, OpenFAST has incorporated a new FVW model—cOnvecting LAgrangian Filaments (OLAF)—was added to the National Renewable Energy Laboratory engineering tool OpenFAST to allow for the aerodynamic modeling of highly flexible turbines along with the aerohydro- servo-elastic response capabilities of OpenFAST.
- Open-source wind turbine simulation tool
- Used in accordance with NREL, can be considered the top choice for simulation construction. Bert can research more into this.
- Well-documented GitHub Repository
- A new API has been added that provides a high-level interface to run OpenFAST through a C++ driver code helping to interface OpenFAST with external programs like CFD solvers written in C++
- Might be easier to program
- Licensed under apache

Project Relevance | How the Software Relates to The Project

Since OpenFAST has vast learning tutorials and excellent documentation, we are considering this simulation tool as one of the potential candidates for this project. While C and C++ do provide a more complex challenge as compared to Python-written simulation tools, its capability far outweighs the liability, meaning that the framework OpenFAST composed of couples computational modules for aerodynamics, hydrodynamics for offshore structures, control and electrical system (servo) dynamics, and structural dynamics to enable coupled nonlinear aero-hydro-servo-elastic simulation in the time domain, many of which are what the project sponsor at BP are looking for as project deliverables. We will do further research to make comparison among the software listed, specifically looking at what inputs and outputs will each simulation tool offer and what BP would like to see as well.

Legal & Financial | Why This Items May or May Not Cause Legal/Financial Issues

There will not be potential legal issues as OpenFAST is a recognized open-source software maintained by groups at NREL, the National Renewable Energy Laboratory, which allows for use in academic studies. The OpenFAST software, including its underlying modules, are licensed under Apache License Version 2.0 open-source license.

Utilization | Whether or Not the Software Will Be Used in The Project

As a potential candidate to building the simulation on, we will need to investigate the differences in the modeling parameters each potential tools have. According to a study led by Sebastian Perez-Becker, "OpenFAST and QBlade are set up so that their only difference is the implemented aerodynamic model. OpenFAST uses AeroDyn – an implementation of the BEM method – and QBlade uses an implementation of the LLFVW method". In their conclusion, the different choices of the aerodynamic models led to some quite drastic outputs. We will need to consult on our sponsors at BP to know which one is more closely related to their data, or to say, a more accurate simulation.

References | Links

Sebastian Perez-Becker, et al:
https://wes.copernicus.org/articles/5/721/2020/#:~:text=OpenFAST%20and%20QBlade%20are%20set,implementation%20of%20the%20LLFVW%20method.

OpenFAST Documentation:

https://openfast.readthedocs.io/en/main/

Floris | Researched by David Rohrbaugh

Software Solution |Name of the Product

The software is called FLORIS and it stands for Flow Redirection and Induction in Steady State. Floris is an open-source software developed by the National Renewable Energy Laboratory (NREL).

Description | Work Summarization

Floris is a python program that implements a steady state engineering wake model with a focus on performance. Floris takes in many inputs including the wind speed, wind direction, x and y coordinates of the wind turbines, wake deflection parameters, wake velocity parameters, and wake turbulence parameters. After these inputs are provided the simulation can provide the power output of each of the wind turbines for the specified wind speed and wind direction. The simulation also allows for the user to manually change the yaw of individual wind turbines as well as the ability to perform wake steering on the wind farm and it provides the optimal yaw angles for the wind turbines. Floris also has other output options like calculating the annual energy production. It calculates this by having the user input possible wind speeds and wind directions and the simulation assumes that all wind speeds and directions are equally likely to occur. One more output Floris has is it can output a 2d visualization of the modeled wake for the wind farm.

Project Relevance | How the Software Relates to The Project

Floris lays the groundwork for a lot of the project as it provides several models that can be used for simulating a wind farm. It also provides a lot of the outputs we are looking for like the annual energy production and the visualization of the wake. One component that Floris does not have that we may be looking for is that there is no graphical user interface where someone could modify the values in real time and see how that affects the simulation. So, if we choose to move forward with this simulation that would be something we would need to implement ourselves. Although another advantage it has is that because it is built in python it will likely be easier for us to use and develop with compared to some other software out there.

Legal & Financial | Why This Items May or May Not Cause Legal/Financial Issues

There will not be any legal or financial concerns with this software. Floris has an Apache license which means we can use the software for any purpose without the need for any financial obligation.

Utilization | Whether or Not the Software Will Be Used in The Project

At this time, we are not sure if this will be used but it certainly is a contender for use within our project.

References | Links

https://www.nrel.gov/wind/floris.html

https://github.com/NREL/floris

Ashes | Researched by Seyilayo Olagbami and Nelloe Anonyuo

Software Solution | Name of the Product

Ashes which stand for aero-servo-hydro-elastic simulation is a Wind turbine simulation software developed by Simis is a spin-off company from the Norwegian University of Science and Technology (NTNU) established in 2013.

Description | Work Summarization

Ashes is a software that performs integrated analyses of onshore and offshore wind turbines. The script for the software is written in Python.

Ashes provides a set of built-in templates that enables you to quickly create a wind turbine model which can be further customized. Airfoil data for a set of commonly used airfoils is integrated into Ashes, and these can be used when defining the blades on the turbine.

A fully integrated simulation of a wind turbine in Ashes includes loads such as wind loads, sea waves, gravity, buoyancy, and generator loads. Arbitrarily large motions of the full structure can be simulated accurately, which is especially important in the design of floaters. Ashes is capable of modeling flexible blades, thus including effects that are becoming increasingly important in today's larger and more slender designs. Both the built-in control system or an external one can be used to control the generator and pitch/yaw actuators.

Project Relevance | How the Software Relates to The Project

Ashes visualizes wind and wave loads and the resulting response of the wind turbine in a live, real-time manner during simulations. At any time, the simulation speed can be increased or decreased, and different parts can be studied close-up.

Data generated during the simulation is gathered in a collection of sensors, where each individual time series can be viewed live in graphs.

Legal & Financial | Why This Items May or May Not Cause Legal/Financial Issues

A 2-week evaluation is required by the developers for the full version of the application to be acquired. We would need to send the developers an email detailing what we plan to use the software for. It may also need a more powerful device to run on for optimal results

Utilization | Whether or Not the Software Will Be Used in The Project

Although the application is very well suited to our end goal it may be too detailed and complicated for us to consider using at this time. However, we are still considering our options.

References | Links

https://www.simis.io/#Products_Ashes_Features

https://www.simis.io/#Products_Ashes_References

https://www.simis.io/#Products_Ashes_Download

Pywake | Researched by Shuaipeng Dong

Software Solution | Name of the Product

The name of the software is Pywake

Developed by MIT for DTU wind energy

Description | Work Summarization

Pywake is an open-source library in Python that can simulate wind turbines and wind farms. It can calculate flow fields, power generation, and AEP (Annual energy production) of wind farms. It provides a unified interface and well-established APIs to create different wind turbine models. Pywake also provides predefined wake models such as NOJ, Fuga, BastankhahGaussian; Wind farm models like EllipSys Model.

Pywake also utilizes vectorization and numerical libraries as well as parallel processing to increase computation speed. Pywake supports three gradient computation methods: Finite Difference, Complex Step, and Automatic differentiation. Pywake has extensive built-in methods for gradient optimization, supports all wind turbine and wind farm classes.

Pywake also models change of operation due to reduced inflow speed, misalignment between thrust and downwind direction, and wake deflection die to traversal thrust component reaction. It also supports validation for wake and momentum deficit.

Project Relevance | How the Software Relates to The Project

Pywake library is relevant to the project because it provides modeling abilities to create wind turbines and wind farms with user defined parameters. It provides multiple wind farm base classes, that can handle blockage effects, and able to automatically achieve effective wind speed coverage, iterates until the effective wind speed coverage is achieved.

Legal & Financial | Why This Items May or May Not Cause Legal/Financial Issues

There are no legal or financial issues for this library because it is open-sourced, with Open-source MIT Licensing. Available for commercial use and modification of any kind, without liability and warranty.

https://github.com/DTUWindEnergy/PyWake/blob/master/LICENSE

Utilization | Whether or Not the Software Will Be Used in The Project

We are still considering which software to use

References | Links

https://topfarm.pages.windenergy.dtu.dk/PyWake/index.html#

https://github.com/DTUWindEnergy/PyWake

QBlade | Researched by David, Shuaipeng, and Bert

Software Solution | Name of the Product

QBlade v2.0

Description | Work Summarization

- QBlade uses Blade Element Momentum method (BEM) for its mathematical formulation (Mustafa et al, 2019)
- In a study led by Mustafa at University of Baghdad, they have concluded that the obtained simulation results using QBlade were of high accuracy, and it was proved that the QBlade software is reliable to analyze the blades of wind turbine.
- The software lists "Windfarm Simulations / Wake Interaction Studies" as one of its prominent use case/features, which can prove useful to this project.
- A highly advanced multi-physics code that covers the complete range of aspects required for the aero-servo-hydro-elastic design, prototyping, simulation, and certification of wind turbines.
- Allows you to run highly detailed simulations of any wind turbine design, with superior physics models more than 20x faster than real-time
- Easy to use GUI
- Dual Licensing – QBlade Community Edition, QBlade Enterprise Edition
    - Under the academic (Community) licensing, functionality of the platform is extremely limited as compared to the Enterprise edition.

Project Relevance | How the Software Relates to The Project

- QBlade implements very complex models for a wind turbine simulation that will be useful for this project. These complex models will allow us to generate accurate information regarding the power output of a wind farm.
- The GUI will allow for the user to change variables in real time to see how the change will affect the simulation, which is something that will be included in the software our team develops so this could provide a baseline on how we implement the GUI.

- The wake interaction feature from QBlade will be useful for this project as the main goal with this project is to optimize the wake steering to maximize the power output.

Legal & Financial | Why This Items May or May Not Cause Legal/Financial Issues

- This may encounter Legal/Financial issues for commercial use of this software, including consulting activities, design of commercial hardware or software networking products. Where we need to contact the author for appropriate licensing.
- https://qblade.org/assets/APL.txt

Utilization | Whether or Not the Software Will Be Used in The Project

QBlade would be a convenient software to use for research purposes. Since the software allows for wake interaction studies, it would be a great asset for us as that is the intended simulation scenario we want. As the software was suggested by the sponsors at BP, we will do more research on whether this is the platform we can build our project on or if QBlade has already done the necessary work we are supposed to do for this project. On the legal side of things, we will need to contact Cindy to find out if we can use this software as is or we will need to purchase the Enterprise license.

References | Links

Analysis of Wind Turbine Using QBlade Software, Mustafa Alaskari et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 518 032020

Qblade Official Website: https://qblade.org/