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Wind Turbine Modeling for Computational Fluid Dynamics

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Introduction and Motivation

In this work, a state-of-the-art wind turbine fluid dynamics model was implemented into an NREL-developed computational fluid dynamics (CFD) solver. The wake it produces was compared to high-quality experimental data. As the market for wind energy grows, wind turbines and wind farms are becoming larger. The wakes of upstream turbines affect the flow field of the ones behind them, decreasing power production and increasing mechanical loading. The distance over which these wakes extend depends strongly on the amount of turbulence contained in the atmospheric boundary layer. These complex fluid dynamics are not well understood. With a better understanding, wind farm developers could plan better performing, less maintenance-intensive wind farms.

Horns Rev wind farm off the coast of Denmark. The wakes of the first row of turbines propagate and affect the downstream turbines.
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Computational Approach

Wind Farm CFD

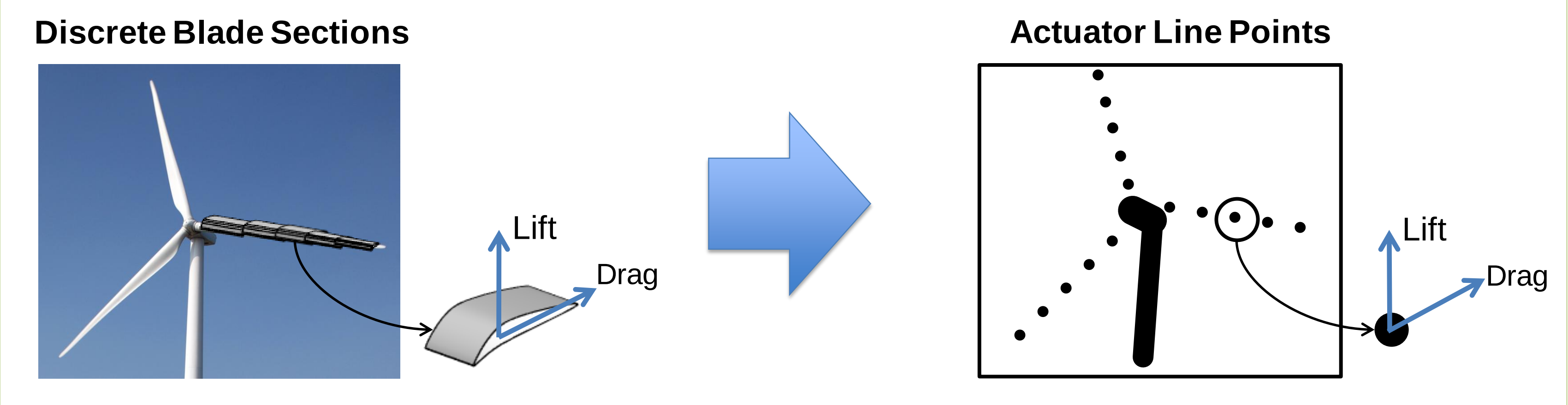
- Large Eddy Simulations (LES): A type of CFD which models smaller scales while resolving larger turbulent scales.
- Simulate the atmospheric boundary layer first to get an accurate representation of the turbulent wind field.
- Add in turbine model to simulate wind farm flow.

CFD Toolbox

- *Open F*ield *O*perations and *M*anipulations (OpenFOAM): Open-source, free, parallel, extremely flexible, finite-volume framework for solving complex physics, like wind farm flows.
- ParaView and Vapor: open-source, free, for scientific visualization.

Actuator Line Turbine Model

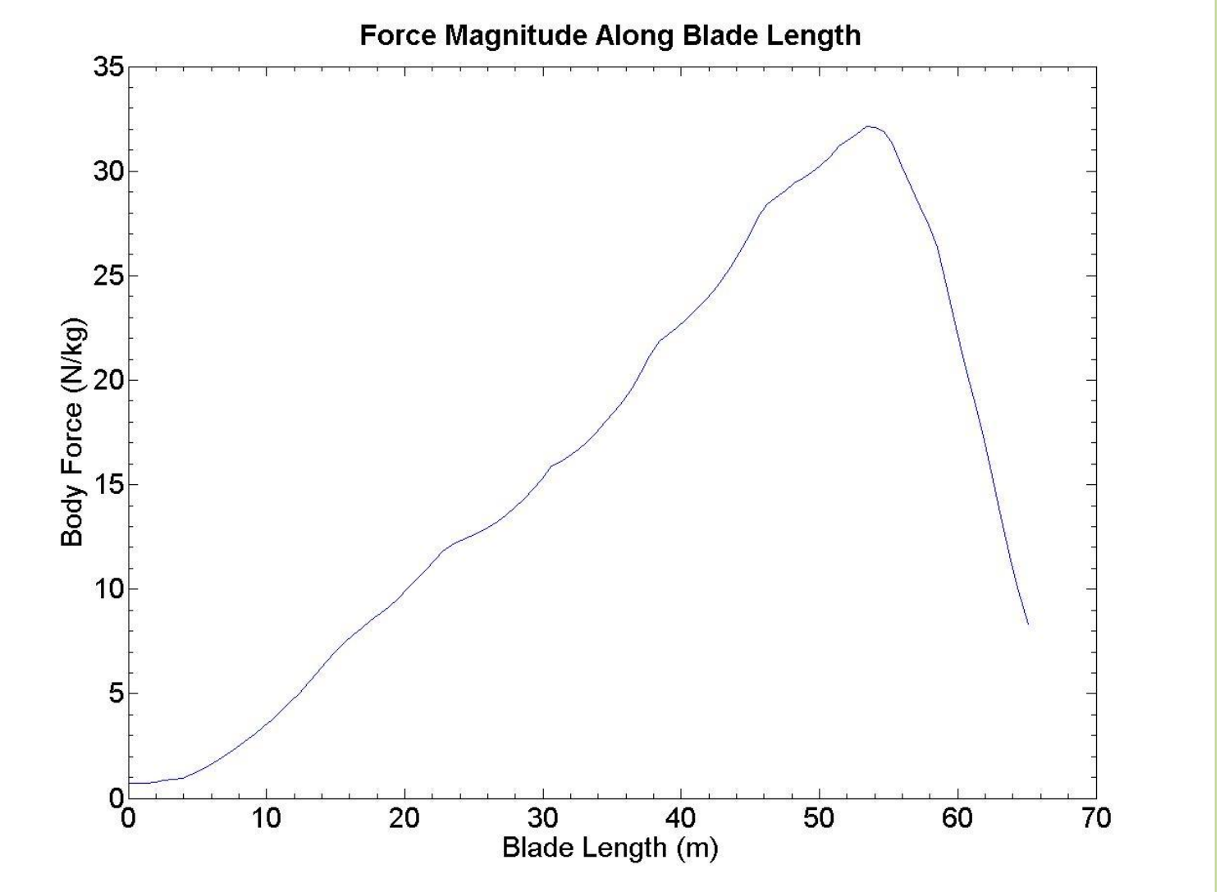
The wind turbines are modeled using the actuator line method (ALM) of Sørensen and Shen (2002). The actuator line method does not resolve the full geometry of the turbine blades, but rather models them as a set of points along each blade axis. Each point represents a discrete section of the blade, and tabulated airfoil data is used to calculate the lift and drag forces imposed upon the discrete blade section by the wind field. Each point then imposes a force on the wind field equal and opposite to that experienced by the corresponding blade section.



In order to avoid numerical oscillations in the CFD solution due to the application of forces at discrete actuator line points, the forces are distributed as body forces over the surrounding finite-volume CFD cells using a Gaussian distribution. The body forces enter the large-eddy simulations through an additional body force term in the filtered Navier-Stokes incompressible momentum equation.

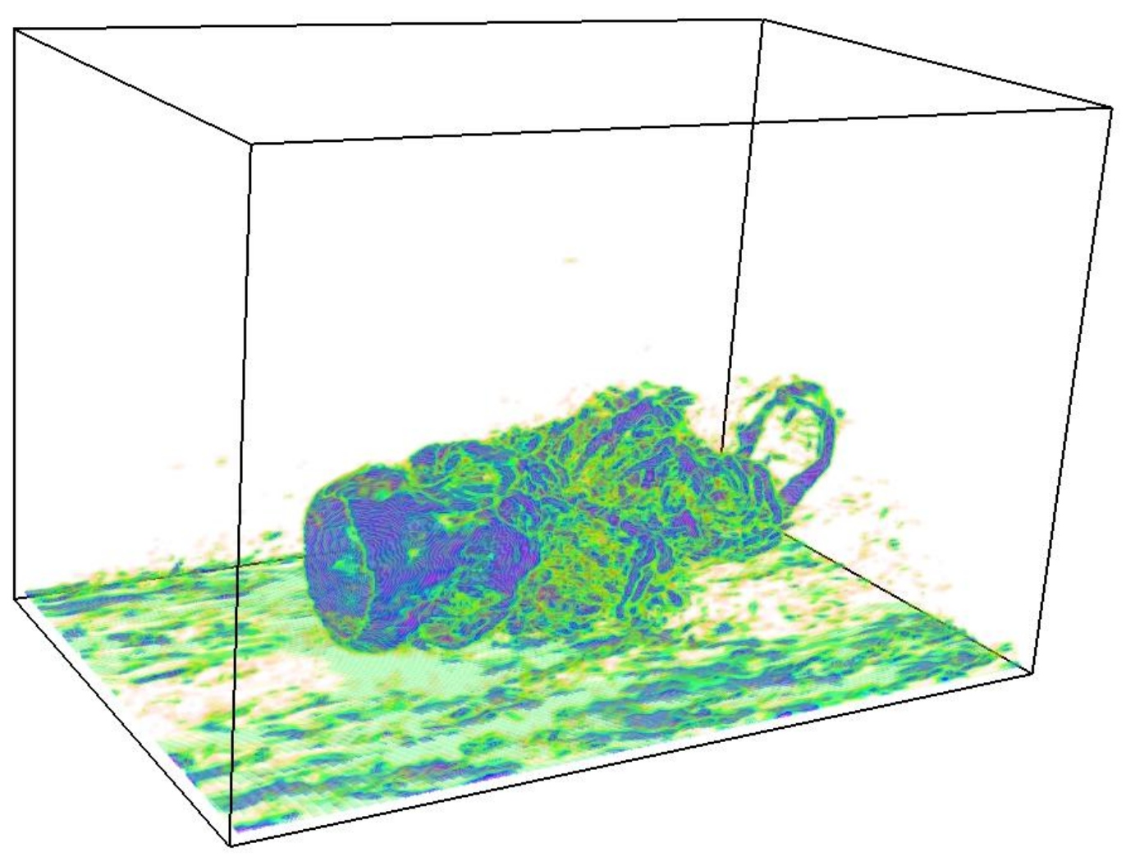
$$\vec{\mathrm{f}}_{\mathrm{turb}} = \frac{\vec{\mathrm{F}}_{\mathrm{turb}}}{\epsilon^3 \pi^{3/2}} \exp\left[-\left(|\vec{r}|/\epsilon\right)^2\right]$$

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = -\frac{1}{\rho} \nabla p + \nabla \vec{\vec{\tau}} + \vec{\mathrm{f}}_{\mathrm{grav}} + \vec{\mathbf{f}}_{\mathbf{turb}}$$

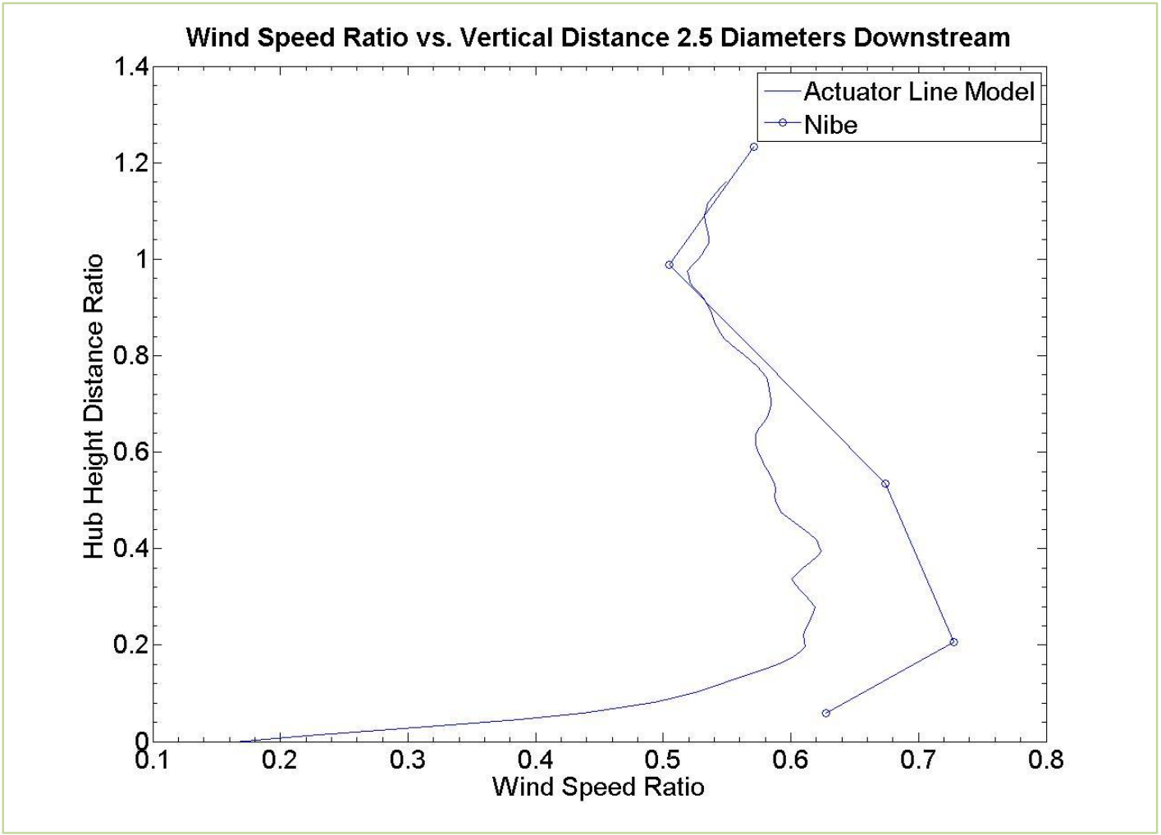


Results

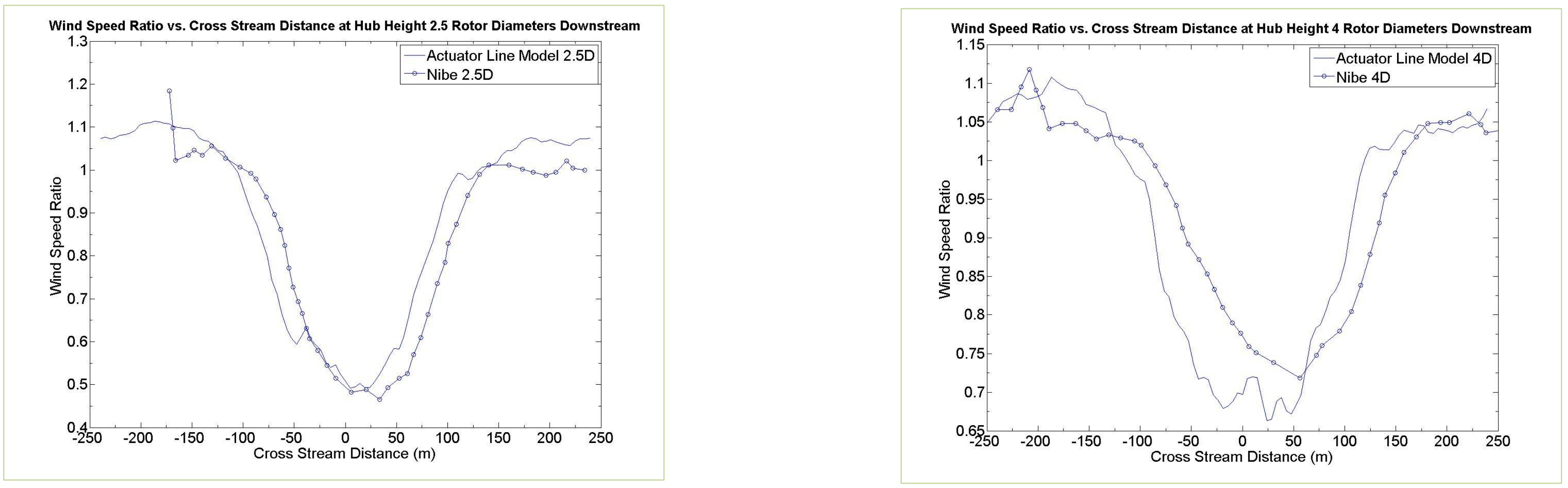
The model was compared to data from the Nibe experimental turbines located in Denmark. Data, including wind speed ratio (local wind speed divided by incoming wind speed at turbine hub height), from the Nibe experiment was obtained using four well instrumented meteorological towers at distances up to 7.5 rotor diameters (D) downstream.



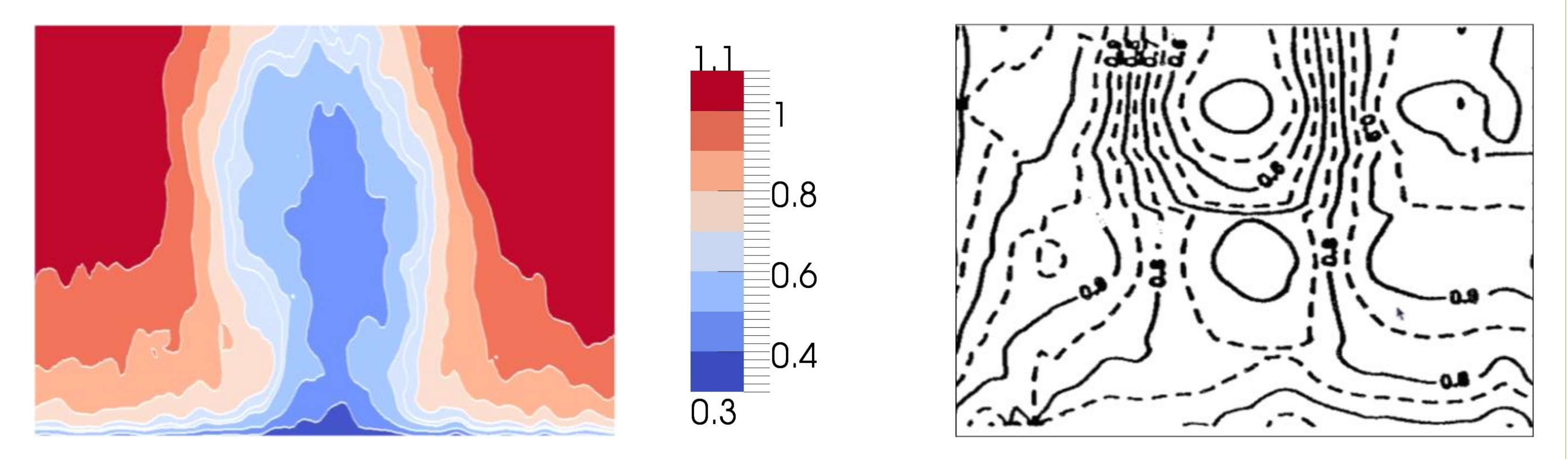
- A volume rendering of vorticity magnitude that shows the wake structure.



- A vertical profile of the wind speed ratio at 2.5 rotor diameters downstream.



- Horizontal wind speed ratio plots of the wake at 2.5 and 4 rotor diameters downstream. The plots show wind speed ratio profiles at hub height in the spanwise direction.



- A contour plot of simulated wind speed ratio at 2.5 rotor diameters downstream (left) compared with the Nibe experimental data (right).

Discussion

The actuator line model creates a wake structure behind the turbine which agrees qualitatively with experimental measurements. Velocity profiles behind the turbine are similar to experimental data from the Nibe turbines. Horizontal velocity profiles are shifted to one side in the Nibe data due to different terrain conditions depending on the angle of the incoming wind. The contour plot shows the wake structure although there is a slight difference due to the tower and nacelle, which are not incorporated into the current actuator line model.

Conclusions

The actuator line model is a useful tool for modeling wind turbines in CFD codes without having to fully resolve the blade geometry. The model was validated with good characterization of the wake.

Future Work

The nacelle and tower will be incorporated into the model. The actuator line model will be used to simulate wind farms and the interaction of wakes with other wakes, turbines, and the atmosphere.

References

J.N. Sørensen and W.Z. Shen, “Numerical Modeling of Turbine Wakes,” *Journal of Fluids Engineering*, vol. 124, pp. 393-399, June, 2002.

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