Benchmarking of Non-Linear Wake Interactions of Two Turbines of Marine and Wind

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Objectives

The eddy viscosity model is a wake model that is widely employed by industry for wind farm far wake calculations and energy output predictions. In this presentation, we are outlining a validation exercise to:

- benchmark eddy viscosity wake model to single turbine and two turbine configurations,
- show dependence of eddy viscosity model on different parameters such as turbulence intensity, Reynold stresses, filter parameters for a two turbine configuration.
- comparison is made to full three dimensional Phoenics solver RANS with closure models $k-\varepsilon$ and RNG $k-\varepsilon$
- bring to your attention the importance of this topic on everyday industrial and business applications.

Modelling of wake losses is an important part of the production estimation for wind farms. Next slide;
Wind Turbine Wakes

Objectives
- Wind Turbine Wakes
  - Eddy viscosity model
  - Actuator Disc model
  - Validation Exercise
  - Conclusion
  - Questions

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Wind Turbine Wakes

- Wake modelling and wind farm design
- Linear wind resource grid
  - Wasp, Windfarm, WindFarmer, Openwind, Wasp Engineering
  - Park Model and its variants
- Non-linear wind resource grid
  - Fluent, MeteoDyn, WindSim, Ellips3D etc
  - Actuator disc, Eddy Viscosity
Wind Farm Design

Coding Flow For Wake Modeling

- Wind Resource Grid and Parameters, Constraints, Boundary Conditions

- Park Model Subroutine
  - Constraints and Parameters
  - Subroutine for Turbine Configuration
    - Subroutine for Algebraic Solver
    - Subroutine for Wind Farm configuration
  - Subroutine for Turbine Configuration
  - Subroutine for Wind Farm configuration

- Eddy Viscosity Subroutine
  - Constraints and Parameters
  - Subroutine for Turbine Configuration
  - Subroutine for Discretization
  - Subroutine for Boundary Conditions and Solver
  - Subroutine for Wind Farm configuration

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Park model
Eddy viscosity model

mass:
\[
\frac{1}{r} \frac{\partial}{\partial r} (r U_r) + \frac{\partial}{\partial z} (U_z) = 0 \tag{1}
\]

z-momentum:
\[
\left( U_r \frac{\partial U_z}{\partial r} + U_z \frac{\partial U_z}{\partial z} \right) = \epsilon \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u_z u_r}{\partial r} \right) \right] \tag{2}
\]
Field conditions

For eddy-viscosity model boundary conditions The $U_z$ boundary conditions are chosen as $U_o$ which is free stream boundary condition at the radial direction. As result of the symmetry, the gradient of the $U_z$ will equal to zero at the center line. The boundary condition for $U_r$ is equal to zero at the boundary.

For eddy-viscosity model initial conditions which is for a single turbine configuration; inlet or initial center line velocity deficit field is a Gaussian curve

$$D = U_z/U_o = U_o \left(1 - D_m e^{(-3.56 \frac{r^2}{b^2})}\right)$$

that employs the following semi-empirical relation: This function at the initial iteration $D_m = D_{mi}$ has the following definition for velocity deficit:
Boundary conditions, field conditions and closure for eddy viscosity

\[ D_{mi} = C_t - 0.05 - (16 \ C_t - 0.5) \frac{l_o}{1000} = U_z/U_o \]  \hspace{1cm} (4)

Herein \( l_o \) is the ambient turbulence intensity which is defined in percentage. Through this relationship a semi empirical closure for eddy viscosity can be obtained:

\[ \epsilon = F \ K_1 \ b \ D_m \ U_o + F \ \kappa^2 \ \frac{l_o}{1000} \]  \hspace{1cm} (5)

The parameters \( F, K_1, b, \kappa \) are filter coefficients, dimensionless constant based on experimental data and wake width \( b \) and von Karman constant \( \kappa \) respectively. Wake width \( b \) is defined as
Boundary conditions, field conditions and closure for eddy viscosity

Wake width $b$ is defined as

$$b = \sqrt{\frac{3.56 \ C_t}{8 \ D_m \ (1 - 0.5 \ D_m)}}$$

and $F$ term for the filter is defined as

$$F-z > 5.5 : \quad F = 1.0 \quad (7)$$

$$F-x < 5.5 : \quad F = \left(\frac{x - 4.5}{23.32}\right)^{1/3} \quad (8)$$
Eddy viscosity model

Figure: a) Figure a illustrates wind speed contours for a turbine placed on the left inlet. Notice that numerical solution of eddy-viscosity is a propagating solution on the x-axis. b) Figure b on the right illustrates the computational domain with turbine placed at the origin. The grid on the right figures is to emphasize that the solution is computed on a regular and uniform grid.
Actuator Disc model

Figure: a) Figure a illustrates wind speed contours for 80m height. b) Figure b on the right illustrates the computational domain with turbine placed on the mesh where the triangle is located.
Validation Exercise

Figure: a) Downstream profile b) Cross stream profile at rotor diameter distance 2.5 c) Cross stream profile at rotor diameter distance 5 d) Cross stream profile at rotor diameter distance 10
Effects of ambient turbulence intensity on the profile

Figure: Ambient turbulence intensity variations effect wake
Effect of filter on ambient turbulence intensity and wake

Figure: Effect of filter on ambient turbulence intensity and wake;
Effect of two turbine wake interaction
Effect of two turbine wake interaction
Effect of two turbine wake interaction

$x = 3.0$ rotor diameter from first turbine

- Actuator Disc; Windsim k-epsilon standard
- Eddy Viscosity Wake

Normalized wind speed

y-rotor diameters
Effect of two turbine wake interaction
Effect of two turbine wake interaction

- Actuator Disc model
- Eddy Viscosity model

Validation Exercise

Figure: Effect of two turbine wake interaction

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Effect of two turbine wake interaction

![Diagram showing wind speed normalized by rotor diameter with labels Actuator Disc; Windsim k-epsilon standard and Eddy Viscosity Wake.]
Turbulence Intensity at $x = 3.0$ rotor diameter from second turbine
Effect of two marine turbine wake interaction
Effect of two marine turbine wake interaction
Effect of two marine turbine wake interaction

![Graph showing the effect of two marine turbine wake interaction](image)

- **x = 4.0 rotor diameter from first turbine**
- **U/Uo** Normalized wind speed
- **y-rotor diameters**

**Legend:**
- **Eddy Viscosity Wake**
Conclusions

- Ambient turbulence intensity has significant effect on eddy viscosity calculations.
- The turbulence intensity influences the eddy viscosity calculation through the eddy viscosity term.
- The eddy viscosity demonstrated a reasonable accuracy compared to the model’s simplicity for two turbine configuration.
- The eddy viscosity model was benchmarked to nonlinear wake model. Averaging of wake showed reasonable results considering simplicity.
Questions?

Openwind, Theoretical basis and validation Version 1.3 (04/2010) AWSTRUEPOWER LLC.


