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

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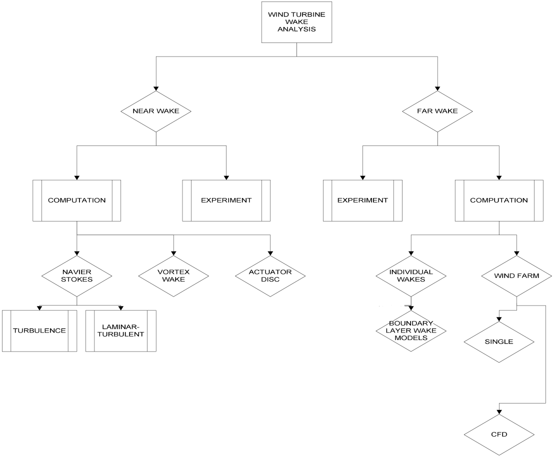
Objectives

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-ϵ and RNG k-ϵ
- 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;

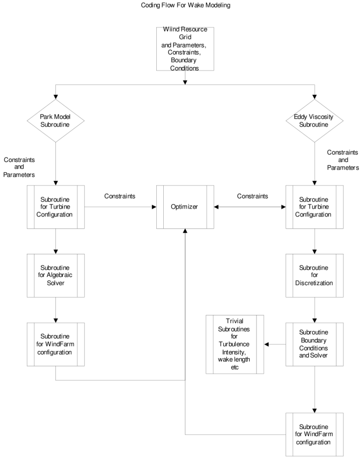
Wind Turbine Wakes



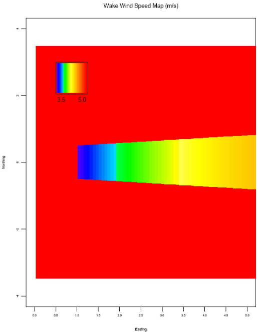
Wind Turbine Wakes

- 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



Park model


Wake Wind Speed Map (m/s)
3.5
5.0
Northing
Easting
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Eddy viscosity model

$$\text{mass}: \quad \frac{1}{r}\frac{\partial}{\partial r}(rU_r) + \frac{\partial}{\partial z}(U_z) = 0 \tag{1}$$

$$z\text{−momentum}: \quad \left(U_r\frac{\partial U_z}{\partial r} + U_z\frac{\partial U_z}{\partial z}\right) = \epsilon\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \overline{u_z u_r}}{\partial r}\right)\right] \tag{2}$$

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

$$D = U_z/U_o = U_o\left(1 - D_m e^{\left(-3.56\frac{r^2}{b^2}\right)}\right) \tag{3}$$

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

$$D_{mi} = C_t - 0.05 - (16\ C_t - 0.5)\frac{I_o}{1000} = U_z/U_o \tag{4}$$

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

$$\epsilon = F\ K_1\ b\ D_m\ U_o + F\ \kappa^2\ \frac{I_o}{1000} \tag{5}$$

The parameters F, K_1, b, κ are filter coefficients, dimensionless constant based on experimental data and wake width b and von Karman constant κ respectively. Wake width b is defined as

Boundary conditions, field conditions and closure for eddy viscosity

Wake width b is defined as

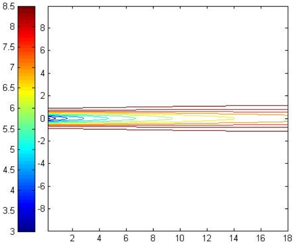
$$b = \sqrt{\frac{3.56\ C_t}{8\ D_m\ (1 - 0.5\ D_m)}} \tag{6}$$

and F term for the filter is defined as

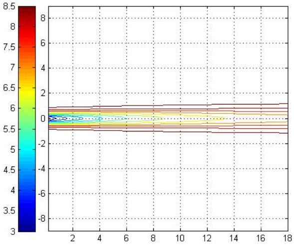
$$F\text{—z} > 5.5: \qquad F = 1.0 \tag{7}$$

$$F\text{—x} < 5.5: \qquad F = \left(\frac{x - 4.5}{23.32}\right)^{1/3} \tag{8}$$

Eddy viscosity model



[a]



[b]

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

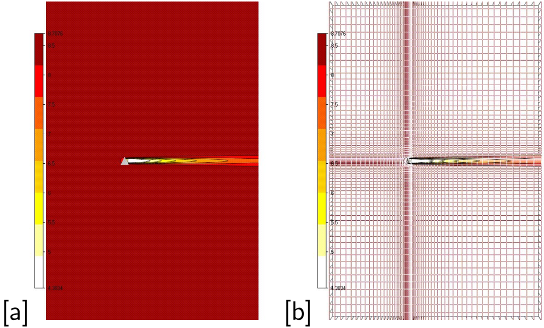


Figure : a) Figure a illustrates wind speed contours for 80m height. b) Figure b on the right illustrates the computational domain with turbine placed on the mesh where the triangle is located.

Validation Exercise

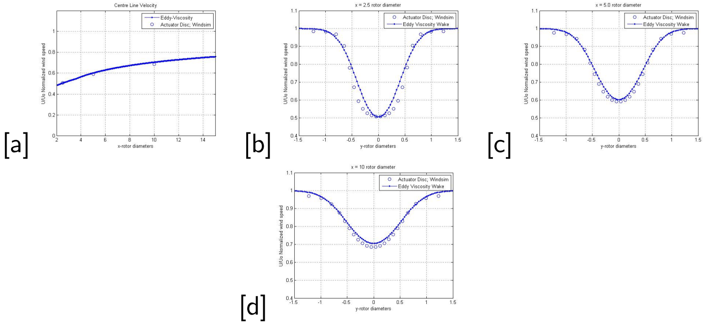


Figure : a) Downstream profile b) Cross stream profile at rotor diameter distance 2.5 c) Cross stream profile at rotor diameter distance 5 d) Cross stream profile at rotor diameter distance 10

Effects of ambient turbulence intensity on the profile

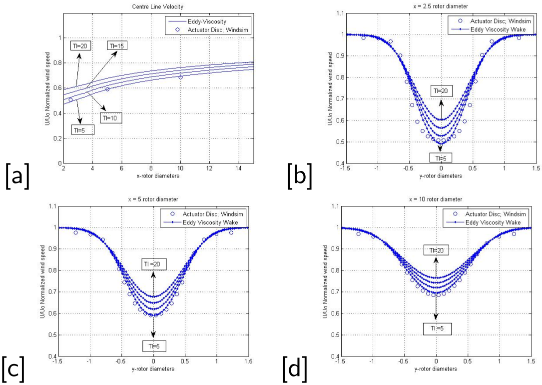


Figure : Ambient turbulence intensity variations effect wake

Effect of filter on ambient turbulence intensity and wake

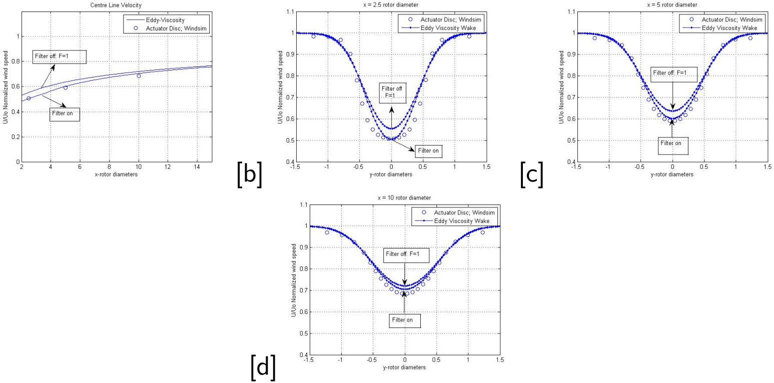
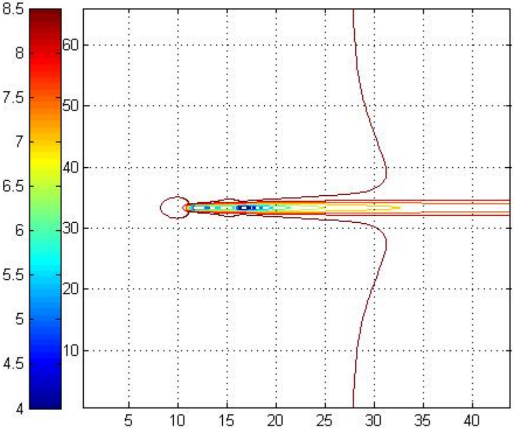
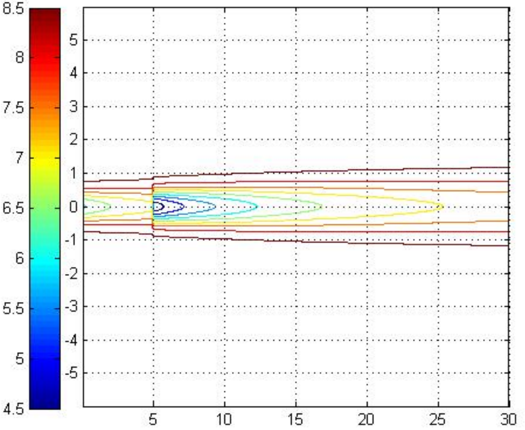


Figure : Effect of filter on ambient turbulence intensity and wake;

Effect of two turbine wake interaction



Effect of two turbine wake interaction



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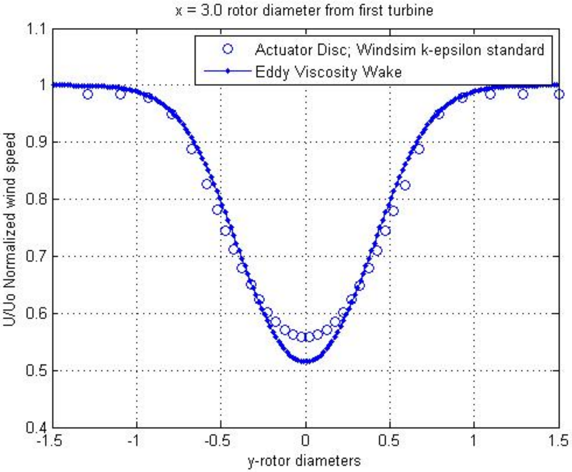

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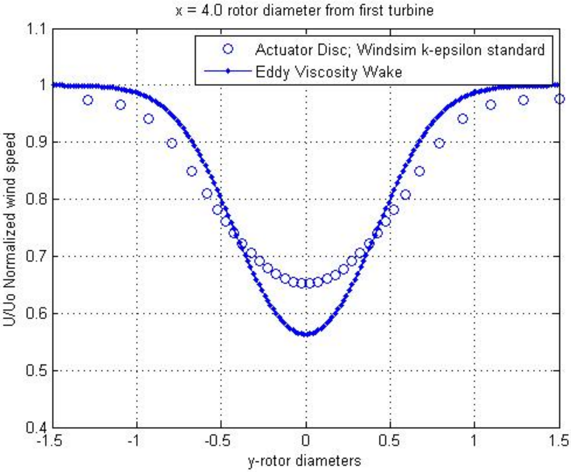
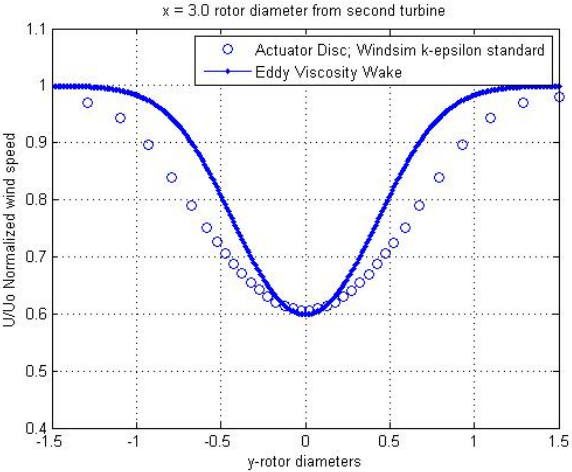


Effect of two turbine wake interaction



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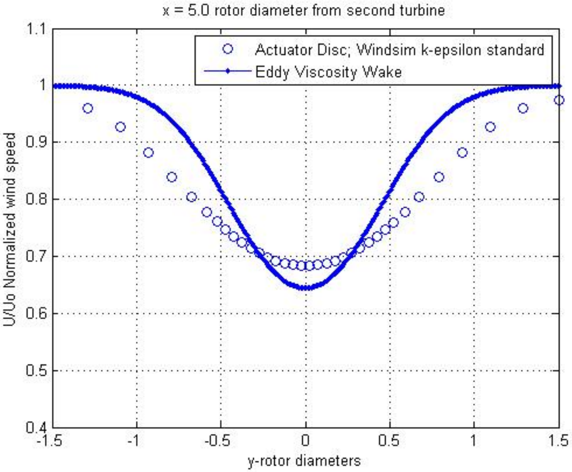
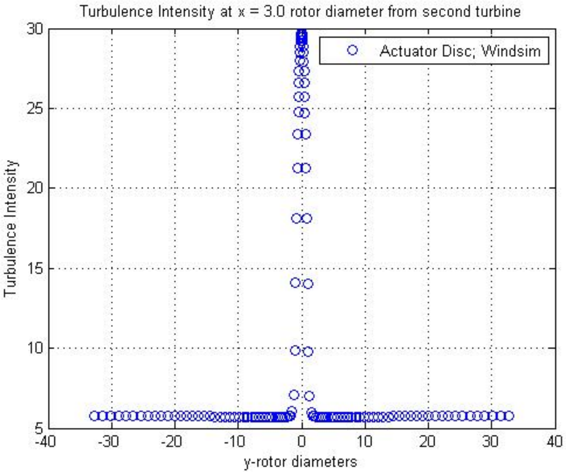
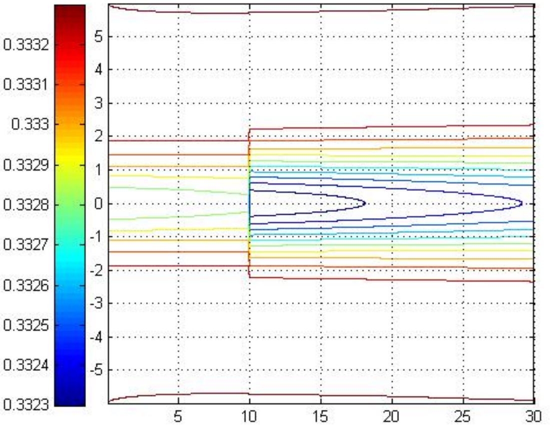


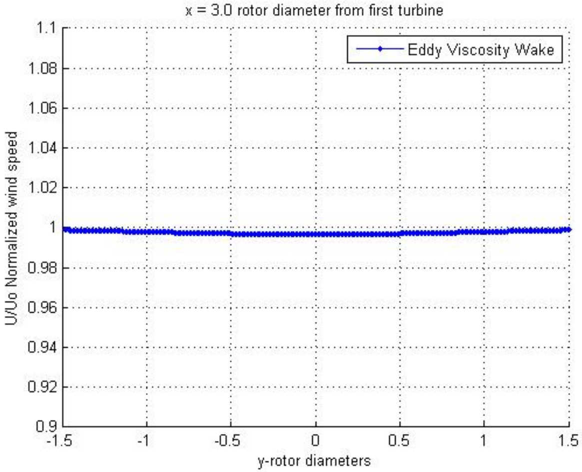
Turbulence Intensity



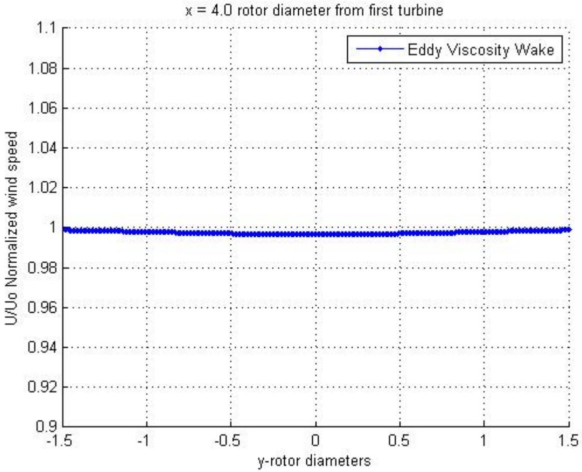
Effect of two marine turbine wake interaction



Effect of two marine turbine wake interaction



Effect of two marine turbine wake interaction



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?

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- Windfarmer, The wind farm design software, Theory Manual (11/2006) *Garrad Hassan and Partners LTD.*.
- Openwind, Theoretical basis and validation Version 1.3 (04/2010) *AWSTRUEPOWER LLC*.
- J.F.Ainslie Calculating the velocity field in the wake of wind turbines. *Journal of Wind Engineering and Industrial Aerodynamics*, **27**, 213–224 (1988).
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- Benchmarking of Eddy Viscosity Model with nonlinear wake models , Uzunoglu, B. , Zou. F and Ivanell, S CFD Optimization - ECCOMAS, Antalya, Turkey. (2011)