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Dynamic Wake Meandering Model Comparison with Varying Fidelity Models for Wind Turbine Wake Prediction

Brandon L. Ennis, Christopher L. Kelley,
David C. Maniaci

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Introduction

- Currently, there is over 65 MW of installed wind turbines in the U.S.; producing around 5% of the nation’s energy supply
- This capacity is installed mostly in large wind farms; the largest current wind farm having a capacity of 1548 MW coming from around 600 turbines
- Wind farms are growing; proposed projects include farms with up to 1000 turbines and 3000 MW of capacity
- Operating turbines in a wind farm means operating in a complex flow environment; has resulted in observations of 10-20% losses from total wind farm performance predictions

Introduction

- High-fidelity modeling advances have enabled more accurate prediction of wind farm performance and loads; for a given farm layout, only a few cases can be afforded to analyze
- There has been a shift from a single turbine design approach towards an integrated systems design approach; depends upon the availability of accurate and fast wind turbine wake models
- Future wind plant control algorithms are designed using high-fidelity modeling; in-field implementation will require the ability to rapidly predict power and loads using high-efficiency wake models

Introduction

- This presentation will compare results using three common approaches for modeling wind turbines wakes.
  - Dynamic Wake Meander (DWM) Model
  - CACTUS Model [Kelley; Sandia National Labs, 2015]
  - VWiS Model [Yang, et al.; University of Minnesota, 2015]

Model Comparison

Model	Type	Run Time
Dynamic Wake Meander	Simplified Navier-Stokes	Minutes; one core
CACTUS	Free-wake vortex method	Days; ten cores
VWiS	Actuator-line LES	Weeks; hundreds of cores

Increasing Fidelity

DWM Wake Model

- The DWM model combines three independent modules for:
  (1) Calculating a steady wake deficit
  (2) Imposing rotor added turbulence using the Mann model
  (3) Including the effects of wake meandering to shift the downstream quasi-steady wake based on the turbulent length scales

- In this comparison, the (1) steady wake deficit model is solely used.
  - For DWM model rotor added turbulence doesn’t affect the steady characteristics which are compared
  - Laminar flow-field is compared so there is no energy content in the (>2D) length scale to drive meandering, per the model
  - It’s important to isolate the effects of the wake deficit model to verify its accuracy apart from other contributors

DWM Wake Model

Model Assumptions:

- Steady, incompressible flow conditions
- Axisymmetric wake
- No rotational swirl
- Pressure terms are disregarded
- Gradients of mean flow are much greater in radial direction than in axial direction ($\partial r \gg \partial x$)

- Goal is to describe the far-wake behavior accurately, with significant modeling of the near-wake behavior (3-5 diameters downstream)

$$\boxed{U\frac{\partial U}{\partial x} + V_r\frac{\partial U}{\partial r} = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\overline{u'v'_r}\right)}$$

DWM Wake Model

Governing Equations:

$$U\frac{\partial U}{\partial x} + V_r\frac{\partial U}{\partial r} = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\overline{u'v'_r}\right)$$

$$\frac{\partial U}{\partial x} + {}^{1}\!/_{r}\frac{\partial}{\partial r}(rV_r) = 0$$

→ Known to be an incomplete representation of the flow physics for an actual wind turbine, but are chosen to reduce computational demands of the solution

Turbulence Model:

$$-\overline{u'v'_r} = v_T\frac{\partial U}{\partial r}$$

→ Eddy viscosity model is chosen for turbulence closure, contains corrections for the incorrect model assumptions for the near-wake

DWM Wake Model

<u>Eddy Viscosity Model</u>: $-\overline{u'v'_r} = \nu_T \frac{\partial U}{\partial r}$

- The Eddy viscosity term is used to account for the effects of:
  - I. Wake shear-layer generated turbulence
  - II. Atmospheric inflow turbulence
  - III. Additional source of turbulence generation due to the presence of a velocity profile driven by atmospheric shear

$$\boxed{\nu_T = \underbrace{\nu_{T,atmosphere}}_{\textbf{II., III.}} + \underbrace{\nu_{T,wake}}_{\textbf{I.}}}$$

DWM Wake Model

$$\boldsymbol{\upsilon_{T,Madsen\ 2010}} = F_1 k_1 TI_{amb} U_{amb} R + F_2 k_2 b\left(U_{amb} - U_{def,min}\right)$$

- Original 1-dimensional eddy viscosity model developed by Madsen

$$\boldsymbol{\upsilon_{T,Keck\ 2012}} = F_1 k_1 TI_{amb} U_{amb} R + F_2 k_2 b^2 \left|\frac{\partial U}{\partial r}\right|$$

- Improvement to model the 2-dimensional nature of the wake-generated turbulence by Keck

$$\boldsymbol{\upsilon_{T,Keck\ 2013}} = \upsilon_{T,Keck\ 2012} \frac{\frac{\partial U}{\partial r}_{Total}}{\left|\frac{\partial U}{\partial r}_{DWM}\right|}$$

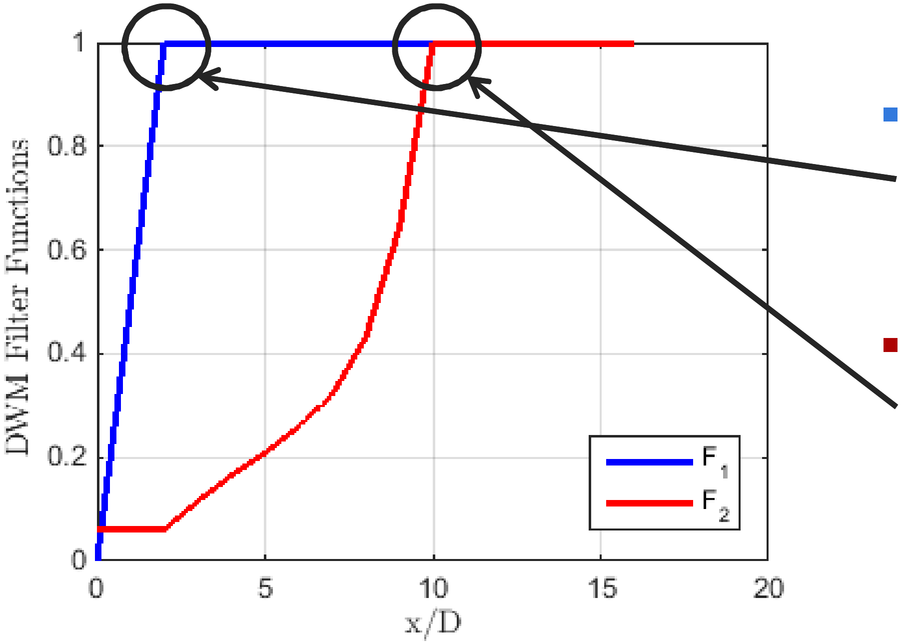
- Model adjusted for inclusion of the effects of atmospheric shear increasing turbulence generation

$$\frac{\partial U}{\partial r}_{Total} = \frac{A_{Total}}{2\pi} \qquad A_{Total} = \begin{cases} 2\pi \, {}^{\partial U}/_{\partial r_{DWM}} & if, \left|{}^{\partial U}/_{\partial r}\right| \geq {}^{\partial U}/_{\partial z_{ABL}} \\ 2\pi \, {}^{\partial U}/_{\partial r_{DWM}} + 2A_{1,2} & if, \left|{}^{\partial U}/_{\partial r}\right| < {}^{\partial U}/_{\partial z_{ABL}} \end{cases}$$

Model Initialization

- Eddy viscosity term is calibrated using spatial filters (F_i) and calibration constants (k_i)
- Values from Keck 2012 (2-d Eddy viscosity) are repeated

$$\upsilon_{T,Keck\ 2012} = F_1 k_1 TI_{amb} U_{amb} R + F_2 k_2 b^2 \left|\frac{\partial U}{\partial r}\right|$$

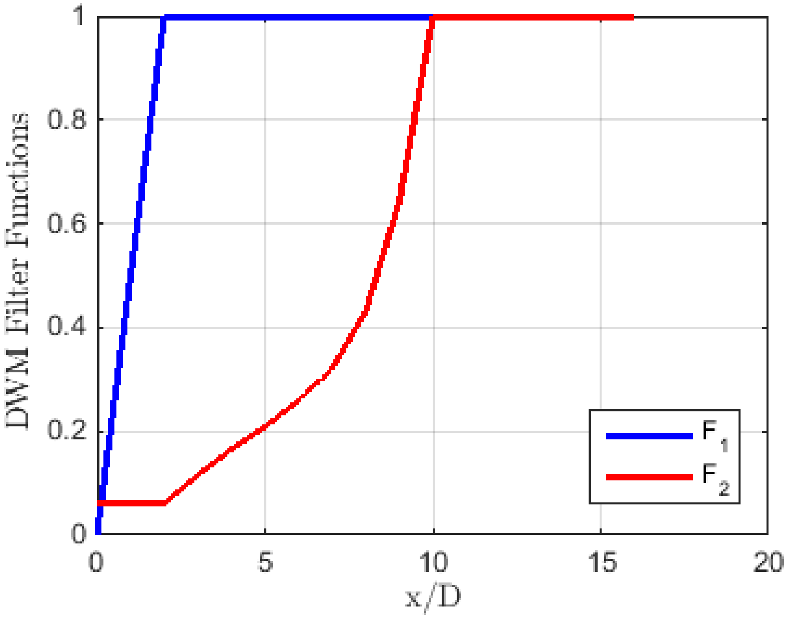


- F_1 compensates for effects on turbulence caused by pressure expansion at the rotor disk plane, ~2D [Sanderse, 2009]
- F_2 governs development of turbulence generated by the wake shear layer, ~10D based on Actuator Line simulations [Keck 2011]

Model Initialization

- Eddy viscosity term is calibrated using spatial filters (F_i) and calibration constants (k_i)
- Values from Keck 2012 (2-d Eddy viscosity) are repeated

$$\upsilon_{T,Keck\ 2012} = F_1 k_1 TI_{amb} U_{amb} R + F_2 k_2 b^2 \left| \frac{\partial U}{\partial r} \right|$$



$$k_1 = 0.0914$$

$$k_2 = 0.0216$$

$$TI_{amb} = 0$$

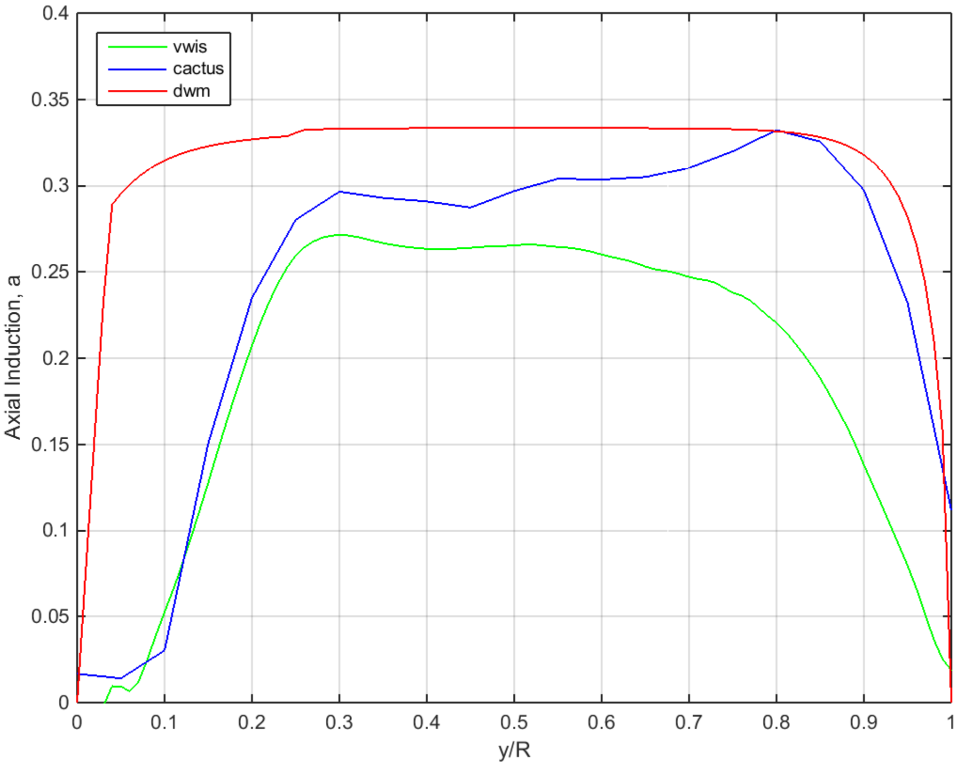
Calibration constants (and filters) derived for a modern utility-scale wind turbine, Neg Micon NM80, and is supposed to be valid in this study.

Model Initialization

- Rotor Boundary Condition is input to the model in terms of the disk-averaged axial induction, a
  - Axial velocity assumed at its far-wake, fully expanded (pressure recovered) value from 1-D analysis: $\boldsymbol{U_{BC} = U_{\infty}(1 - 2a)}$
  - Radial velocity is assumed to be equal to zero at the rotor plane: $\boldsymbol{V_{BC} = 0}$
  - Radial extent of the rotor BC is assumed to be unexpanded: $\boldsymbol{r_{BC} = r}$

Model Initialization

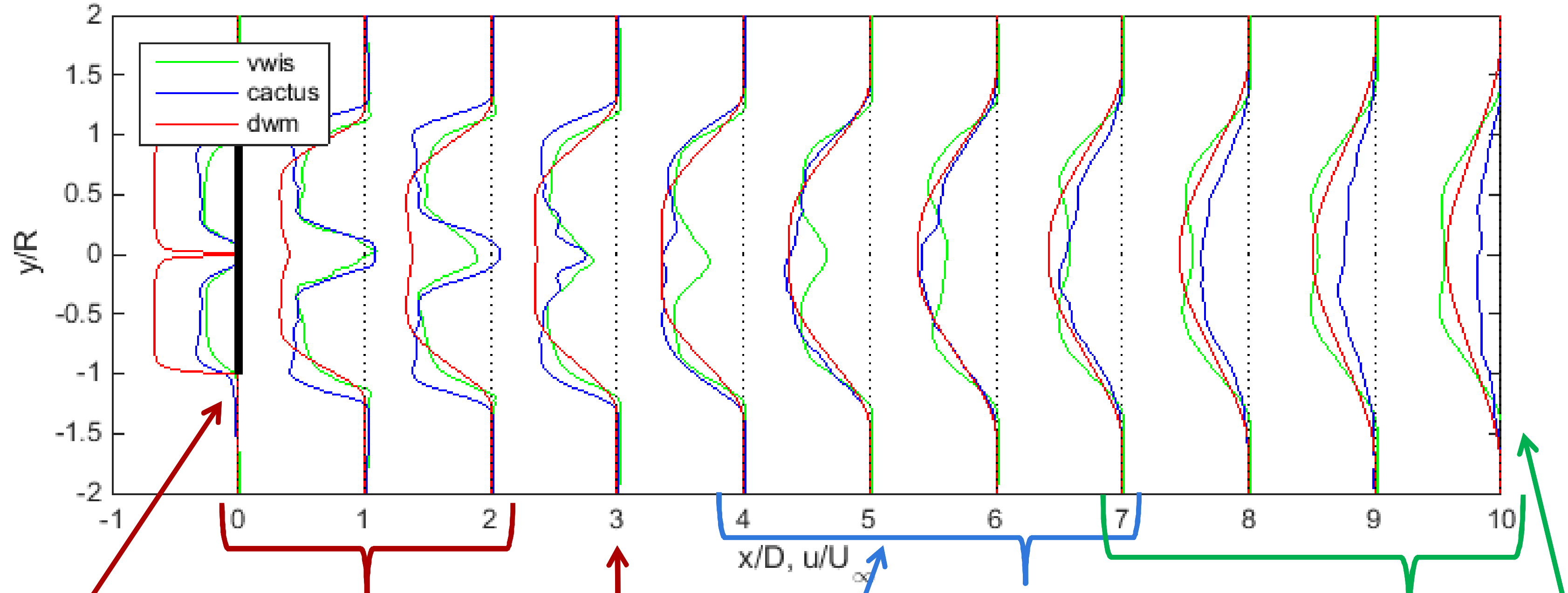
- Rotor Boundary Condition is input to the model in terms of the disk-averaged axial induction, a



- DWM is modeling the design WT
- CACTUS/VWiS realization of the "design" is due partially to structural limitations of a real WT (close to hub)
- CACTUS/VWiS have no hub model (inner ~10%)
- VWiS is additionally using a performance tip-loss model to account for pressure roll-off at the tip [Shen, 2005]

→ Qualitative Comparison.

Results: Wake Deficit Evolution



2-D assumed to be point of pressure recovery and far-wake transition from work by Sanderse

Excellent agreement with CACTUS from [4D, 7D]

Highest agreement with VWiS [7D, 10D]

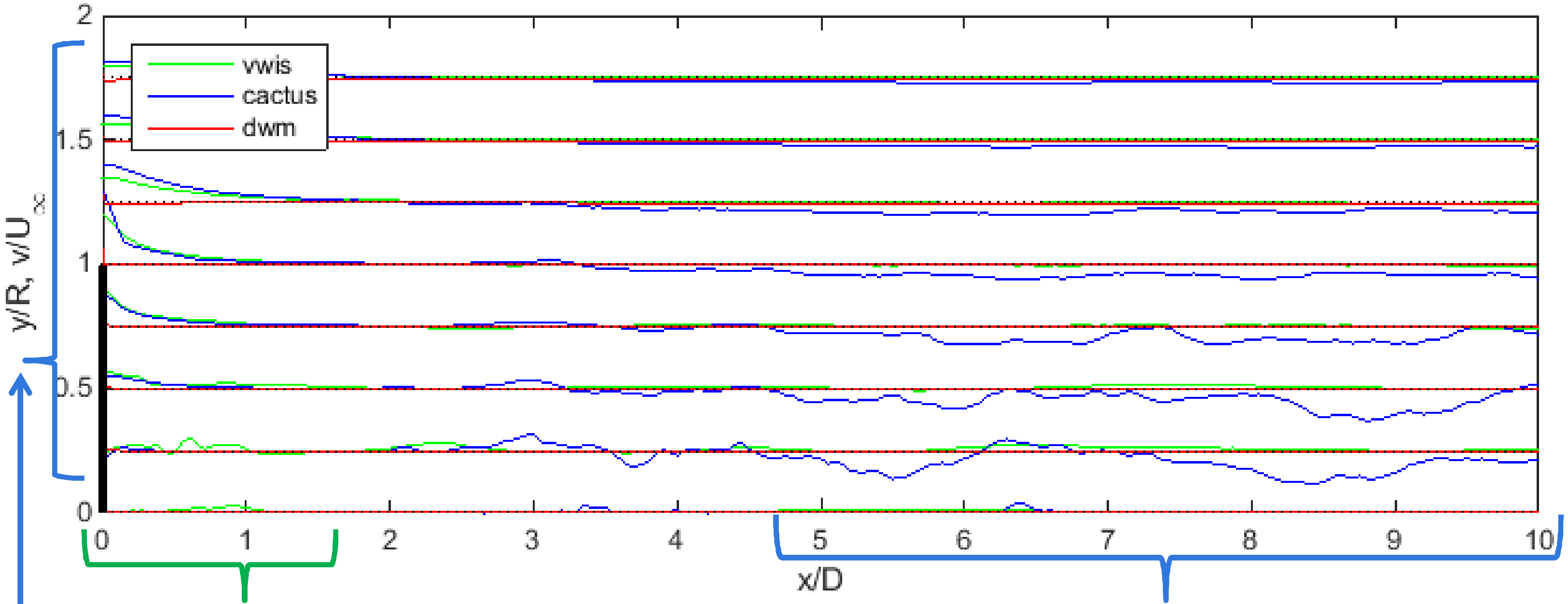
transition to far-wake profile for CACTUS and DWM

DWM rotor BC

3-D downstream considered point of “DWM model validity”

VWiS continues to have near-wake profile at 10D

Results: Radial Velocity Planes



By 1-1.5 D the averaged radial velocity from the rotor pressure build-up goes to zero

CACTUS; radial velocity is non-zero near the centerline; insufficient averaging

CACTUS and VWiS both have similar magnitude non-zero radial velocity at the rotor

→ Averaged over the same number of revolutions, so CACTUS appears to have larger scale vortical structures

Results: Model "Error" Comparison

- To compare the model agreement quantitatively, a standard sum of squares error is used:
  - c = case; d = x-plane; r = r-location

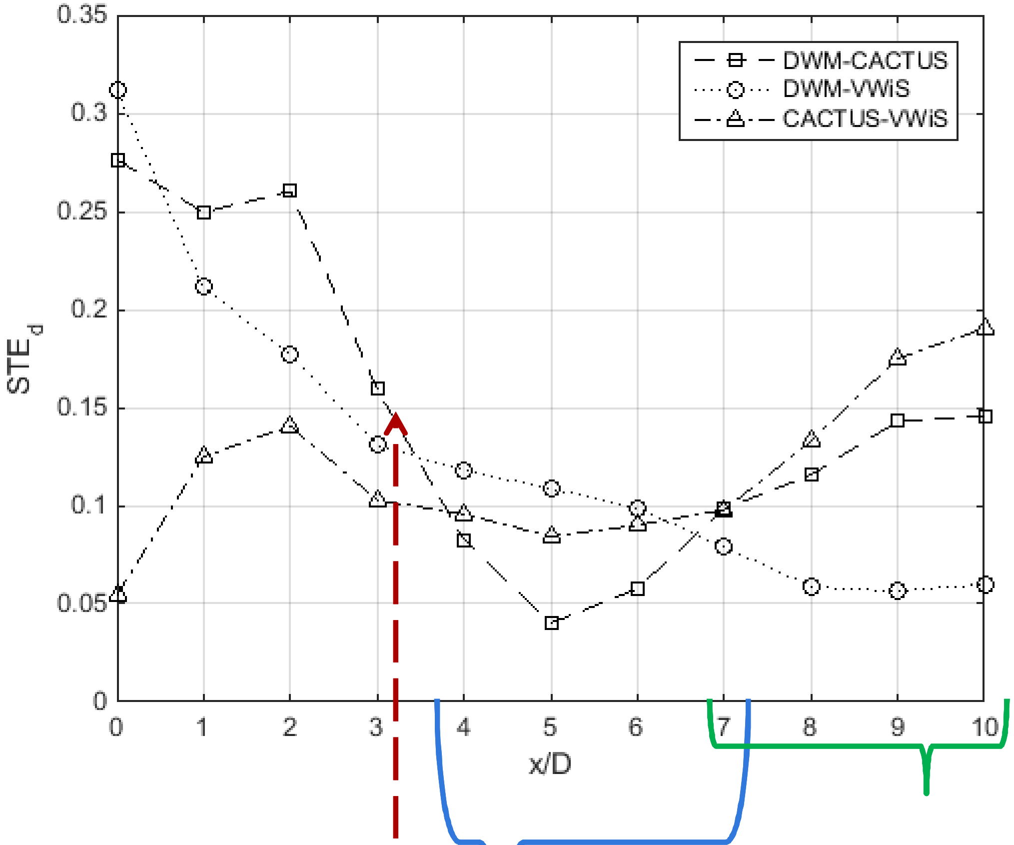
$$STE_c = \sqrt{\frac{1}{n_d}\sum_{d=1}^{n_d}\left(\frac{1}{n_{d,r}}\sum_{r=1}^{n_{d,r}}\left(\bar{U}_{d,r}{}^{model} - \bar{U}_{d,r}{}^{DWM}\right)^2\right)}$$

- Comparison is performed at each downstream plane, d, in terms of STE_d to show agreement with *x*

Results: Model “Error” Comparison

$$STE_d = \sqrt{\frac{1}{n_r}\sum_{r=1}^{n_{d,r}}\left(\bar{U}_{d,r}{}^{model} - \bar{U}_{d,r}{}^{DWM}\right)^2}$$

- Comparison should be **qualitative**
- DWM results in better agreement with CACTUS in transition to far-wake
- DWM results have total “error” of only “5%” compared to VWiS far downstream
- CACTUS-VWiS has lowest agreement far downstream



After point of DWM “model validity” error stays below 15%

Best agreement with CACTUS from [4D, 7D]

Best agreement with VWiS from [7D, 10D]

Results: Wake Recovery Mechanics

- **Diffusion** from vortex generation/turbulence driven recovery:
  - Described by the net momentum deficit within the wake

$$-\int_{A_i} \rho \vec{U}_\infty \left| \vec{U}_\infty \cdot d\vec{A}_i \right| + \int_{A_e} \rho \vec{U} \left| \vec{U} \cdot d\vec{A}_e \right| = -D$$

$$\boxed{C_D = 4 \int_0^{r_e/R} \frac{U}{U_\infty}\left(1 - \frac{U}{U_\infty}\right)\left(\frac{r}{R}\right) d\left(\frac{r}{R}\right)}$$

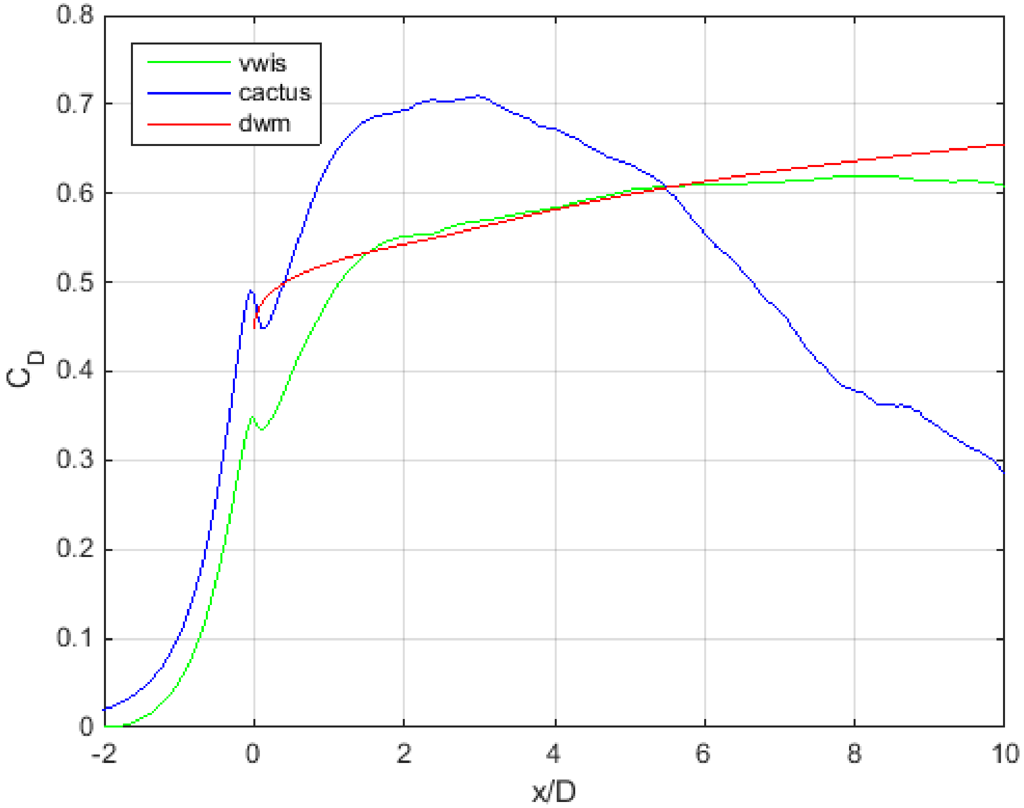
- **Wake expansion** from shear layer growth driven recovery:
  - Described by the wake width, b, containing 95% of the velocity deficit

$$U_{def,total} = 2\pi \int_0^{\infty} \left(1 - \frac{U}{U_\infty}\right)\left(\frac{r}{R}\right) d\left(\frac{r}{R}\right)$$

$$\boxed{b_{95} = r\left(0.95 U_{def,total}\right)}$$

Results: Wake Recovery Mechanics

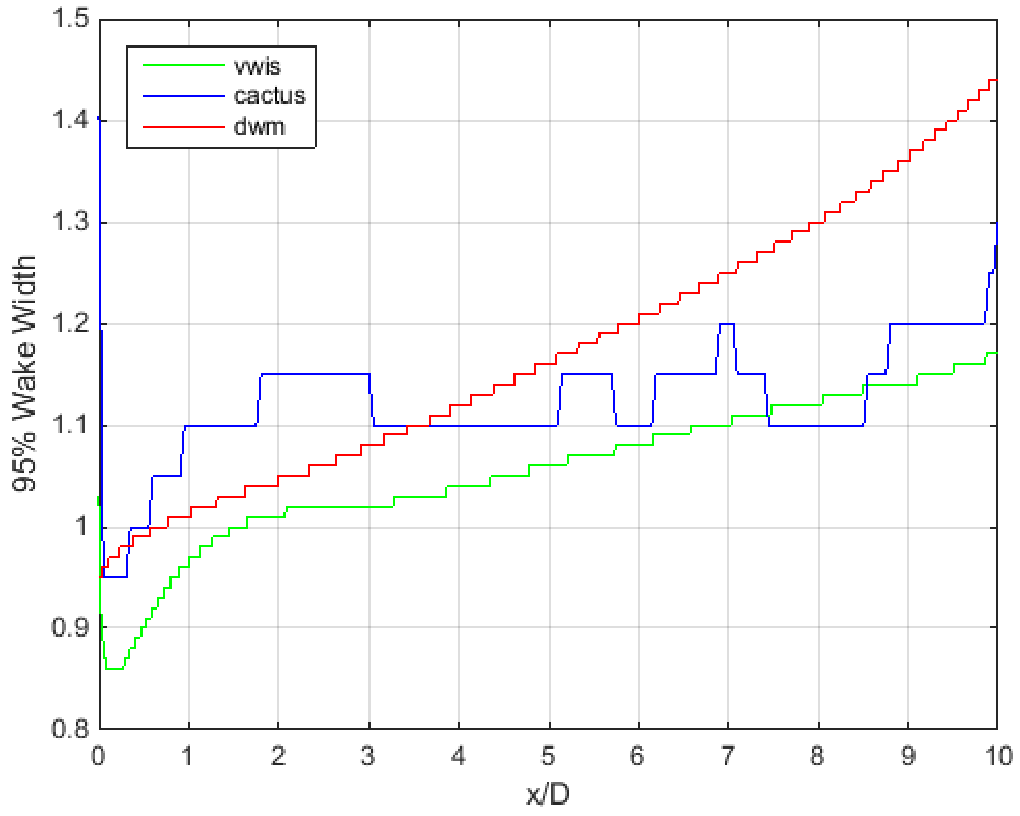
- **Diffusion** from vortex generation/turbulence driven recovery:



- CACTUS introduces the most diffusion between the models
- Momentum recovery begins at 3D for CACTUS, compared to 8D for VWiS
- DWM and VWiS have similar momentum “recovery” characteristics

Results: Wake Recovery Mechanics

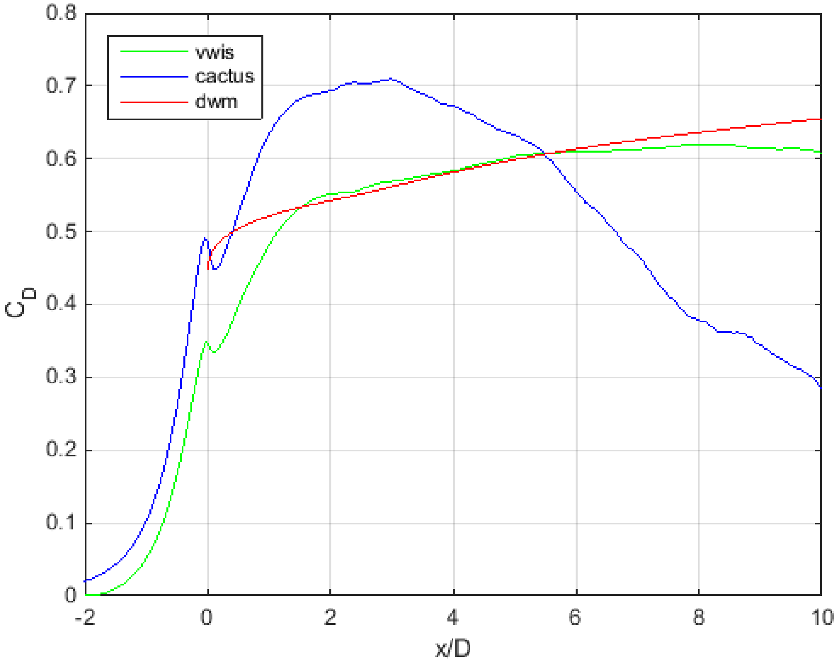
- **Wake expansion** from shear layer growth driven recovery:

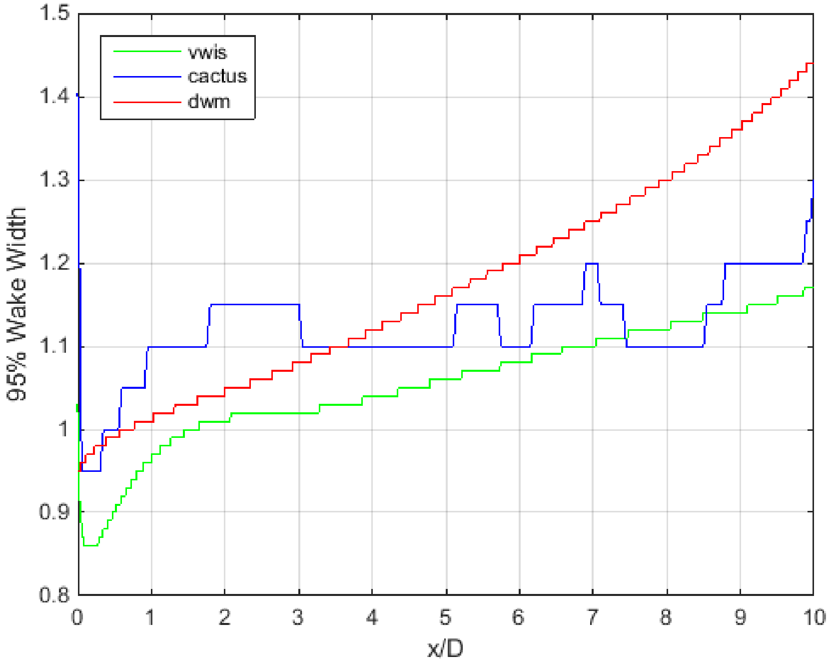


- DWM wake expansion is significantly higher than other models (more loaded at the tip)
- DWM and VWiS have similar wake expansion characteristics

Results: Wake Recovery Mechanics

- **DWM** wake recovery is expansion driven; at 10D there is no true momentum recovery
- **CACTUS** wake recovers fastest; diffusion driven
- **VWiS** wake recovers slowest; low diffusion and expansion

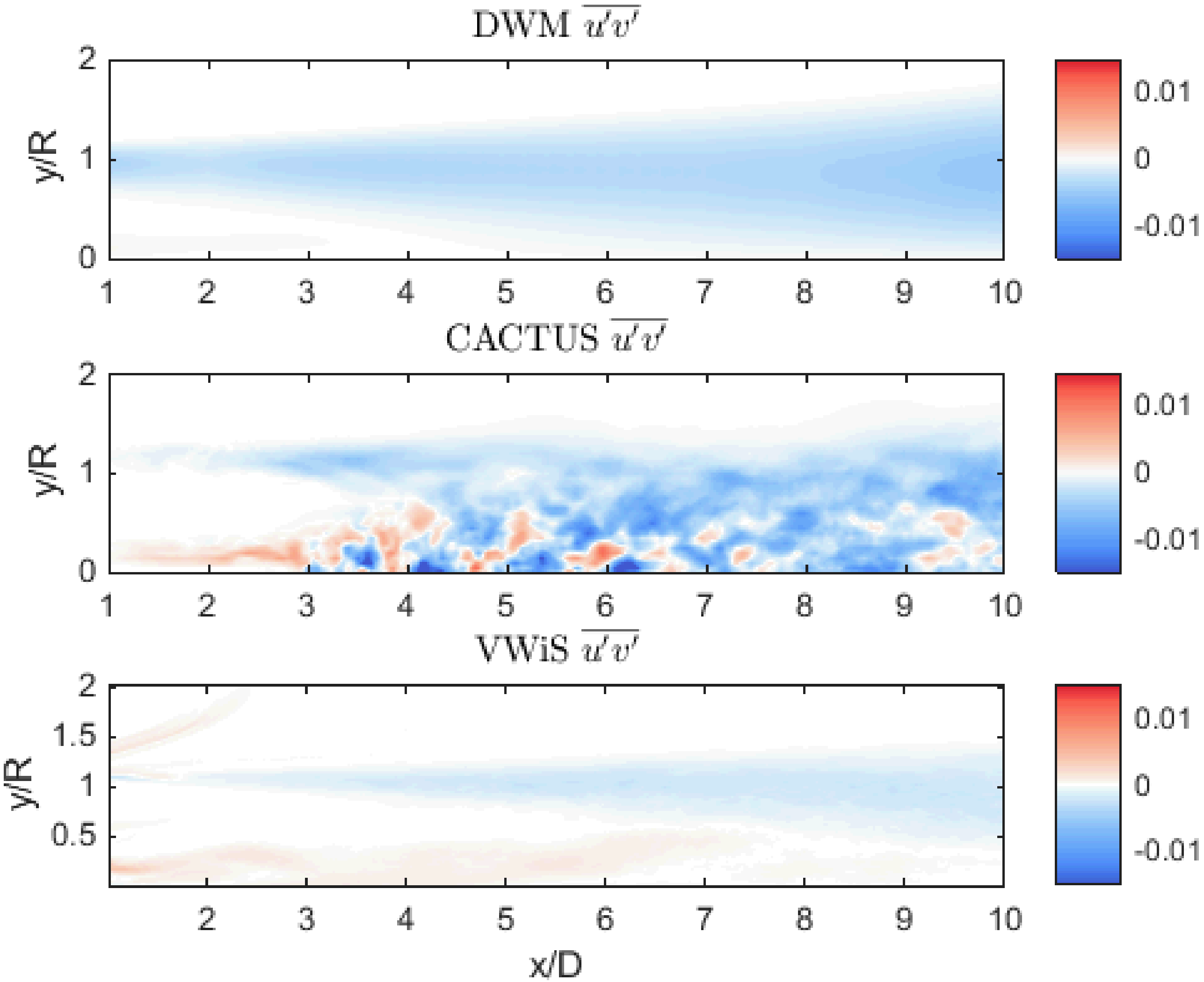




Results: Reynold’s Shear

$$-\overline{u'v'}_r = \nu_T \frac{\partial U}{\partial r}$$

- Reynold’s shear stress accounts for all of the turbulence in the DWM model
- Shear stress pattern similar for the three models
- Magnitude of shear stress follows same trend as speed to recovery for the three models
- CACTUS results, again, clearly not averaged sufficiently



Results: Boundary Condition

- DWM Boundary conditions shown to be inconsistent with results from CACTUS and VWiS in comparison
  - Design rotor induction, a, not achieved
  - Radial velocity not zero at rotor plane
  - Eddy viscosity model from DWM differs by +/- 50% from VWiS and CACTUS, respectively

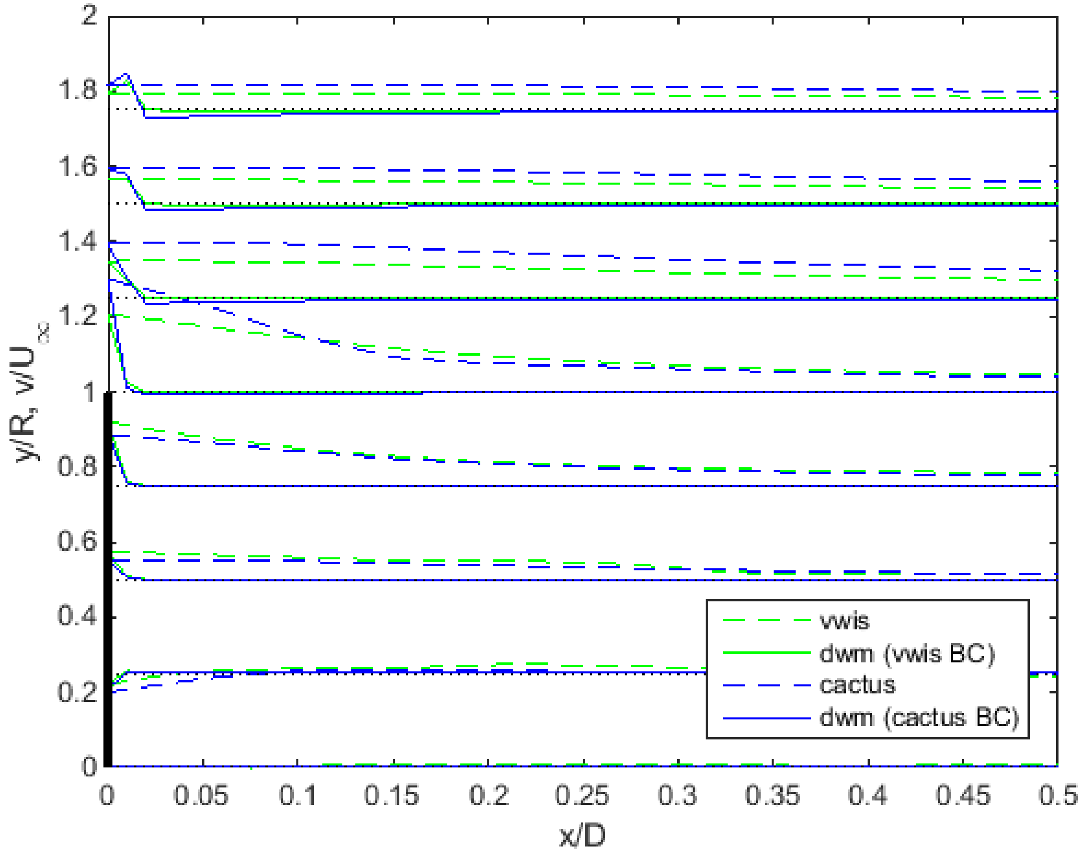
DWM Model Boundary Condition Sensitivity

DWM BC	DWM-CACTUS	DWM-VWiS
Original Design	0.086	0.077
Matched Induction, a	0.079	0.076
Matched a, V_r	0.079	0.074
Matched a, V_r and ν_T	0.073	0.065

(comparison shown in model STE_c, [3, 10] D)

Results: Boundary Condition

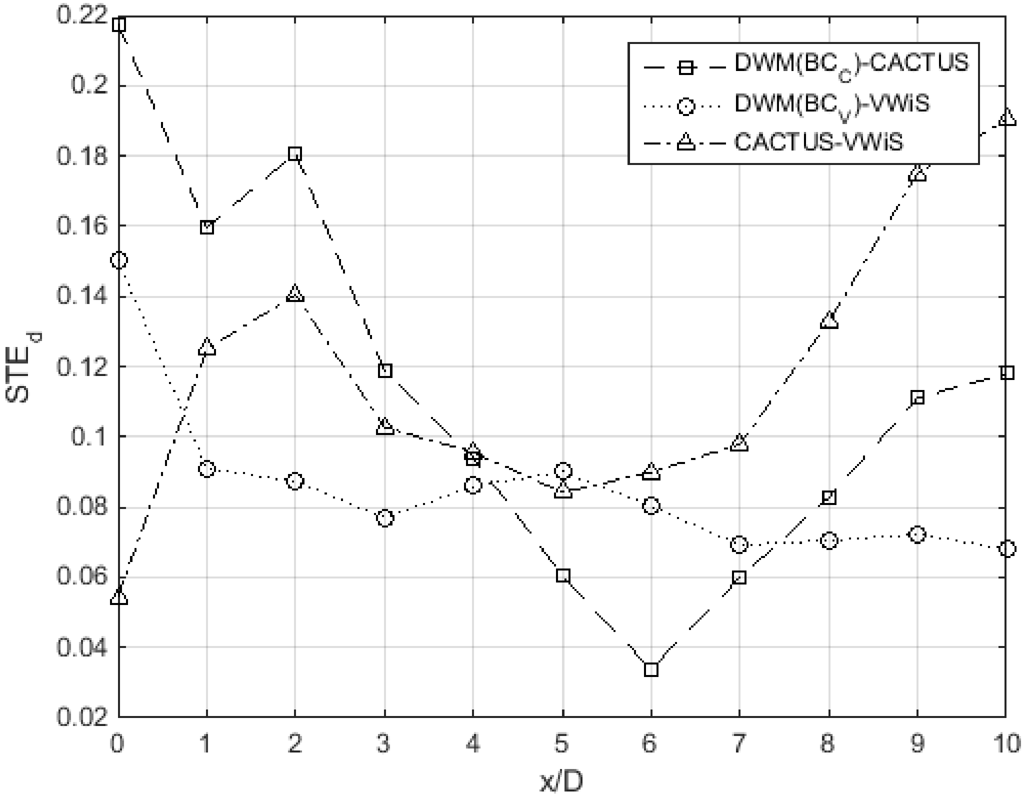
- Addition of the radial velocity boundary condition has little effect because of nearly immediate return to zero.



Results: Boundary Condition

- Error calculation with BC’s matched between DWM-CACTUS and between DWM-VWiS

- Results are still **qualitative** in the comparison of CACTUS and VWiS since they are essentially modeling two different rotors
- Model agreement significantly improved for DWM-VWiS
- Even with increased Eddy Viscosity, CACTUS still recovers much more quickly than DWM



Concluding Remarks

- The DWM steady wake deficit model produced wake velocity profiles that had average “errors” of around 7% compared to VWiS and CACTUS
- The mechanism for wake recovery differed substantially between the three models
- DWM predicted wake deficit is not as highly sensitive to the change in rotor induction from [3, 10] D as expected
- A clear error of the DWM model radial velocity BC was observed, but with little change when included

Concluding Remarks

- Further analysis is needed to draw significant conclusions between the three models including:
  - Direct input of the Reynold’s shear stress field to the DWM
  - Comparison with turbulent inflow
  - CACTUS and AL-LES simulations where the same resultant disk-averaged rotor induction is produced

Acknowledgments

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