SAND2020-9993C

Quantifi… ke using Nalu-Wind simulations

Thomas Herges[1], Christopher Kelley[1], Alan Hsieh[1], Kenneth Brown[1], David Maniaci[1], and Jonathan Naughton[2]

[1]Sandia National Laboratories, Albuquerque, N.M., U.S.A.

[2]University of Wyoming, Laramie, W.Y., U.S.A.

Abstract

- **Goal: understand if field campaigns can capture quantities required to calculate rotor thrust forces from a momentum deficit analysis of a wind turbine wake**
- Inflow and wake velocities typically acquired during a field campaign are sufficient for simplified 1D momentum analysis of the wake
- Control volume surface analysis around a SWiFT turbine was conducted using 10-minute Nalu simulation with neutral inflow
- Extracted necessary quantities for a full Reynolds-Averaged Navier-Stokes analysis along the control volume surfaces
- Full RANS approach matched wind turbine thrust force well at all downstream locations
- 1D analysis results in 70% difference in rotor C_t at 2D and 40% from 5D to 8D
- Results suggest typical field campaign measurements are insufficient to capture accurate rotor thrust measurements
- Relative difference improves to less than 10% if streamwise pressure is included

Introduction

- Understanding and predicting how wind turbine wakes evolve downstream for different atmospheric inflow stratifications is important for both wind turbine and wind plant design [1]
- Measurements and simulations can be used together through validation efforts to improve understanding and prediction of wind turbine wakes

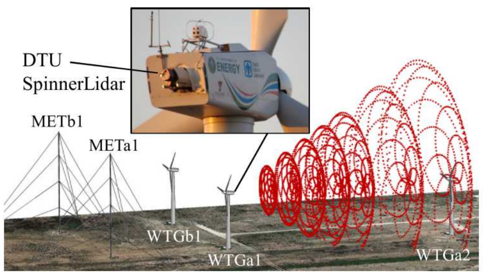

Figure 1: Schematic of how SWiFT benchmark data was acquired

- Inflow measured using meteorological tower (METa1), inflow and wind turbine model were only aspect of the benchmark used in analysis
- Benchmark included line-of-sight velocity measurements in wake using DTU SpinnerLidar, but wake measurements are not used for comparison in current work

Method

- Paper detailed derivation of control volume RANS formulation
- Final RANS formulation applied along control volume surfaces:

$$\rho\left(\oiint \overline{u}\overline{u}\,\hat{n_x}dydz + \oiint \overline{u'u'}\,\hat{n_x}dydz + \oiint \overline{u}\overline{v}\,\hat{n_y}dxdz + \oiint \overline{u'v'}\,\hat{n_y}dxdz + \oiint \overline{u}\overline{w}\,\hat{n_z}dxdy + \oiint \overline{u'w'}\,\hat{n_z}dxdy\right)$$

$$= F_x - \rho \oiint_{wall} \left(\overline{w'u'}^2 + \overline{w'v'}^2\right)^{\frac{1}{2}} \hat{n_z}dxdy - \oiint \overline{p}\,\hat{n_x}dydz$$

- 1D momentum formulation:

$$\rho \oiint \overline{u}\overline{u}\,\hat{n_x}dydz - \rho \oiint \overline{u}_\infty \overline{u}\,\hat{n_x}dydz = F_x$$

- Coefficient of thrust: $C_t = \dfrac{F_x}{\frac{1}{2}\rho A_{turb} {u_\infty}^2}$

Setup

- Simulation models WTGa1 Vestas V27 turbine
- Hub height = 32.1 m
- Rotor diameter = 27 m
- Neutral ABL
- Freestream hub-height Wind speed = 8.69 m/s
- Simulated 660 seconds (removed first 60 s to remove start up)
- Control volume box dimensions, 283.5 m × 110 m × 100 m
- Control volume extended x = -2.5D upstream (where METa1 is located) to 8D downstream
- Turbine located in center of control volume
- Transverse planes sampled at 2D, 3D, 4D, 5D, 6D, and 7D from rotor
- Upper surface, XY2 at z = 100 m (≈ 3.7D)
- Lower surface, XY1 at z = 0 m
- Side planes, XZ1 and XZ2 at y = ± 55 m (≈ ± 2.0D).
- Transverse planes analogous to experimental configuration of SWiFT site in figure 1 used during neutral benchmark [2,3]

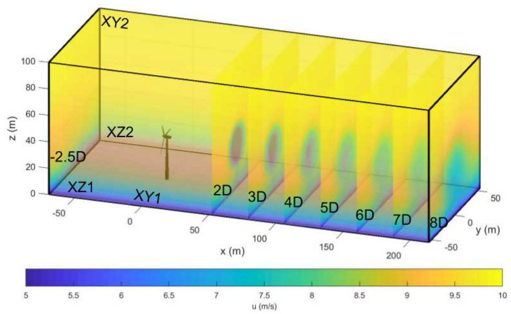

Figure 2: Control volume planes

Results

- **Forces from RANS equation matches wind turbine thrust well throughout wake from 2D to 8D, maximum difference of 0.055 at 5D**
- Figure 3 plots show force contribution of each RANS term (uu, uv, uw, p, $u'u'$, $u'v'$, and $u'w'$) through each control volume plane (YZ, XY, and XZ)
- **Velocity and pressure terms contribute greatest amount to forces in YZ planes**
- **Followed by uv term applied along XZ planes and pressure term along YZ planes**
- **Contributions from uw, $u'u'$, $u'v'$, and $u'w'$ terms is relatively weaker in this particular case**

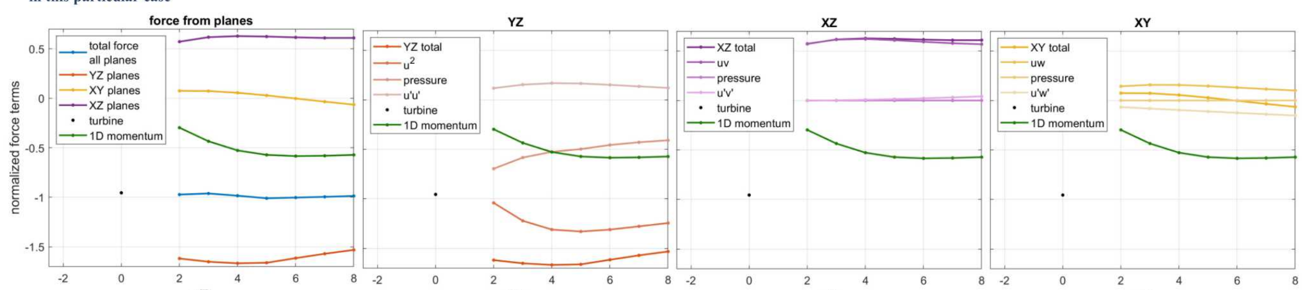

Figure 3: Contribution of each plane and term to C_t

Results (cont.)

- **1D-momentum analysis matches summation of force contributions from velocity component terms (uu, uv, and uw) with largest difference in C_t occurring at 2D (0.026)**
- Shows assumption during 1D momentum derivation that relating momentum flux through sides of control volume to the freestream velocity using continuity was reasonable
- Still large discrepancy between total thrust forces and 1D momentum estimation due to contribution from pressure and Reynolds shear stress terms

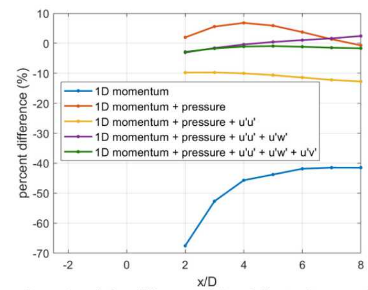

Figure 4: Relative difference of C_t to full RANS approach

- Figure 4 continues analysis showing contribution of each term relative to full RANS analysis as a percent difference
- Comparison starts with contribution of 1D momentum estimation, which has largest contribution in momentum deficit relative to RANS approach
- Figure 4 adds each term with subsequent importance to momentum deficit contribution as determined from figure 3
- **Simplified 1D momentum formulation results in difference ranging from 70% at 2D to 40% from 5D to 8D**
- **Indicates that field test that only captures streamwise velocity of inflow and wake would be inadequate to capture C_t of rotor using momentum deficit analysis of wake**
- **However, if pressure was acquired at streamwise locations, result would be slightly over estimated but to within 10% of correct rotor C_t**
- Adding $u'u'$, $u'v'$, and $u'w'$ reduces difference to almost zero
- **Estimation of rotor C_t can be conducted using 1D momentum analysis and pressure measurements**
- **But an experiment would need to be complemented by full RANS calculation or turbulence estimation to reduce relative difference to less than 5%**

Conclusions

- Nalu-Wind used to simulate WTGa1 wind turbine for neutral SWiFT benchmark case, extracting necessary quantities of interest along control volume surfaces
- Full Reynolds-Averaged Navier Stokes approach applied around six-surface control volume over 10-minute period, matching thrust in wake to wind turbine rotor thrust from 2D to 8D
- Traditional, simplified one-dimensional analysis was included for comparison between RANS approaches
- Simplified 1D analysis resulted in 70% difference relative to the full RANS calculation of C_t at 2D and 40% difference from 5D to 8D
- Appears that capturing inflow and wake velocities is insufficient for C_t analysis of wake unless correction factor is created
- Wake momentum deficit analysis can be within 10% of wind turbine thrust force if pressure is acquired at corresponding streamwise distances
- **Even though 1D momentum terms, or quantities, do not capture full turbine thrust force, these terms are still useful for validation purposes in comparing experiments to simulations**
- **Analysis highlights how 1D momentum quantities evolve downstream and could inform what is not captured in wake when discrepancies exist in validation comparisons**

References

[1] Moriarty P, Rodrigo J S, Gancarski P, Churchfield M, Naughton J W, Hansen K S, Machefaux E, Maguire E, Castellani F, Terzi L, Breton S-P and Ueda Y 2014 IEA-Task 31 Wakebench: Towards a protocol for wind farm flow model evaluation. Part 2: Wind farm wake models *Journal of Physics: Conference Series* **524** 012185.

[2] Doubrawa P, Debnath M, Moriarty P J, Branlard E, Herges T G, Maniaci D C and Naughton B 2019 Benchmarks for Model Validation based on Lidar Wake Measurements. *Journal of Physics: Conference Series* **1256** 012024.

[3] Doubrawa P, Quon E W, Martinez-Tossas L A, Shaler K, Debnath M, Hamilton N, Herges T G, Maniaci D C, Kelley C L, Hsieh A S, Blaylock M L, Laan P v d, Andersen S J, Krueger S, Cathelain M, Schlez W, Jonkman J, Branlard E, Steinfeld G, Schmidt S, Blondel F, Lukassen L J and Moriarty P 2020 Multimodel validation of single wakes in neutral and stratified atmospheric conditions *Wind Energy* doi:10.1002/we.2543.

Contact Information

Tommy Herges, therges@sandia.gov

Acknowledgements

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. Funding provided by the U.S. Department of Energy's Wind Energy Technologies Office.