Validation of Coupled Atmospheric-Aeroelastic Model System for Wind Turbine Load Calculations for Enercon turbine

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June 11, 2025

Introduction and Motivation

Research Objective:

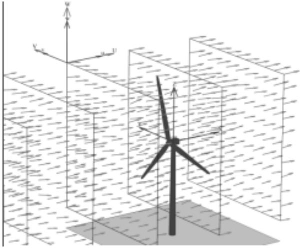
- Validate coupled atmospheric- aeroelastic models for accurate wind turbine simulations with Focus on Enercon turbine.

Traditional Aeroelastic Simulation Limitations:
Synthetic turbulence (Kaimal/Mann spectrum) models :

- Assume statistically stationary, homogeneous turbulence
- Pre-calculated wind fields with simplified atmospheric conditions
- Limited representation of complex flow phenomena (gusts, shear, atmospheric stability)

Wake modeling deficiencies:

- Simplified wake models (Jensen, Frandsen) lack temporal dynamics
- No feedback between turbine operation and atmospheric flow



Actuator Sector Model (ASM) - Concept

Actuator Line Model Limitations:

- Small time steps required (Δt_F)
- High computational cost for LES

Actuator Disk model Advantages:

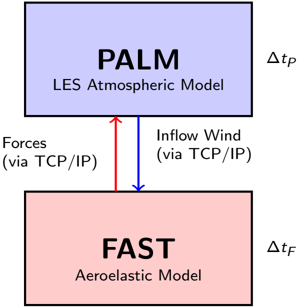
- Larger time steps possible
- Lower computational cost
- No individual blade information

Actuator Sector model Solution:

- Detailed blade output + Computational efficiency
- Decoupled time stepping

Time Step Decoupling Strategy:

- PALM: Δt_P determined by CFL/diffusion criteria
- FAST: $\Delta t_F < \Delta t_P$ for ALM accuracy
- Significant reduction in total computational time



Bi-directional Coupling

ASM allows PALM to use optimal atmospheric time steps while maintaining detailed turbine physics in FAST

ASM Operational Mechanism

ASM Operational Steps:

1. FAST communicates initial blade positions.
2. PALM provides wind speeds from frozen field
3. During Δt_P, rotor sweeps sector:

$$\alpha = \Omega \cdot \Delta t_P$$

   we take velocities from the central line of the sector

4. Using NWC to correct wind speeds
5. Exchange of current blade positions and velocities
6. Calculating turbine response.

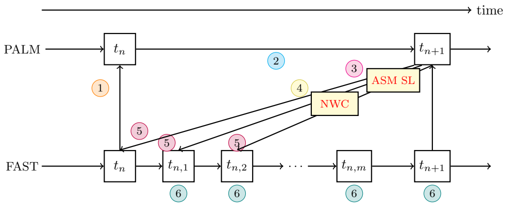


Figure: Schematic of the operation mode of the coupling

Based on research work done by (Krüger et al. 2022; Steinbrück et al. 2024)

Technical Benefits

- Maintains ALM physics in FAST
- Efficient force projection in PALM

Force Projection in PALM

Actuator Sector Method (ASM)

- Forces from bold central line applied to all m lines in sector
- Gaussian-shaped smearing distributes forces in 3D space

Gaussian Distribution

$$\eta = \frac{1}{\epsilon^3 \pi^{3/2}} \exp\left(-\left(\frac{r}{\epsilon}\right)^2\right)$$

where:

- η = regularization function
- r = distance from grid node to turbine
- ϵ = smearing parameter

Key Concept

Forces are not applied as point sources but distributed smoothly using Gaussian smearing to avoid numerical instabilities

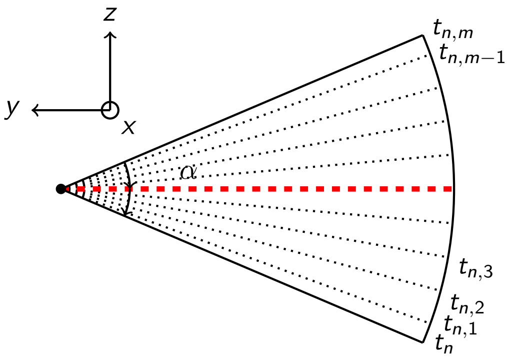


Figure: Sector schematic: values from central line (bold, red) projected to flow. y, z = rotor plane; x = streamwise direction

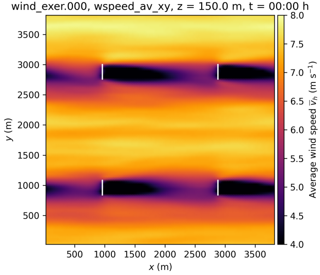
Intended Outcomes

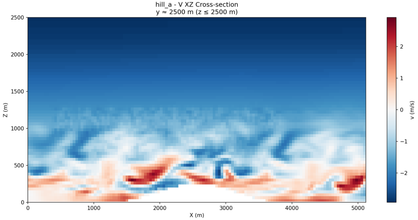
Outcomes:

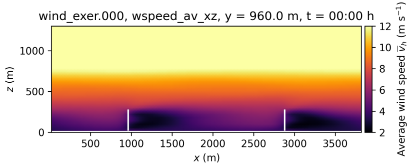
1. **Wake Characterization in Complex Terrain**
   - Detailed analysis of wake dynamics over complex terrain
   - Impact of atmospheric stability on wake evolution
2. **Turbine Performance Assessment**
   - Power production analysis for downstream turbines
   - Load variations due to wake interactions
   - Fatigue damage equivalent loads (DEL) calculations
3. **Model Validation**
   - Comparison with field measurements (SCADA data)

Work Done so far:

1. Installed and Practiced PALM on Linux and in taifun.
2. Most of Literature review including selected stull chapters.
3. Ran ADM-R simulation, rudimentary flow over a hill PALM simulations.
4. Ran the test simulation of PALM-FAST coupling in taifun.







References

Krüger, S. et al. (2022). "Validation of a coupled atmospheric–aeroelastic model system for wind turbine power and load calculations". In: *Wind Energy Science* 7.1, pp. 323–344. DOI: 10.5194/wes-7-323-2022. URL: https://wes.copernicus.org/articles/7/323/2022/.

Steinbrück, S. et al. (2024). "Improved coupling between an atmospheric LES and an aeroelastic code for the simulation of wind turbines under heterogeneous inflow". In: *Wind Energy Science Discussions* 2024, pp. 1–20. DOI: 10.5194/wes-2024-146. URL: https://wes.copernicus.org/preprints/wes-2024-146/.