Validation of Coupled Atmospheric-Aeroelastic Model System for Wind Turbine Power and Load Calculations

Application to Enercon Wind Turbines

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Introduction and Motivation

Research Objective:

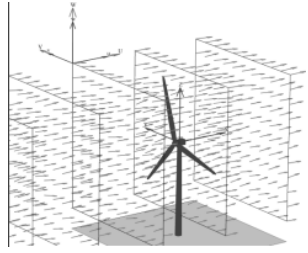
- Validate coupled atmospheric- aeroelastic models for accurate wind turbine simulations.
- Focus on Enercon turbine technology and performance

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 and Motivation

ALM Limitations:

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

ADM Advantages:

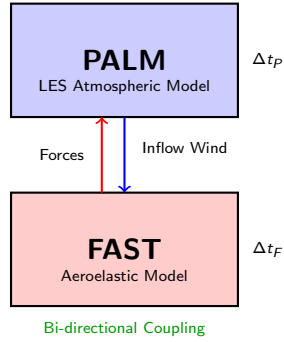
- Larger time steps possible
- Lower computational cost
- No individual blade information

ASM 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



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:

$$\phi = \Omega \cdot \Delta t_P$$

4. Forces from central blade line applied to entire sector
5. Multiple FAST calculations per PALM time step

Technical Benefits

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

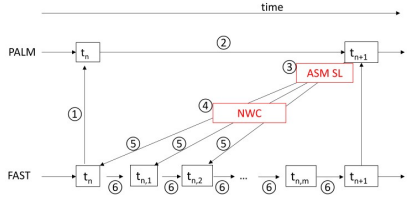


Figure: Schematic of the operation mode of the coupling

Based on research work done by Steinbrück et al. 2024, Krüger et al. 2022

Intended Outcomes

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/.