Dynamics of the center of wind pressure:
From a description of the wind to an estimator of the loads on a wind turbine

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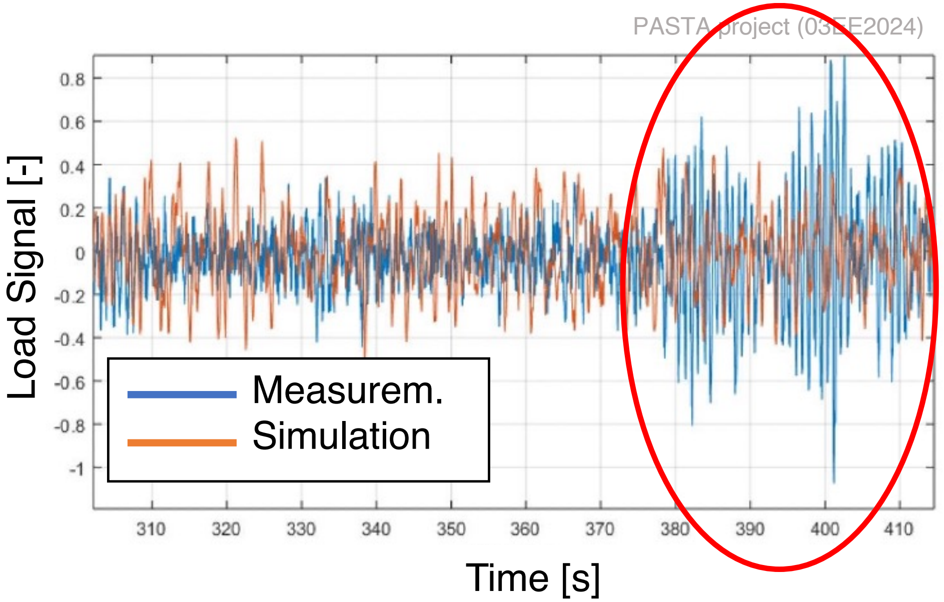
Motivation

- Critical events on loads* of operating wind turbines (WTs), not predicted by numerical simulations
- Measurements and simulations under same standard wind conditions (e.g., $\bar{u}$, TI, shear exp.)



Are some critical load events induced by certain wind structures not included in the current wind models?

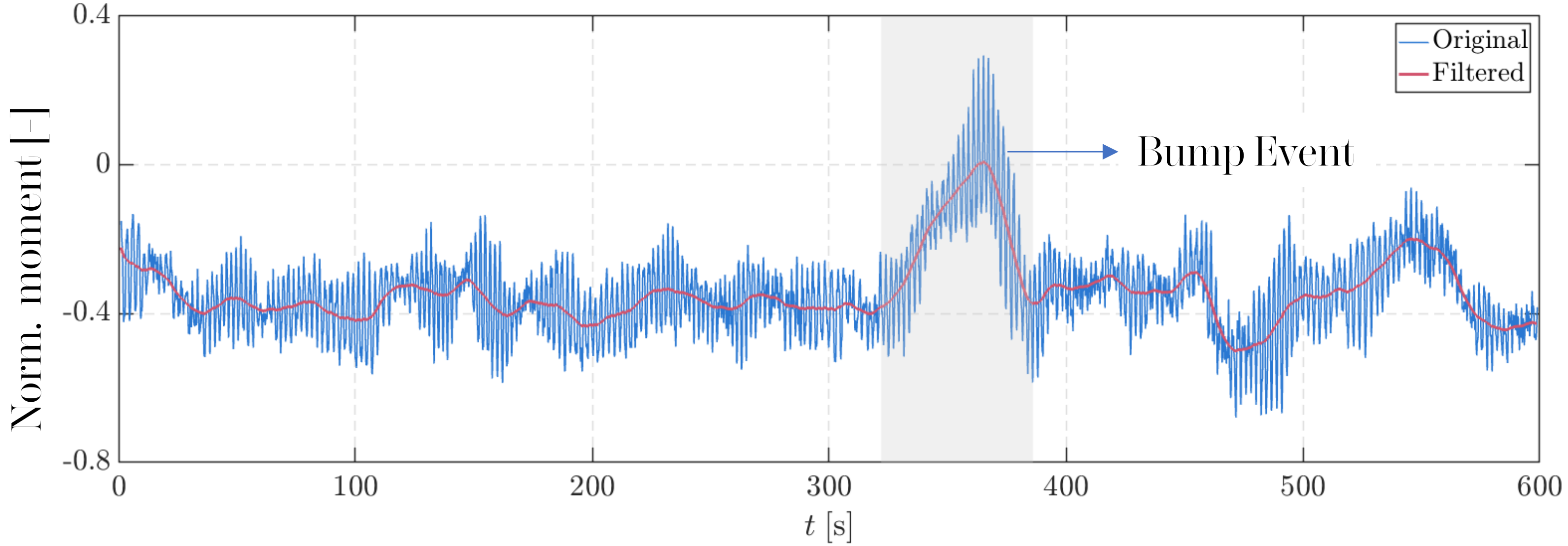
*Tilt and yaw bending moments at the main shaft of the turbine

Motivation

Are those critical load events induced by certain wind structures not included in the current wind models?

- What do we know about the load* events?

[1]



- Bump event: Large scale structure → Large amplitude, low-frequency (>10s)

*Tilt and yaw bending moments at the main shaft of the turbine

Center of Wind Pressure (CoWP)[1]

Definition

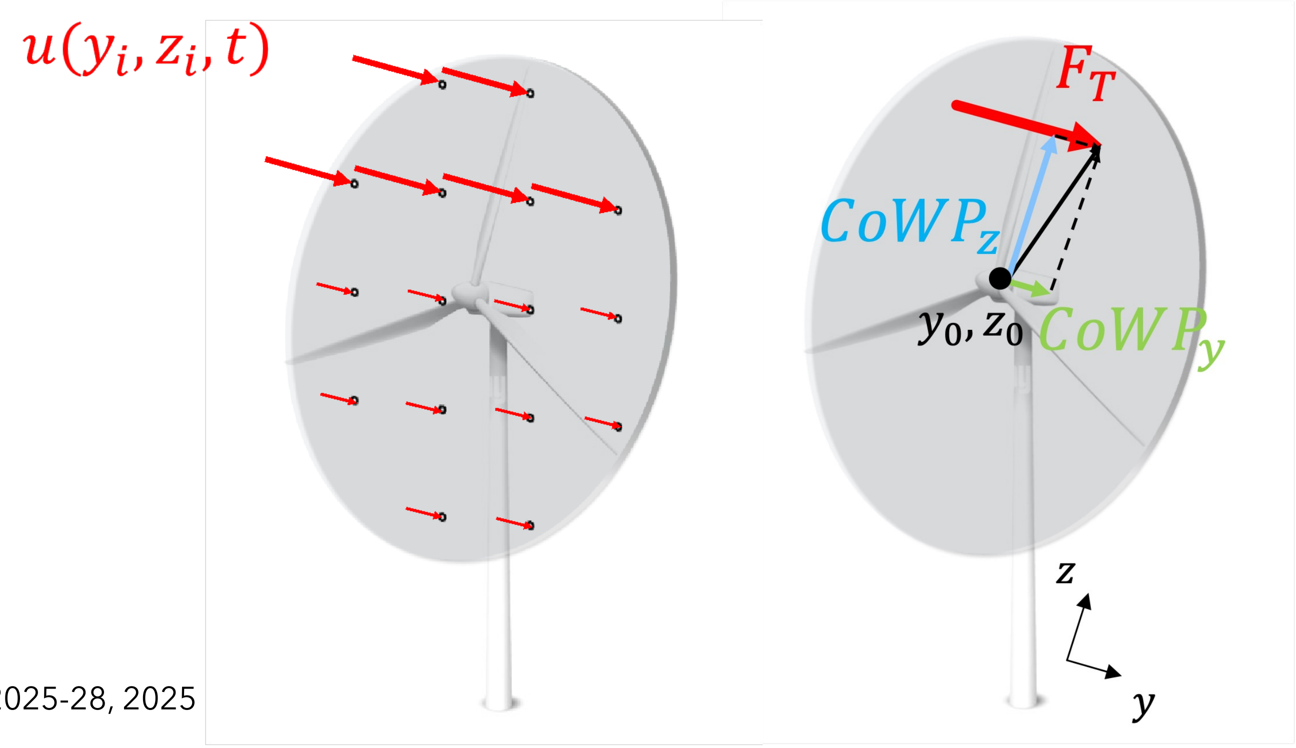
- Description of large-scale wind structures
- Effect on the tilt and yaw moments at the main shaft
- Bending moment, $\boldsymbol{T} = \boldsymbol{l} \times F_T$

  CoWP

- CoWP: Location of point-wise F_T, for inducing $\boldsymbol{T}$
- Calculated purely from a wind field $u(y, z, t)$

$$CoWP_y(t) = \frac{T_y}{F_T} = \frac{\sum_{i=1}^{n} y_i \cdot u^2\,(y_i, z_i, t)}{\sum_{i=1}^{n} u^2(y_i, z_i, t)}$$

[2]



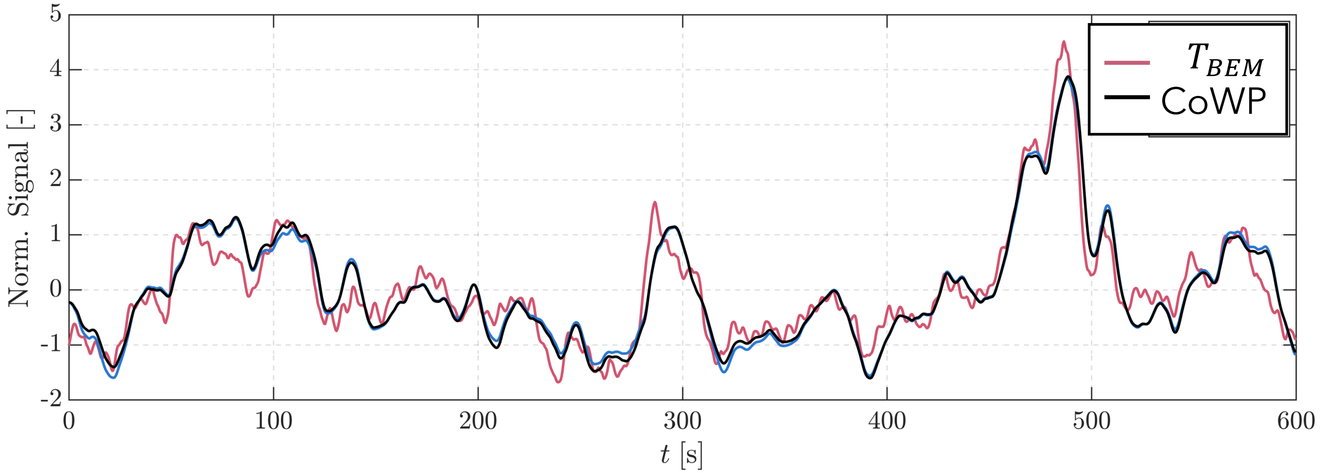
[1] Schubert, C., et al., Wind Energy Sci. Disc., 2025,1–19, DOI: 10.5194/wes-2025-28, 2025

Center of Wind Pressure (CoWP)

Correlation to bending moments

- BEM simulated moment (T_{BEM}) and CoWP
- Filtered and normalized signals: low-pass filter, zero mean and standard deviation equal to 1

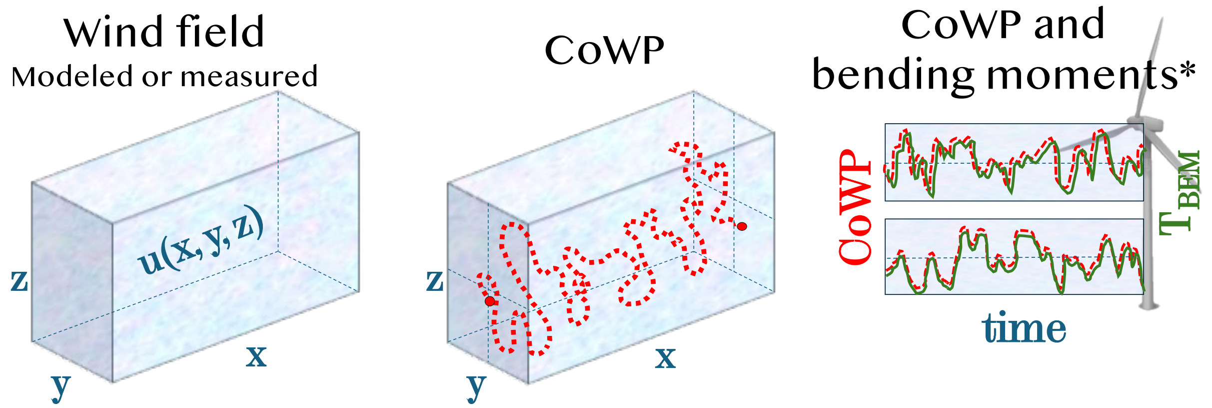
[1]



- Strong correlation: Correlation factor ~0.9

Center of Wind Pressure (CoWP)

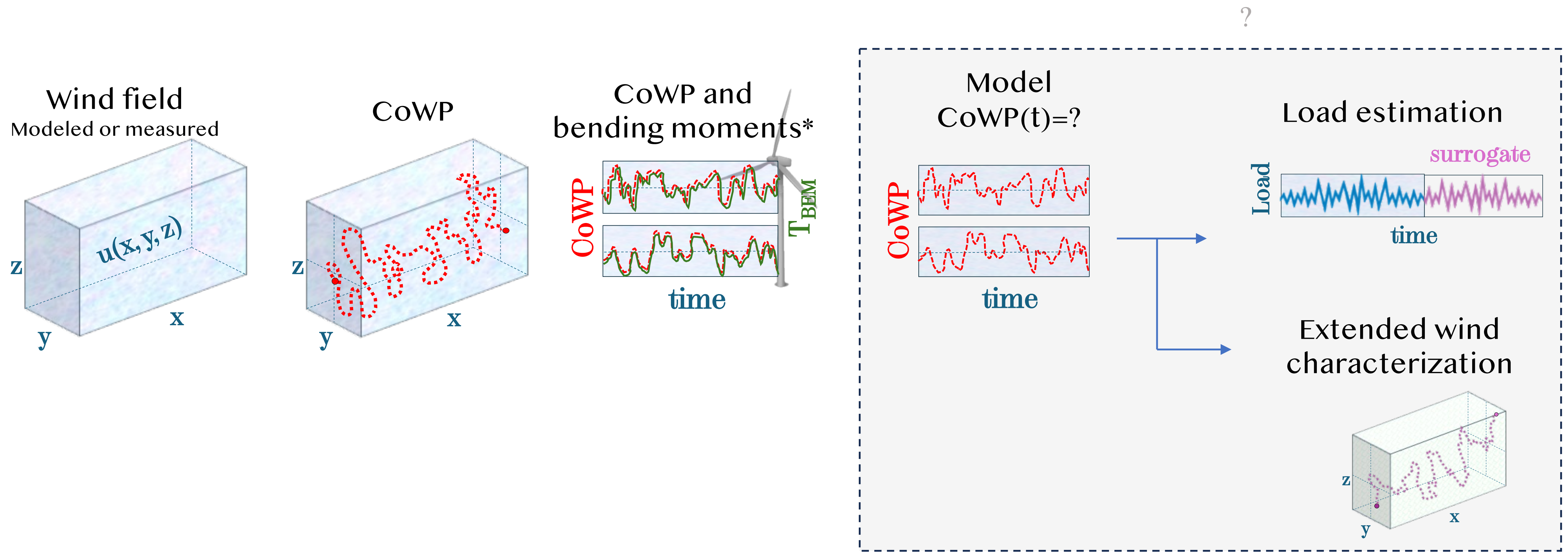
So far…



* low frequency dynamics

Center of Wind Pressure (CoWP)

So far…



* low frequency dynamics

Center of Wind Pressure (CoWP)

Stochastic model

- Description of the dynamics of CoWP
- Langevin stochastic approach

$$\frac{d}{dt}CoWP(t) = \underbrace{\boxed{D^{(1)}CoWP(t)}}_{\text{Deterministic}} + \underbrace{\boxed{\sqrt{D^{(2)}CoWP(t)} \cdot \Gamma(t)}}_{\text{Stochastic}}$$

- $D^{(1)}$ drift coeff., $D^{(2)}$ diffusion coeff., and Γ gaussian noise
- $D^{(1)}$ and $D^{(2)}$ can be extracted from time series of CoWP [3][4]
- Integration of the equation to reconstruct random signals (with statistical properties of original data)

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Center of Wind Pressure (CoWP)

As estimator of the loads

- Comparison between original CoWP, simulated moment (T_{BEM}) and reconstructed CoWP_R
- Probability density function and damage equivalent load (DEL) → $DEL \sim n_i s_i^m$

- Reconstructed signals reproduce the statistics of the original CoWP and BEM bending moments.
- Very long time series can be generated – load assessment over life-time span

* low-frequency dynamics

Conclusions

- The CoWP is introduced as a feature of a wind field
- The CoWP and bending moments* at the main shaft (i.e., tilt and yaw) are strongly correlated
- The dynamics of the CoWP are characterized via the stochastic Langevin approach
- The dynamics of the CoWP are used for reconstruction of random signals of the bending moments*
  Very long time series can be generated → Reduction on time and complexity compared to BEM
- The reconstructed signals agree with the original CoWP: statistics and DEL

*low-frequency dynamics

Current work

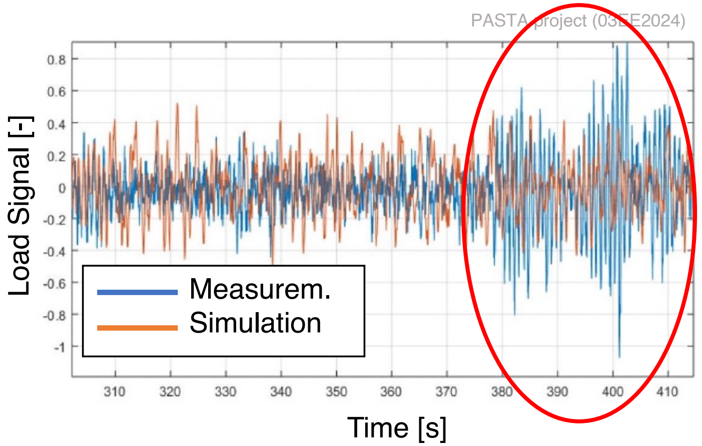
- Comparison of CoWP between atmospheric wind and different wind models

  Larger amplitudes of CoWP within atmospheric wind → Unexpected load events in operating turbines?

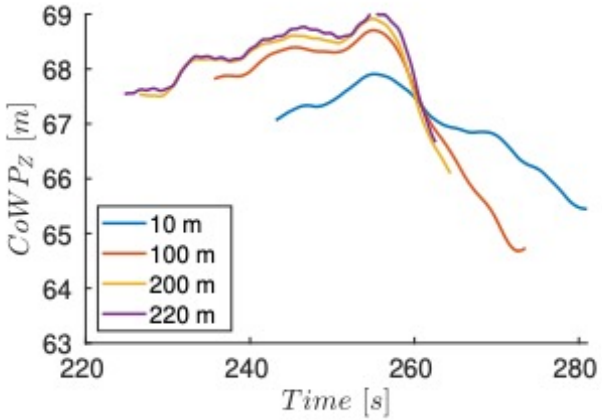
- Correlation of CoWP to different loads on turbine (e.g., on blades, tower)
- Incorporation of dynamics of CoWP into wind models for numerical simulations

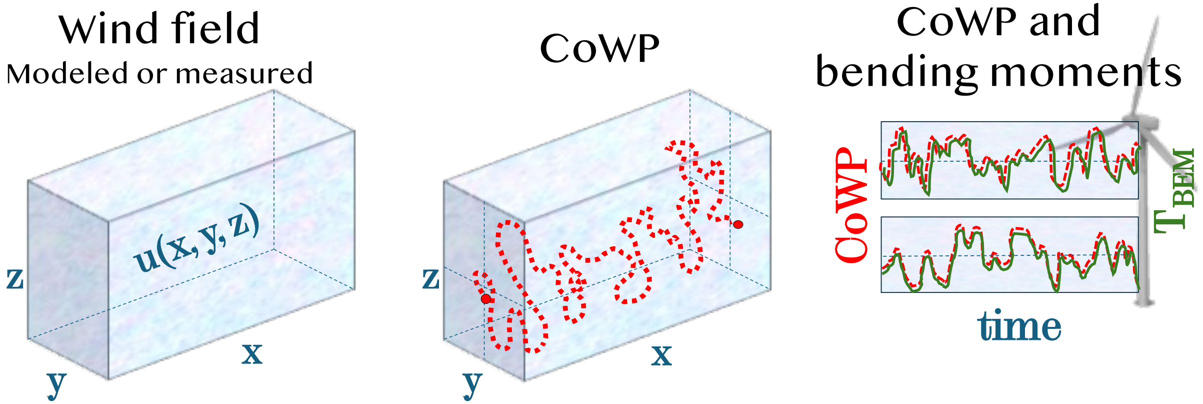
  As characteristic of large-scale wind structures

- Comparison of the CoWP for different simulation methods: LES with actuator line, LES with blade resolved
- Transfer functions: from CoWP to actual values of loads



LES, Actuator line





Thank you for your attention!

Questions?

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References

[1] Schubert, C., et al. 2025. *Introduction of the Center of Wind Pressure for correlating large-scale turbulent structures and wind turbine loads*. Wind Energy Sci. Disc., 2025,1–19, DOI: 10.5194/wes-2025-28.

[2] Moreno, D., et al. 2024. Dynamics of the virtual center of wind pressure: An approach for the estimation of wind turbine loads, Journal of Physics: Conf. Ser., 2767, 022 028,440. DOI: 10.1088/1742-6596/2767/2/022028.

[3] Rinn P, Lind P G, Wächter M and Peinke J. 2016. *The Langevin Approach: An R Package for Modeling Markov Processes.* Journal of Open Research Software, 4. ISSN 2049-9647

[4] Reinke N, Fuchs A, Medjroubi W, Lind P G, Wächter M and Peinke J. 2015. *The Langevin Approach: a simple stochastic method for complex phenomena*. DOI: 10.1007/978-3-319-18206-3_6.

[5] Moreno, D., et al. 2025. From the center of wind pressure to loads on the wind turbine: A stochastic approach for the reconstruction of load signals. *Under preparation.*