Aeroelastic simulations of large reference wind turbines using a flexible actuator line method in Large Eddy Simulations

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Introduction

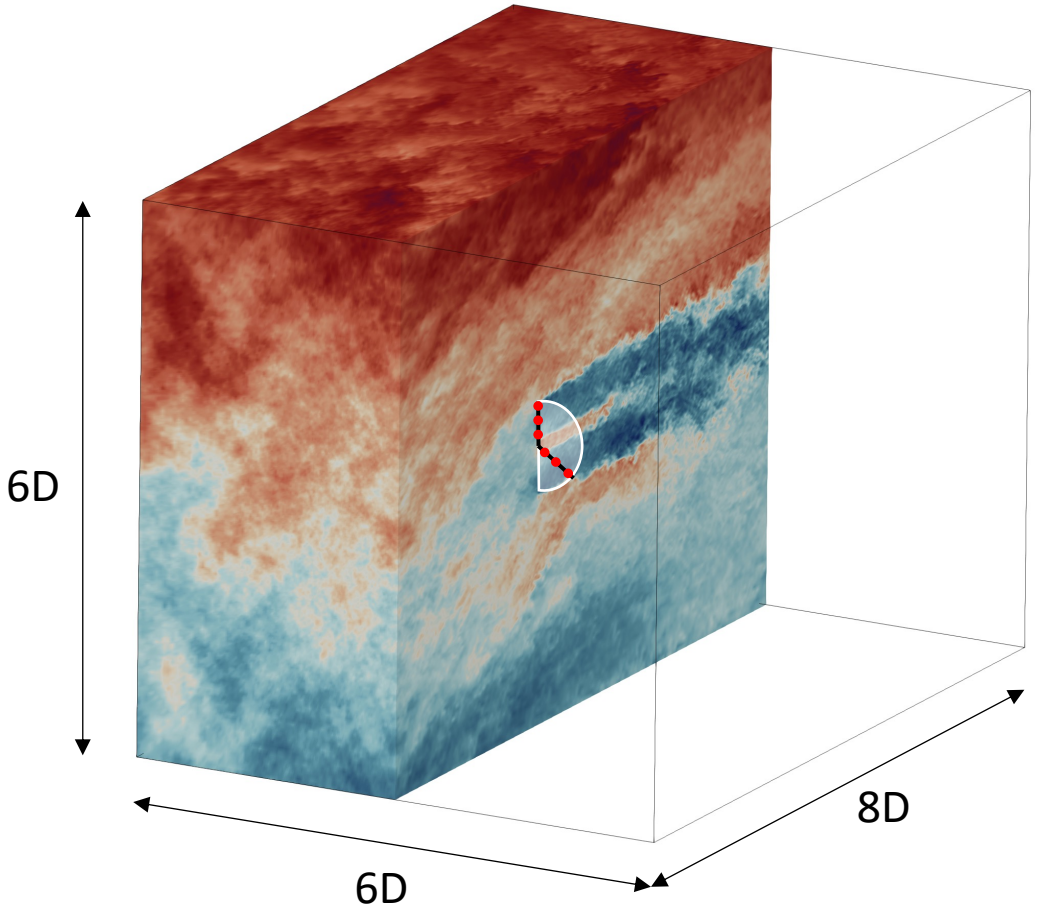
- **Larger wind turbines**:
  More slender and flexible blades, prone to unsteady aero-elastic effects

- **Objectives**:
  1. Understand the determining unsteady aero-elastic effects occuring on the rotor.
  2. Observe their evolution on 3 generations of reference wind turbines

	NREL 5-MW	DTU 10-MW	IEA 15-MW
Rated power [MW]	5	10	15
Diameter D [m]	126	178.3	240
Hub height [m]	90	119	150
Bend-twist coupling	None	Small	Large



Overview of the methodology

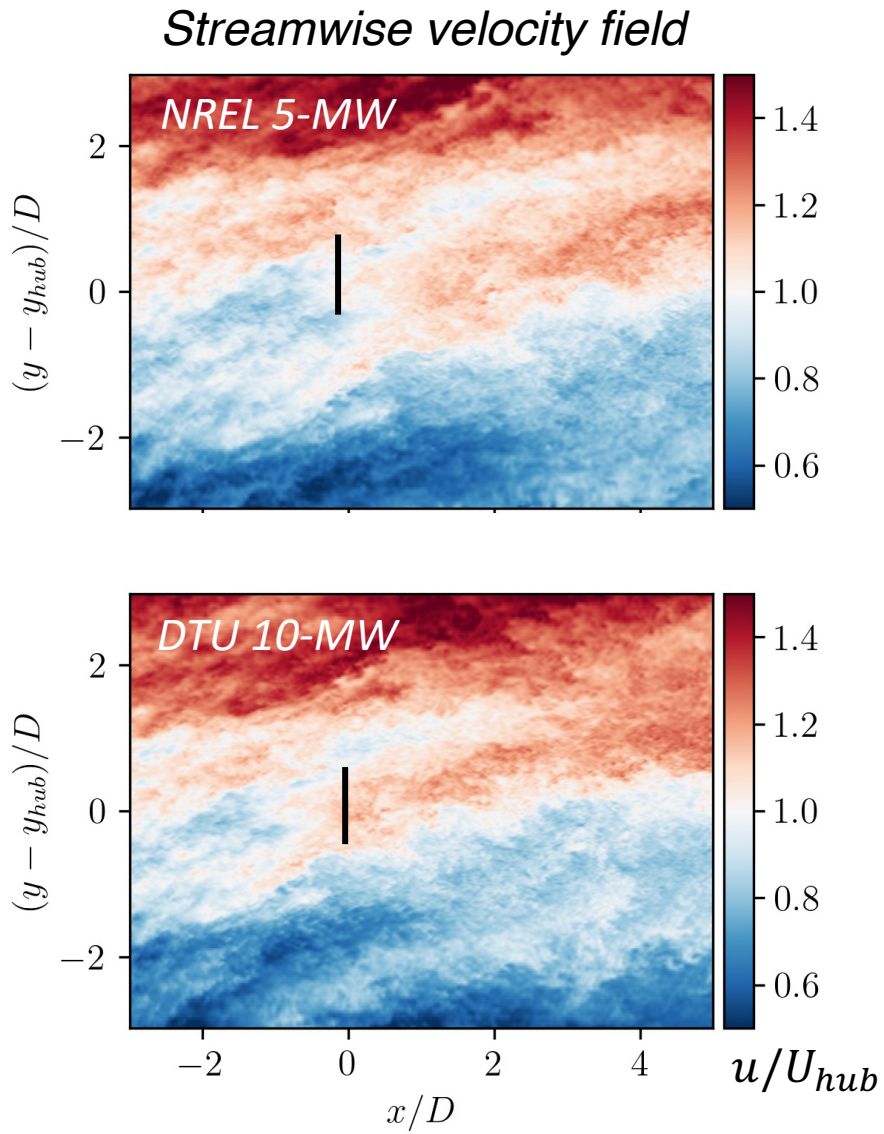


LES velocity field for the NREL-5MW simulation

- **Large Eddy Simulation** (LES) (performed using an in-house 4th order finite difference code) is used with a **flexible actuator line method** coupled to the structural solver **BeamDyn***:*
  - LES is used to simulate the turbulent inflow and the wake,
  - ALM models the blades, allowing multiple rotation cycles (10 mn of real time),
  - BeamDyn is used to solve the structural dynamics of the blade (including large displacement and full cross-section stiffness matrix).

- Simulations of the 5, 10 and 15 MW reference wind turbines are carried in similar operating conditions.

Inflow and domain specifications

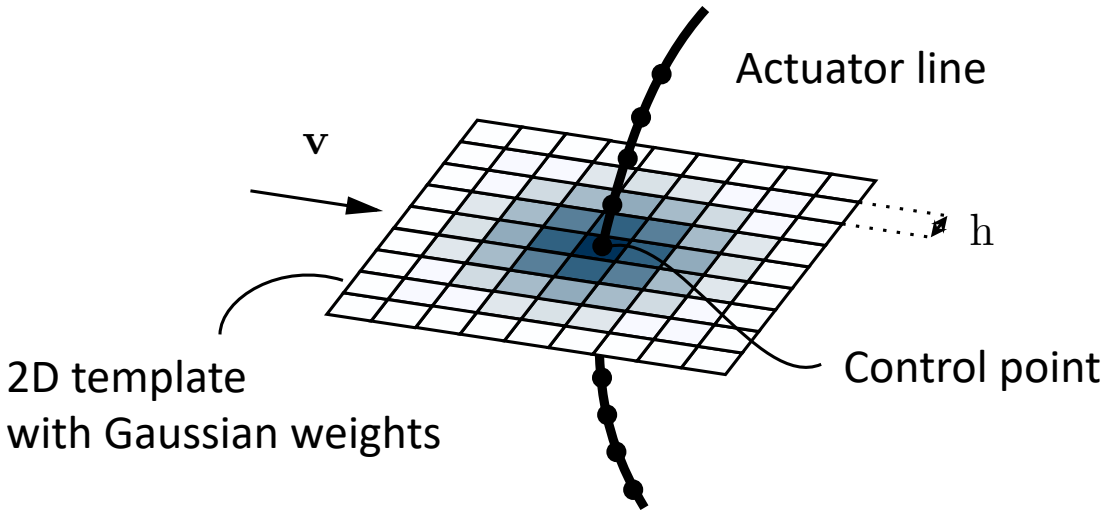


- Inflow conditions:
  - Sheared inflow with turbulent fluctuations generated using the Mann algorithm:
    - U_{hub} = 90% of the WT rated velocity,
    - Turbulence Intensity (TI) ≃ 6% (same fluctuation field for all the simulations),
    - Linear shear with parameter $s = \frac{dU}{dy}\frac{D}{U_{hub}}$.

- Computational domain:
  - 64 grid points / D,
  - Size: 8D (streamwise) x 6D x 6D.

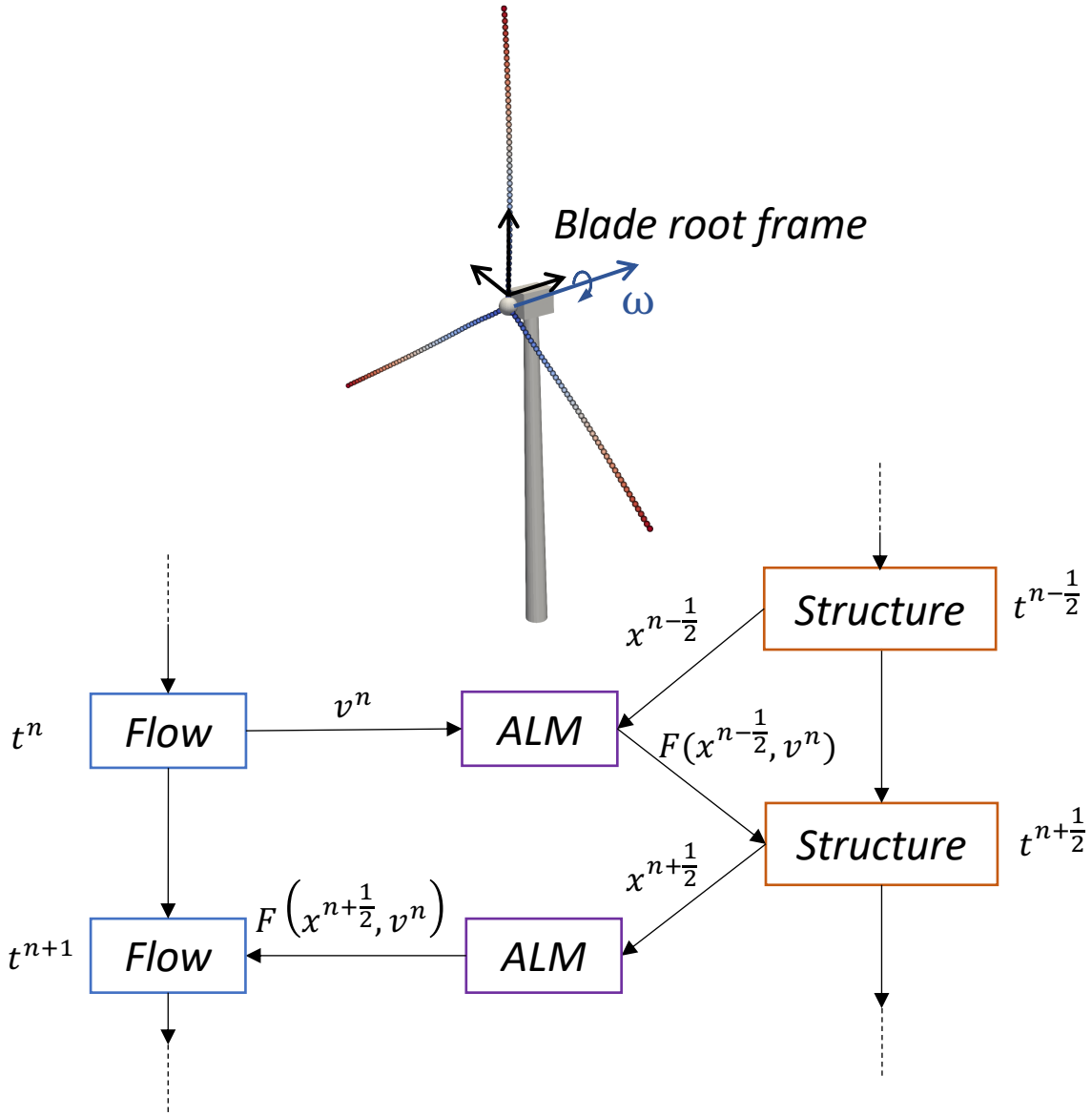
	NREL 5-MW	DTU 10-MW	IEA 15-MW
Inflow wind speed [m/s]	10.26	10.26	9.53
TSR	7.55	7.5	9
Shear parameter s	0.122	0.131	0.140

Flexible actuator line method



- The ALM allows to simulate the effect of the blade on the flow by adding an equivalent aerodynamic force to the flow solver.
- Here, the force distribution to the LES mesh is performed using a 2D template, kept perpendicular to the blade, and with Gaussian weights. The value obtained on each cell of that template is then transmitted the LES nearest mesh points (using linear interpolation).
- This allows to increase the accuracy of the ALM, hence decreasing the need of an additional tip correction.

Structural solver and coupling



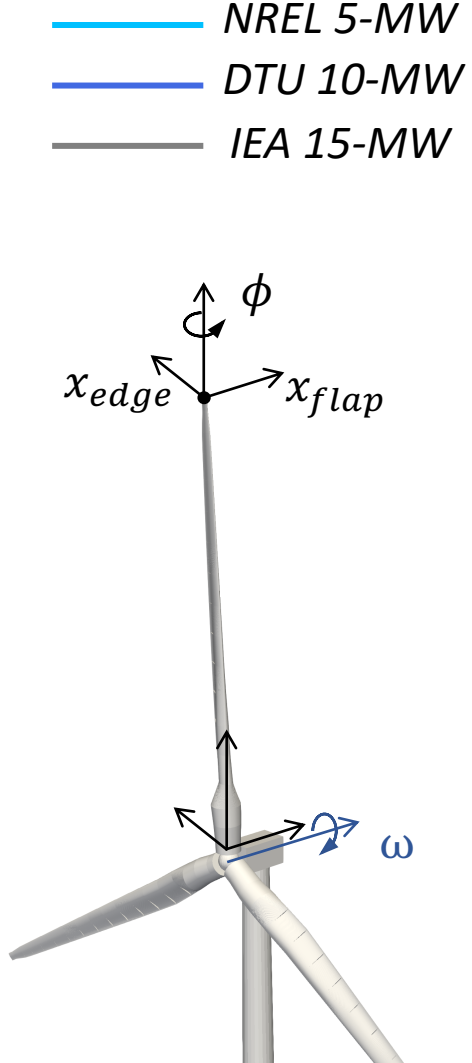
- **BeamDyn** from OpenFAST is used as structural solver:
  - Geometrically exact beam theory solver with 1D finite elements,
  - Large displacements,
  - Fully populated 6x6 mass and stiffness matrices.
- The blades are rigidly connected to the hub at their root, and rotate with a constant rotation speed.
- Explicit coupling with the ALM:
  - 2nd order staggered scheme
  - Subcycling of the structural solver (without reevaluation of the forces).

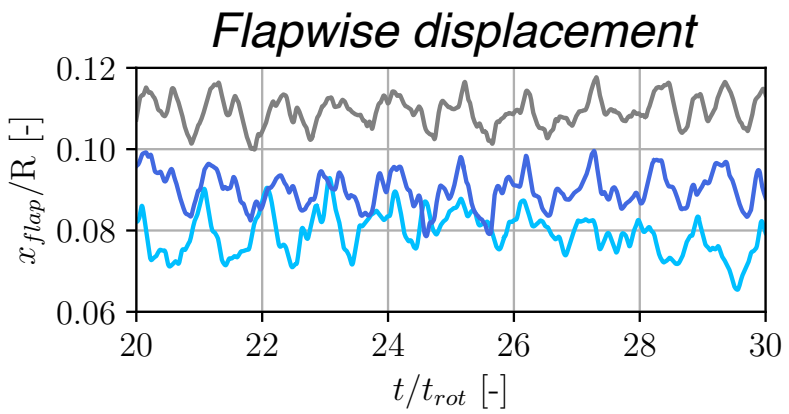
Blade tip displacement/torsion

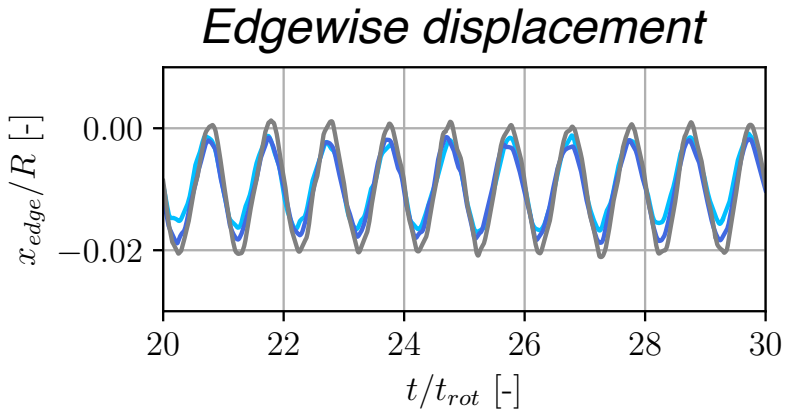
- **Flapwise direction**:
  Increased relative displacement for larger turbines (u_{flap}/R = 8%, 9.5% and 11.4% for 5, 10 and 15 MW, respectively).
  The influence of the turbulence is visible.

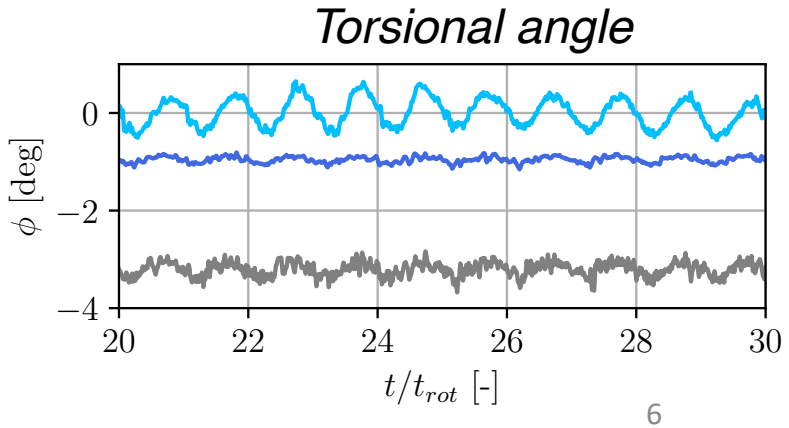
- **Edgewise direction**:
  Variation mostly due to gravity (u/R = 1%).

- **Torsional angle**:
  For the 5MW: no mean torsional angle but important variation during each rotation.
  Larger mean torsional angle for newer generation turbine due to bend-twist coupling, but smaller variations.





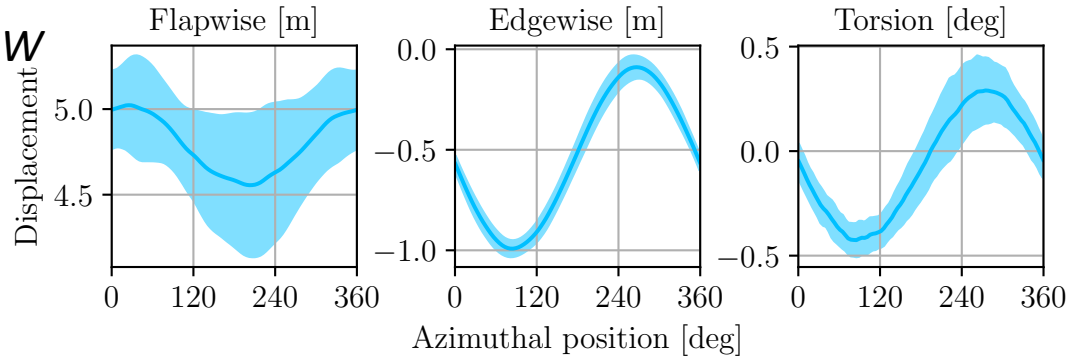




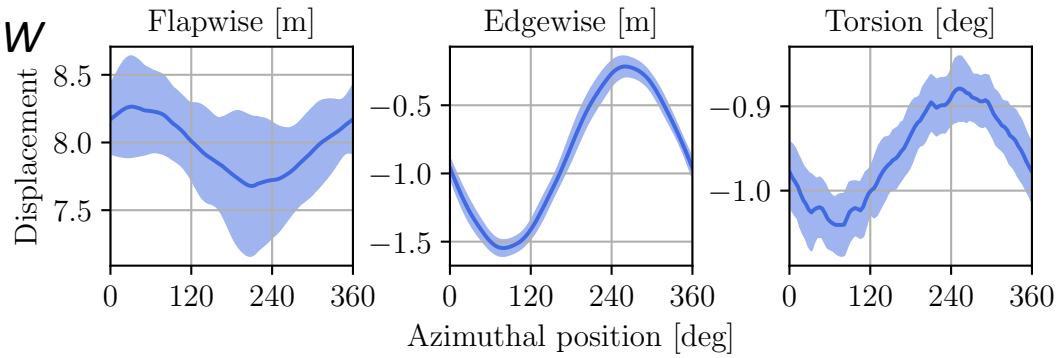
Ensemble averaged blade tip displacement/torsion

- Significant variations during the rotation.
- 10% variation of the flapwise displacement due to the sheared inflow.
- Small variation of the edgewise displacement.
- Non symmetric variation of the torsional angle for the large turbines between the left and right part of the rotor.

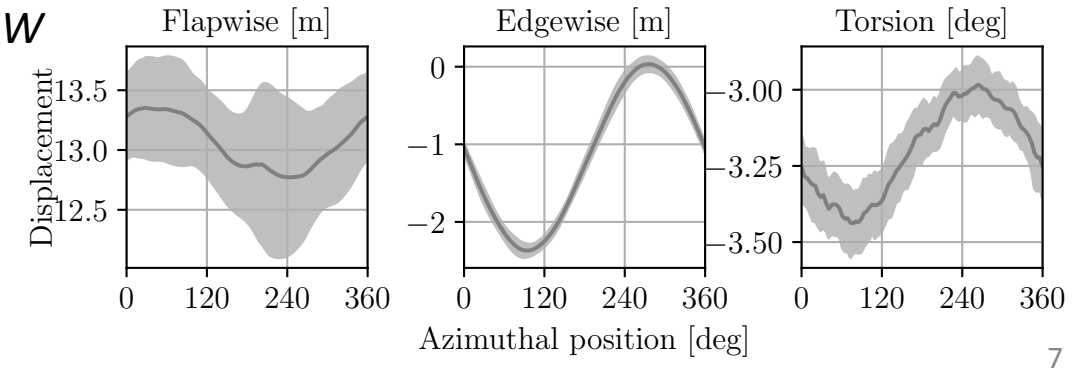
NREL 5-MW



DTU 10-MW

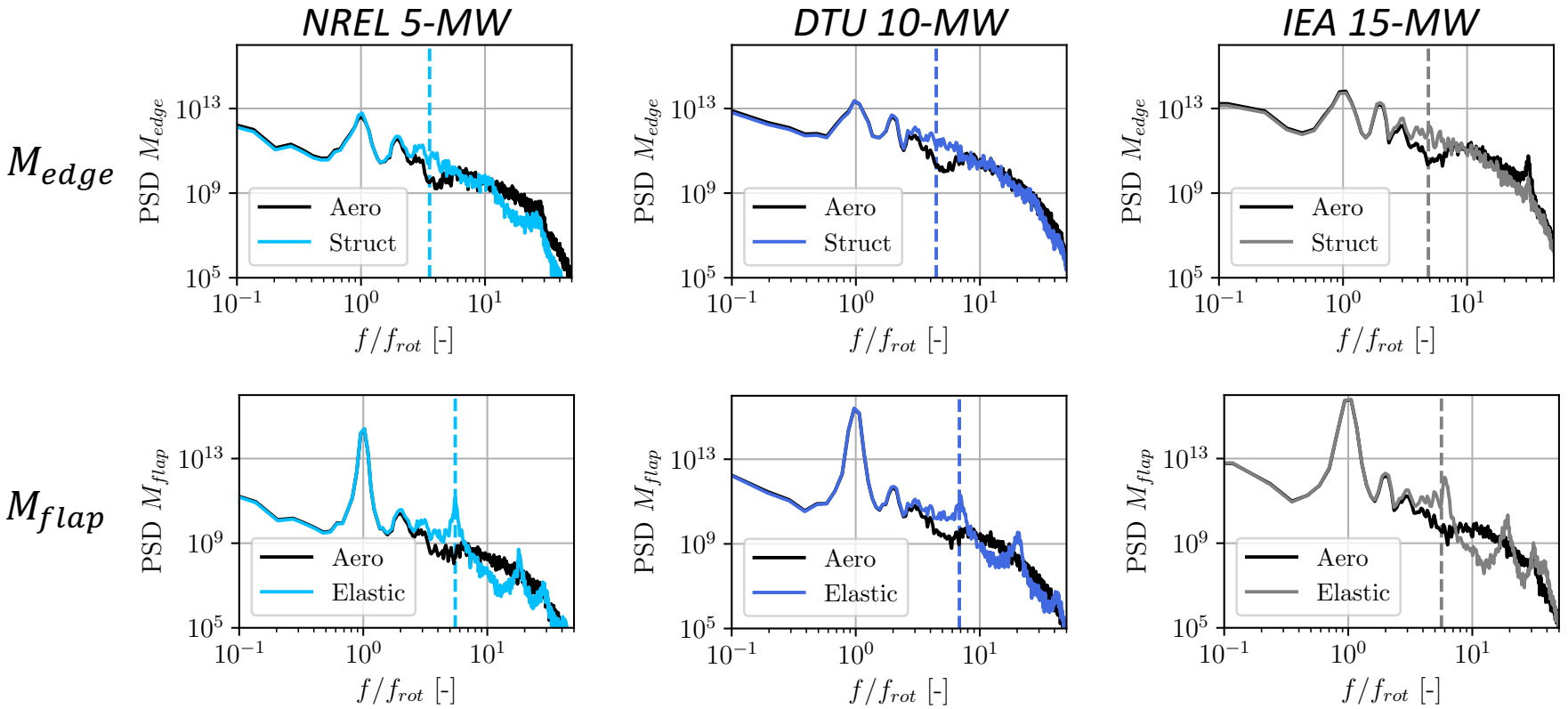


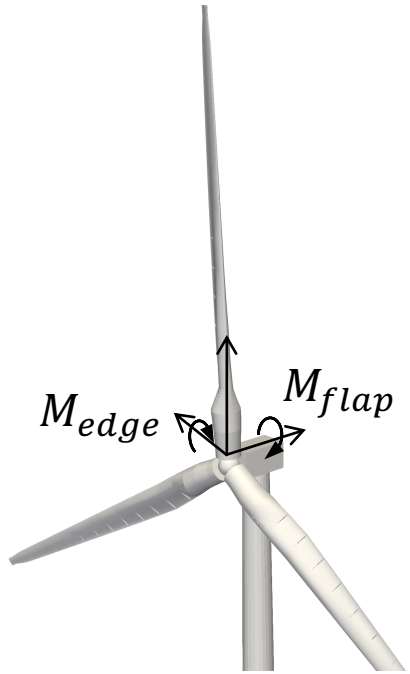
IEA 15-MW



Blade root moment

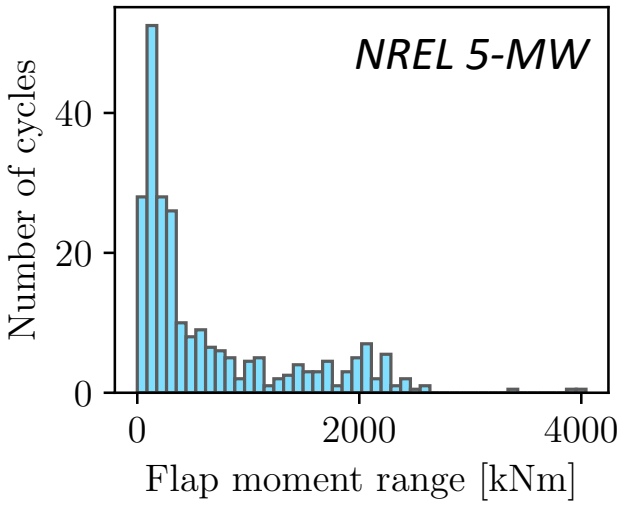
- The blade root moment of the aerodynamic forces (Aero) is compared to the structural response (i.e., the elastic blade bending moment) (Struct)
- The root moment of the aerodynamic loads is decreased at the natural bending frequencies due to the compliance of the blade.
- The structural response has peaks at the edgewise natural frequencies

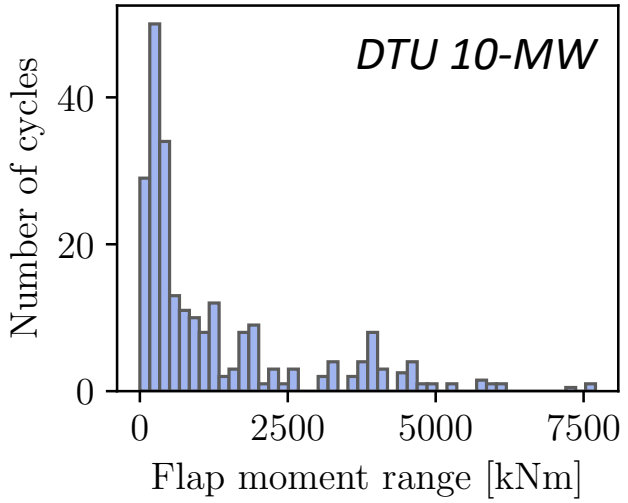


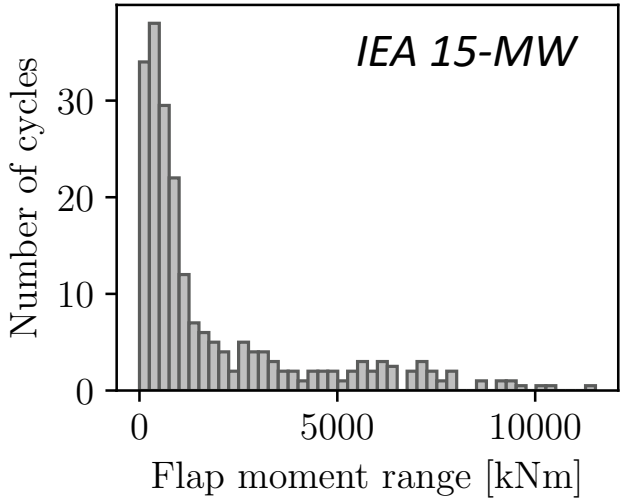


Fatigue Analysis: Blade root moment due to the flapwise loads

- All turbine show a similar distribution of the cycles, with a scaled amplitude
- The equivalent alternating edgewise moment scales linearly with the power





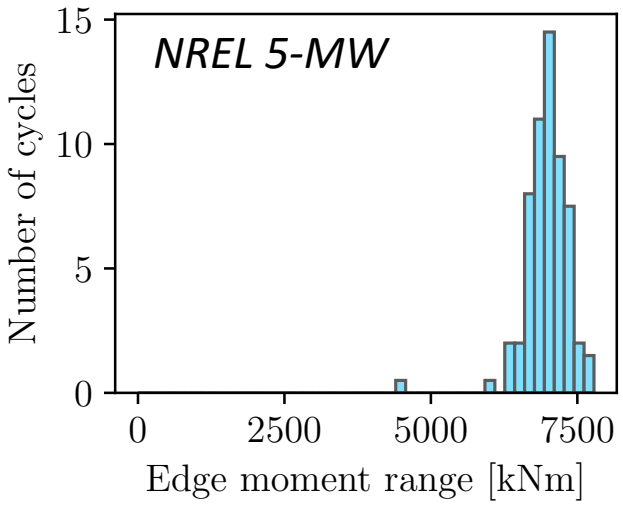


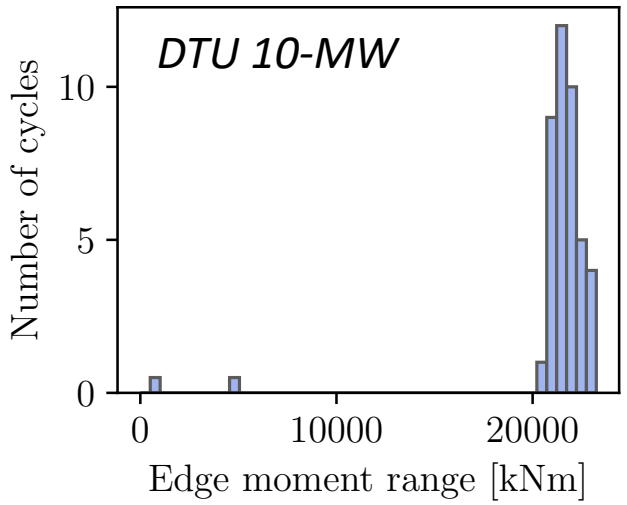
	NREL 5-MW	DTU 10-MW	IEA 15-MW
Equivalent Edgewise moment [MNm]	2.28	4.54	6.71

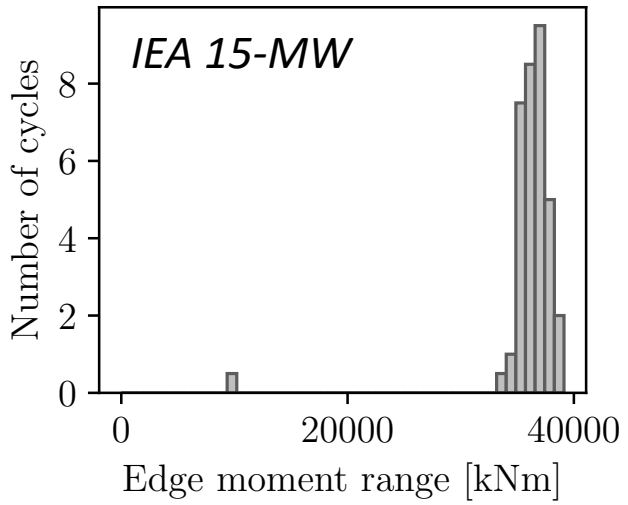
$$M_{edge,eq} \sim R^{1.6}$$

Fatigue Analysis: Blade root moment due to the edgewise loads

- The fatigue in this direction is mostly due to the gravity loads







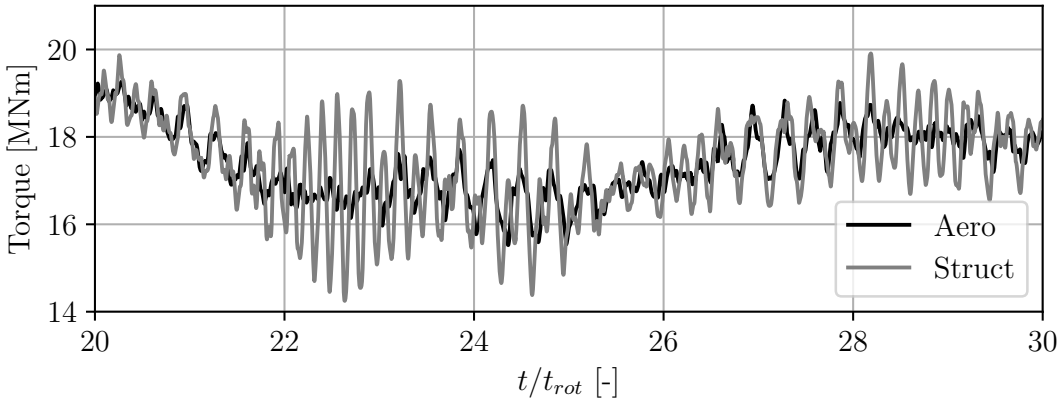
	NREL 5-MW	DTU 10-MW	IEA 15-MW
Equivalent flapwise moment [MNm]	7.03	21.71	36.46
Moment due to gravity [MNm]	6.71	21.10	35.56

$$M_{e,eq} \sim R^{2.2}$$

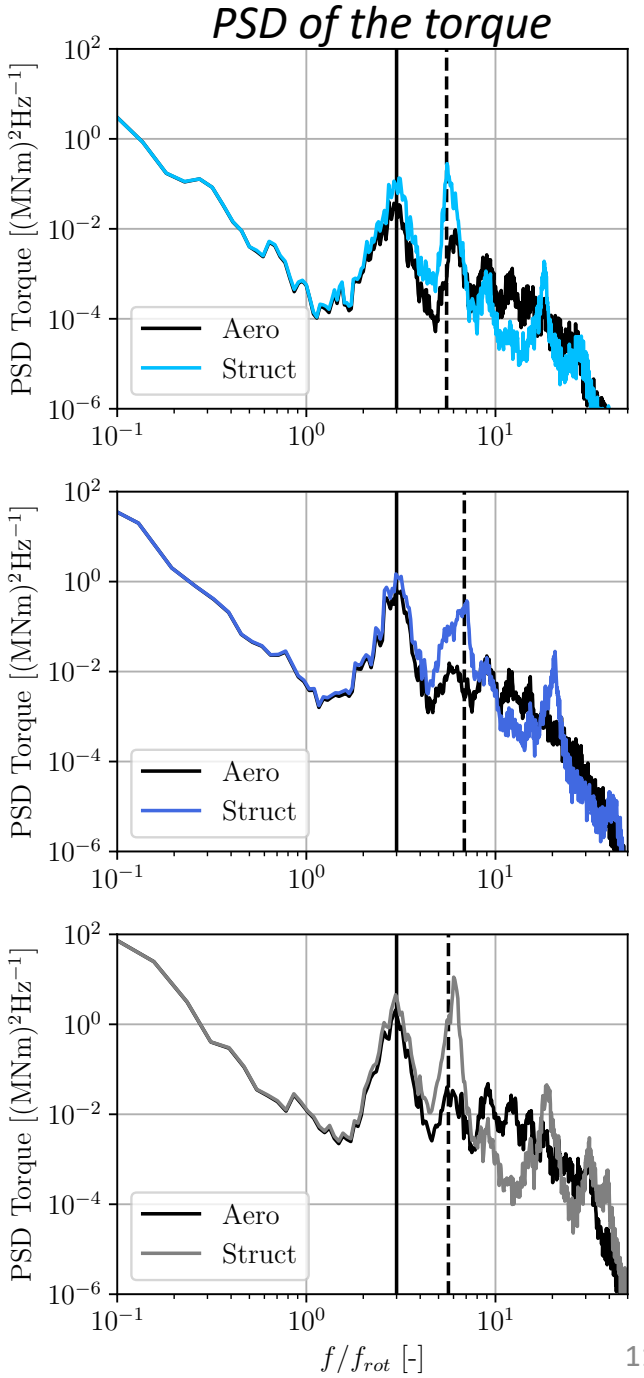
Torque on the rotor hub

- The gravity component of the edgewise root moment is removed when accounting for the torque on the hub induced by the three blades.
- The structural response is much more unsteady than the aerodynamic loads suggest.
- As a result, the 3P rotation frequency and the first edgewise frequency are dominant in the torque signal.

Torque of the IEA 15-MW over a few rotations



PSD of the torque



Conclusion

- Aero-elastic simulations of wind turbines in a turbulent wind with shear using the flexible actuator line method in LES for 3 different turbine size: NREL 5-MW, DTU 10-MW and IEA 15-MW.

- The displacement and torsion all vary during the rotation. The turbulence mostly affects the flapwise displacement, whereas the edgewise displacement is dominated by gravity.
- The amplitude of the displacement also increases with the turbine size. Torsion (due to bend-twist coupling) has become important on the new large turbines.

- Turbulence is important for the fatigue due to the blade root moment of the flapwise loads. In the edgewise direction, gravity is responsible for most of the fatigue.
- Upscaling is moslty detrimental in the edgewise direction due to gravity.

- The torque on the rotor hub exhibits a large dependance on the first edgewise frequency.

- Future work : Integrate the control system and observe the impact of the aero-elastic effects.