AERO-ELASTIC LOADS ON A 10 MW TURBINE EXPOSED TO EXTREME EVENTS SELECTED FROM A YEAR-LONG LARGE-EDDY SIMULATION OVER THE NORTH SEA

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OBJECTIVE AND BACKGROUND

- Activities carried out in the DOWA (Dutch Off-shore Wind Atlas) project https://www.dutchoffshorewindatlas.nl/
- Demonstrate the coupling between a physical LES wind input model (GRASP embedded in a large scale meteo model (ERA5) and an aero-elastic code (PHATAS) based on 2 different aerodynamic models (AeroModule):
  - A Blade Element Momentum Method (BEM)
  - A Free Vortex Wake method, (FVW), AWSM
- Assess the impact of extreme events selected from a year long LES wind fields on the load response of a representative 10 MW turbine
- Assess the impact of the different aerodynamic models on the load response at these extreme events.

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SELECTED REFERENCE WIND TURBINE AND SITE

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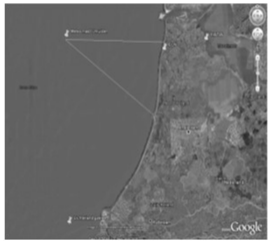
- The 10 MW AVATAR reference wind turbine
- Low induction variant of 10 MW InnWind.EU turbine (http://www.innwind.eu/)
    - D= 205.8 meter
    - H_t = 132.7 meter
    - Ω = 9.8 rpm-> tip speed = 103.4 m/s;
- All design data are publicly available (Sieros et al (2015))
- A design load spectrum has been calculated by many AVATAR partners (Stettner et al (2015))
- Site:
  Met. Mast. IJmuiden (MMIJ) in the North Sea,
  85 km offshore (N52°50.89’ E3°26.14’)



REFERENCE LOAD SPECTRUM

- The loads from the selected events are compared to the design load spectrum of the AVATAR turbine, i.e. the **reference load** spectrum The reference load spectrum (IEC 61400-1) has been calculated in Stettner et al (2015) in cooperation with the industrial AVATAR partners
  - The design load spectrum calculations were repeated in 2019 to ensure compatibility with present models/codes
  - Present assessment considers a comparison with loads from DLC1.2
    - Normal production, 10 minute time series
    - Wind speed from 5-25 m/s, ΔV = 2 m/s,
    - Shear exponent = 0.2,
    - Wind input from stochastic wind simulator SWIFT for 6 seeds
    - Class IA

REFERENCE LOAD SPECTRUM,CTD

- Considered loads:
  - Blade root bending: flatwise, edgewise and torsion moment
  - Shaft: Torque, tilting and yawing moment
  - Extreme loads and equivalent fatigue loads
    - SN = 10 (blades) and 4 (shaft)

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GRASP

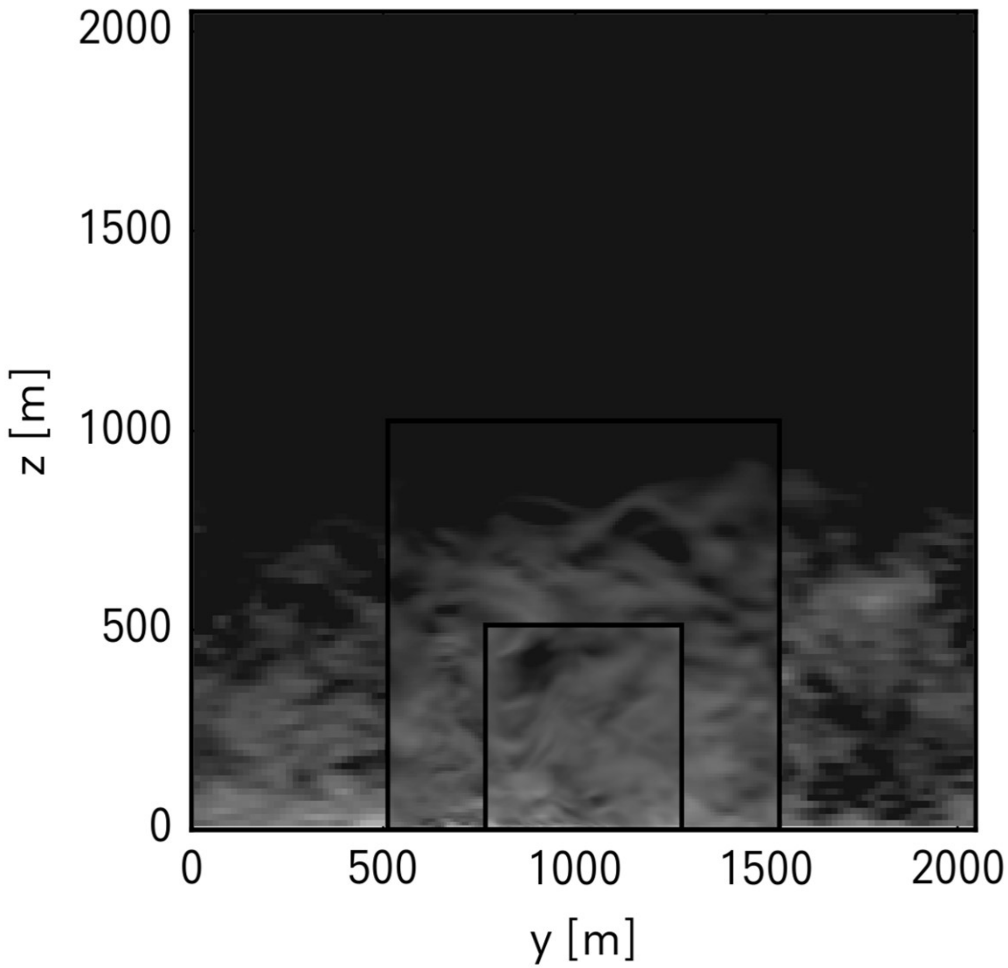
- GPU-based Large Eddy Simulation (LES) platform
- In development by TU Delft spin-off company Whiffle, based on the work of Schalkwijk et al. (2015)
- Platform enables turbulence-resolving weather simulations for forecasting and multi-year hindcasts

Simulation setup

- Large-scale boundary conditions provided by the ERA5 global reanalysis dataset
- Three-way nested simulation
- 8, 4, 2 m resolution; 256 grid boxes in each direction
  -->51 wind speed points per blade
- Finest nest set at fixed 0.1 s time step to generate 10 Hz y,z-slices
  →6 degrees azimuth

GRASP, Simulation setup

Vertical slice of west-east wind component in center of domain
Nested domains indicated by black rectangles



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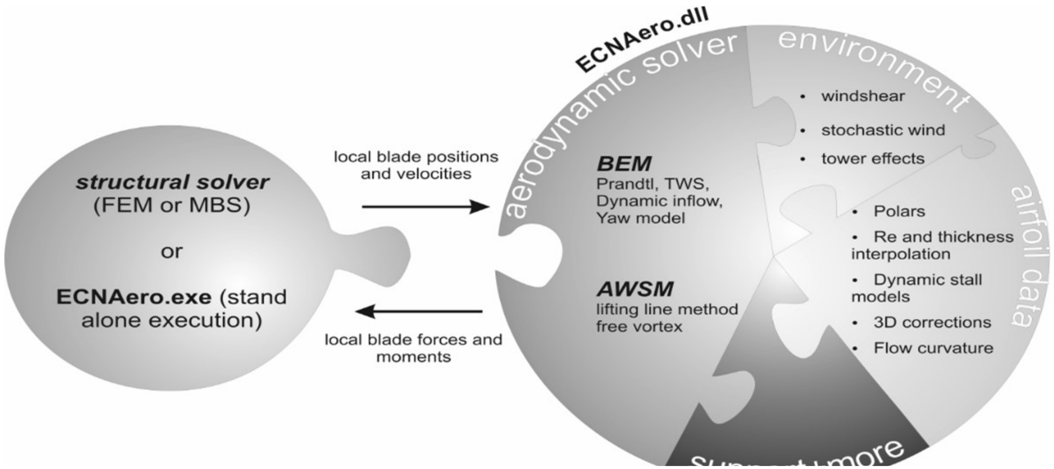
PHATAS AND ECN AERO-MODULE

- ECN Aero Module: One code with aero-models of different degrees of fidelity coupled to same structural solver (PHATAS/FOCUS), taking into account blade, tower and drive train flexibilities.
- Aerodynamic solvers
  - BEM and AWSM (Free and prescribed vortex wake model)
  - Straightforward comparison of different aerodynamic models with same input
- Continuous development amongst others with results from the EU project AVATAR and IEA Task 29 Rotor Aerodynamics



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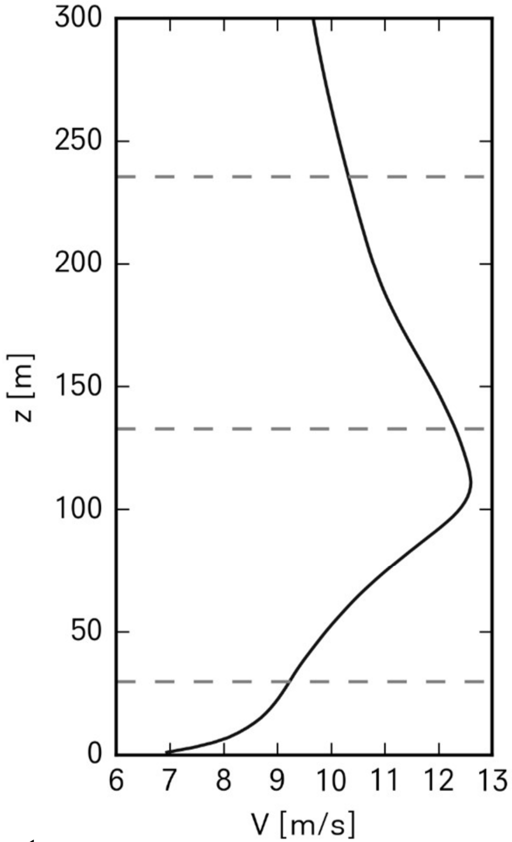
Case selection

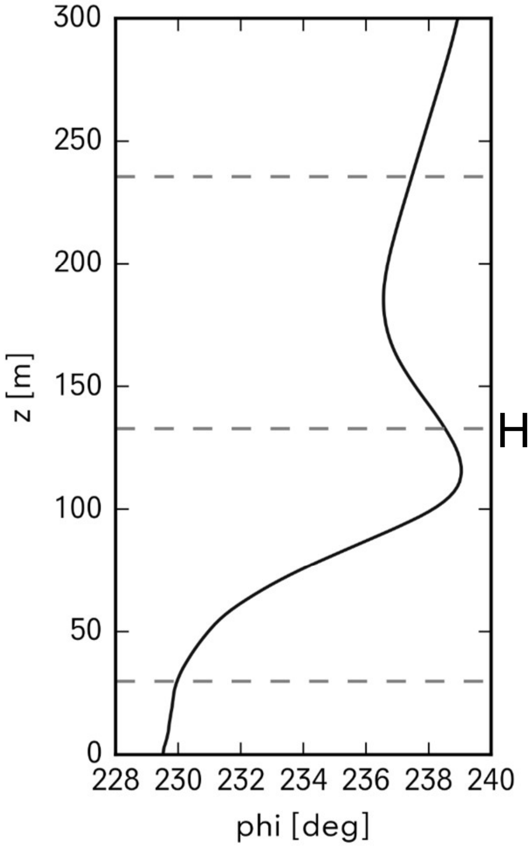
- Selection based on year-long run without nested simulations (2014/12/1 to 2015/12/1)
- Consider heights relevant for wind turbine rotor (z=H-0.5D to H+0.5D; H=132.7 m, D=205.8 m)
- Consider wind speed regime relevant for wind turbine (rated to below cut-out)

Selected five “extreme” cases of 10 minutes :

1. Strongest low-level jet (LLJ) (detection algorithm from Baas et al. (2009))
2. Strongest wind veer over the rotor
3. Strongest shear over the rotor
4. Highest turbulence kinetic energy (TKE) below cut-out wind speed
5. Highest turbulence intensity (TI) around rated wind speed

Low-level jet (LLJ): Shear and Veer profile

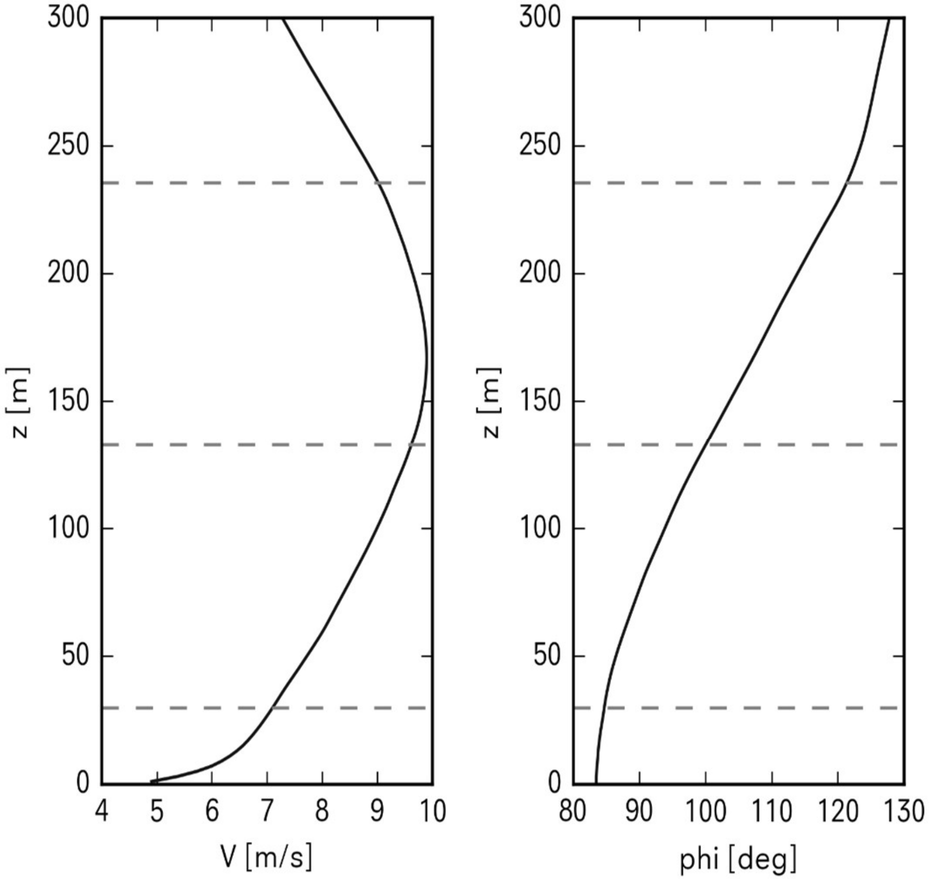




Note:

- The turbulence intensity at hub height (133 meter) is calculated to be 1.6% only which reduces loads
- Validation of the LES events with anemometer and LIDAR measurements from Met Mast IJmuider (and other meteo stations in the North Sea) is currently going on
- Tentative comparisons show such low turbulence intensities at LLJ's indeed, a strong veer where height of maximum velocity (~102 m) is consistent to observations from e.g. Duncan[2018]

Extreme Veer: Shear and Veer profile



Hub height

Extreme Shear: Shear and Veer profile

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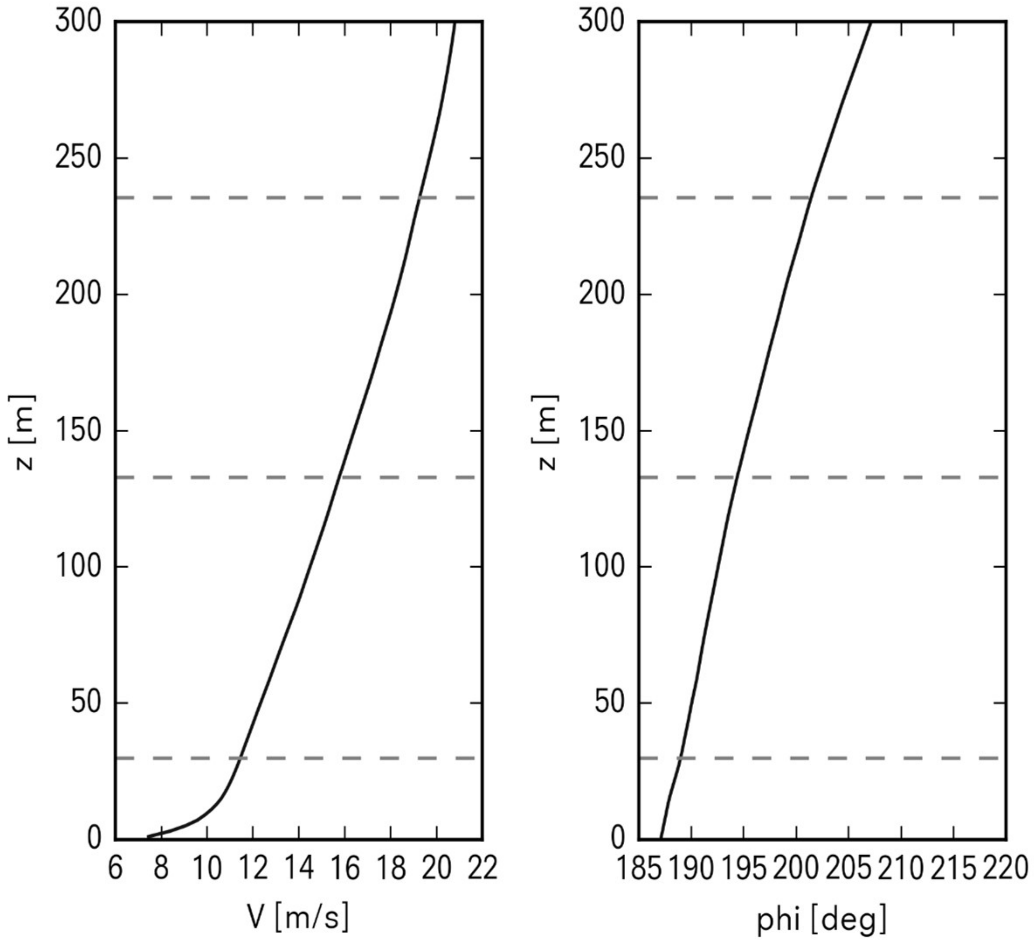

Hub height

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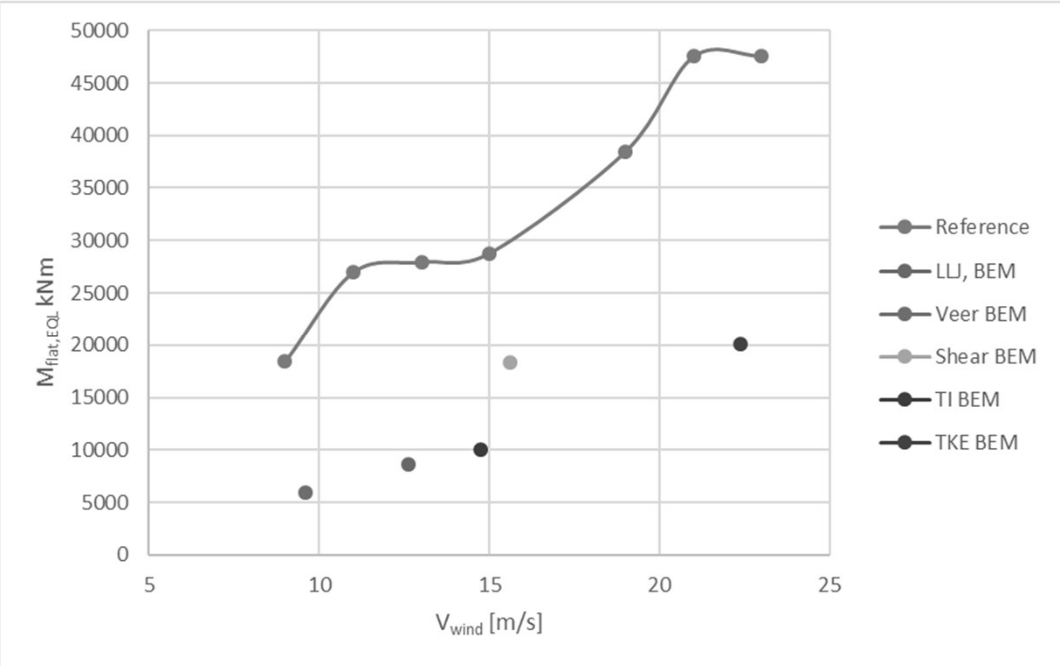
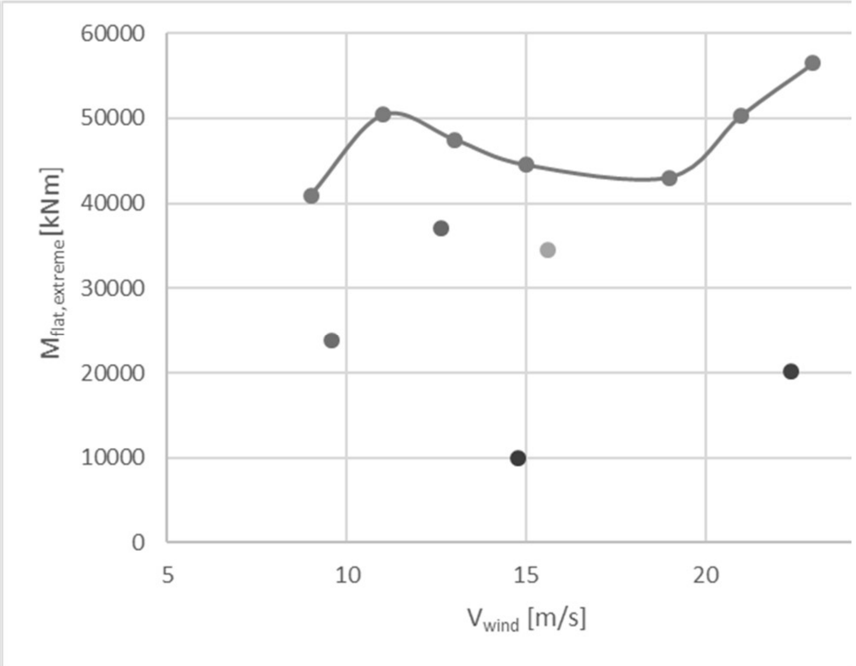
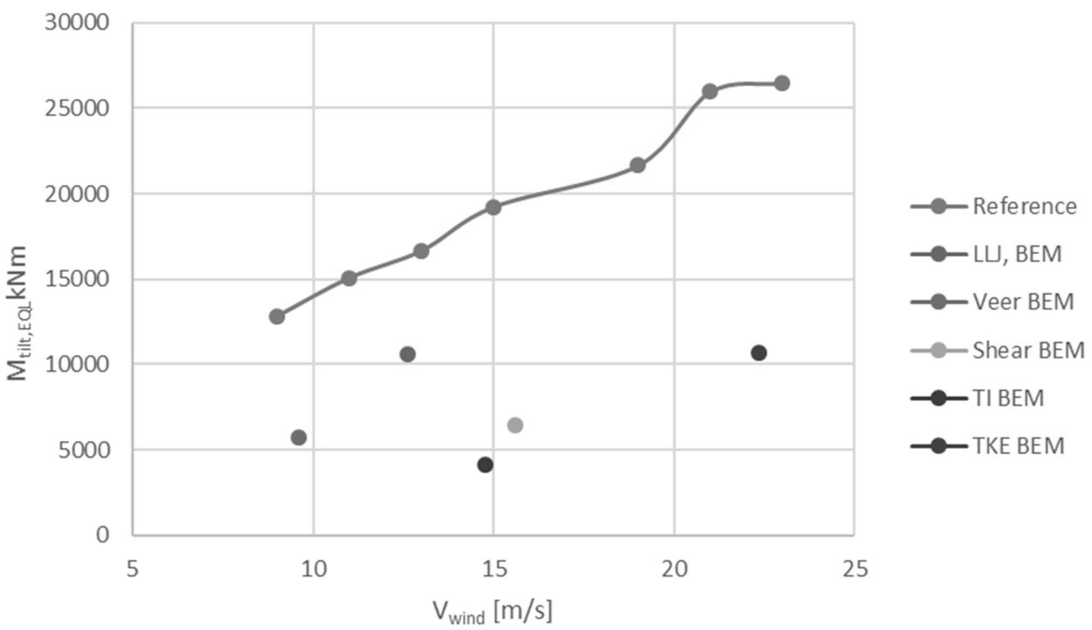
- Background and objective
- Reference turbine, site
- Modelling approach
  - Wind input: GRASP (plus ERA5)
  - Loads: PHATAS/AeroModule
- Case selection
- *Results*
- Conclusions and further activities

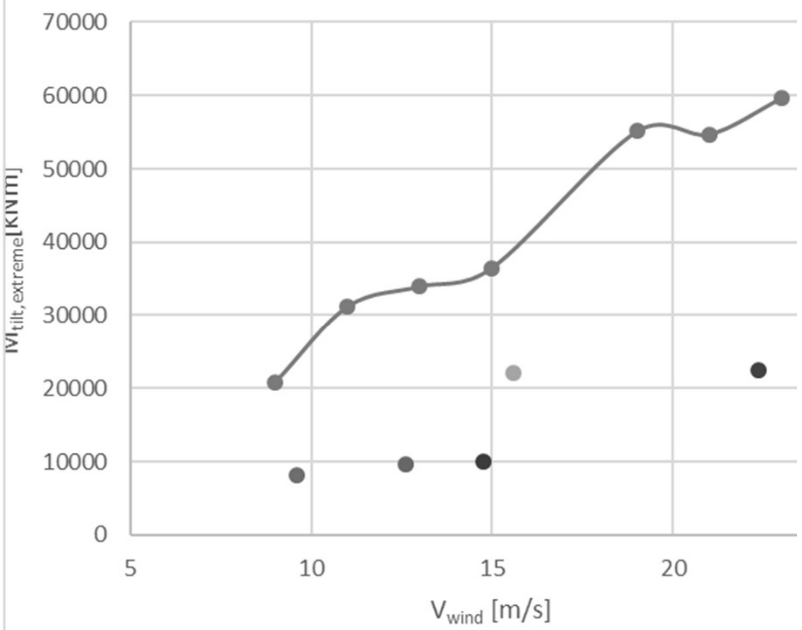
BLADE ROOT FLATWISE MOMENT EQUIVALENT FATIGUE AND EXTREME LOAD





TILTING MOMENT
EQUIVALENT FATIGUE AND EXTREME LOAD





A FURTHER ANALYSIS OF LOW LEVEL JET (LLJ) RESULTS

	$M_{flat, EQL}$ Flexible [Nm]	$M_{flat, EQL}$ Rigid [Nm]	$M_{flat, EQL}$ deterministic [Nm]
DLC1.2(BEM), 13 m/s	27955000		13539000
LLJ(BEM)	8661000	11163000	7308500
LLJ(AWSM)	7633800	9461100	

Equivalent Flatwise moment: Low Level Jet compared with IEC DLC1.2 at comparable wind speed, BEM and AWSM Flexible and rigid; full and deterministic

- $M_{flat,EQL}$ from LLJ << $M_{flat,EQL}$ from DLC1.2. This is also true for the deterministic component
  - Impact from the shear induced fatigue loads at the LLJ event is limited
- $M_{flat,EQL}$ BEM~1.13 $M_{flat,EQL}$ AWSM in agreement with observations from AVATAR project

Lower AWSM loads explained by Boorsma (2016) :

- More synchronised variations of u_i with V_w (less variation in α)
- More realistic modelling of shed vorticity variations in time→ more realistic aerodynamic damping
- Difference for rigid construction is even 23%

CONCLUSIONS AND OBSERVATIONS

- A succesfull coupling has been established between wind fields modelled from GRASP and the aero-elastic code PHATAS/AeroModule
  - Extreme events are selected from a 1 year simulation of GRASP wind fields and simulated for the 10 MW AVATAR RWT.
- The resulting (EQL and extreme) loads donot exceed those from the reference design load spectrum of the AVATAR RWT
- This could partly be explained by a very low turbulence intensities at the selected events but even the deterministic EQL remain within the DLC1.2 EQL
- The EQL from the more physical AWSM model are~ 15% lower than the EQL of BEM model.
  - This difference increases to 23% for a rigid construction

FURTHER STEPS

- Validate the selected events with measurements from Meteorological Mast Ijmuiden
- Calculate the reference load spectrum for a lower turbulence class.
- Understand the difference between AWSM and BEM EQL
  - Calculate the EQL from the ‘’pure” aerodynamic loads
- Assess the effect of different hub heigts on the loads at a LLJ

[redacted]

THANK YOU FOR YOUR ATTENTION

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