Field experiments of wind turbine vibrations in stand still conditions

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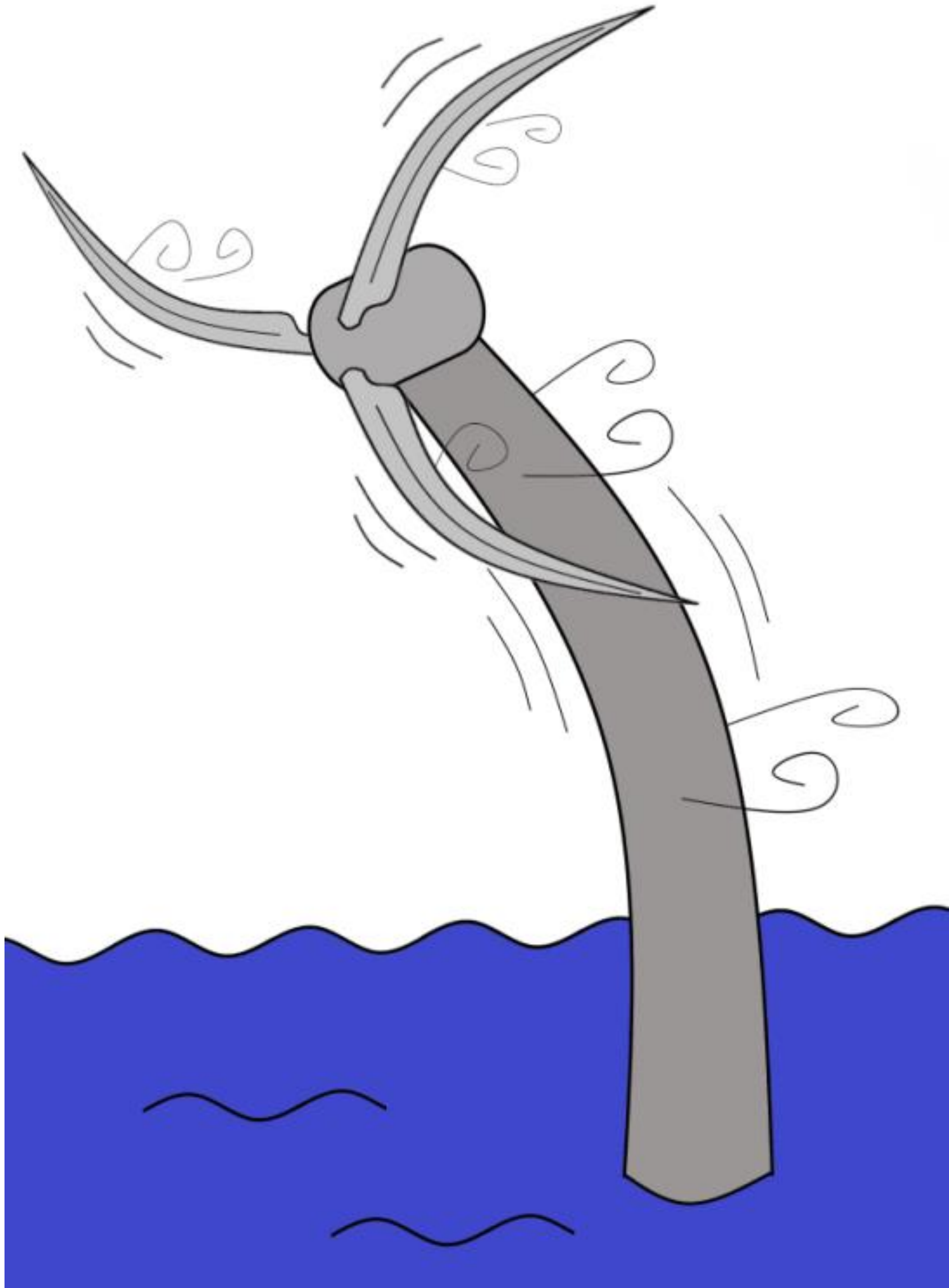
Motivation

- Severe Vibrations are observed in the field at high wind speeds.
- Source of excitation and exact setting like blade pitch, yaw angle and azimuth are unknown.
- Industry is currently struggling with:
  - Instability predicted in design, which does not occur in reality;
  - Occurrence of Stall and Vortex induced vibrations but not predicted during design.



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Project overview

TIADE (Turbine Improvements for Additional Energy)

2020 - 2024

Scope of TIADE project:

- Blade improvement (innovative tip shapes, VGs, turbulator tips)
- Validation (erosion, yawed inflow, stall and/or vortex induced vibrations)
- Measurement innovations (aerodynamic pressure, torsion deformation, fibre optics)
- Digital twin development

K. Boorsma et al, *TIADE final report*, TNO-2024-R12112, December 2024, https://publications.tno.nl/publication/34643564/vPzmF6yO/TNO-2024-R12112.pdf

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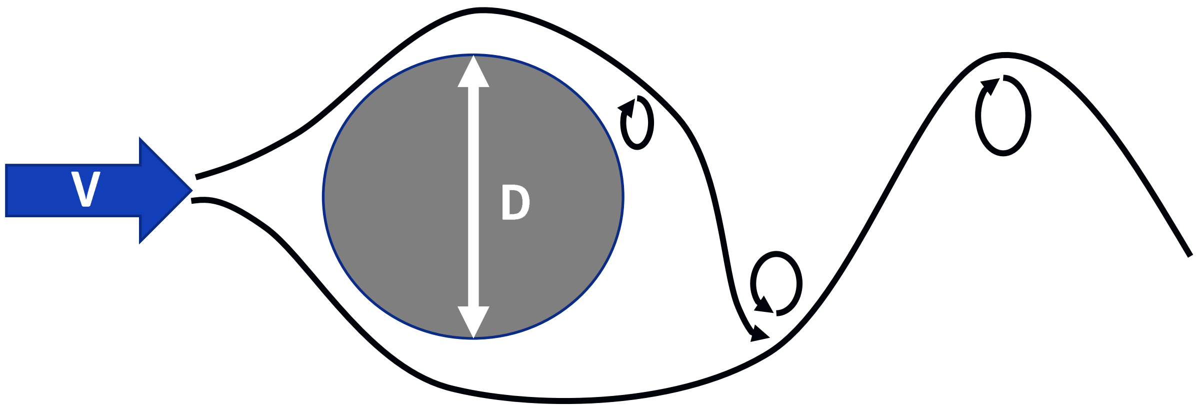
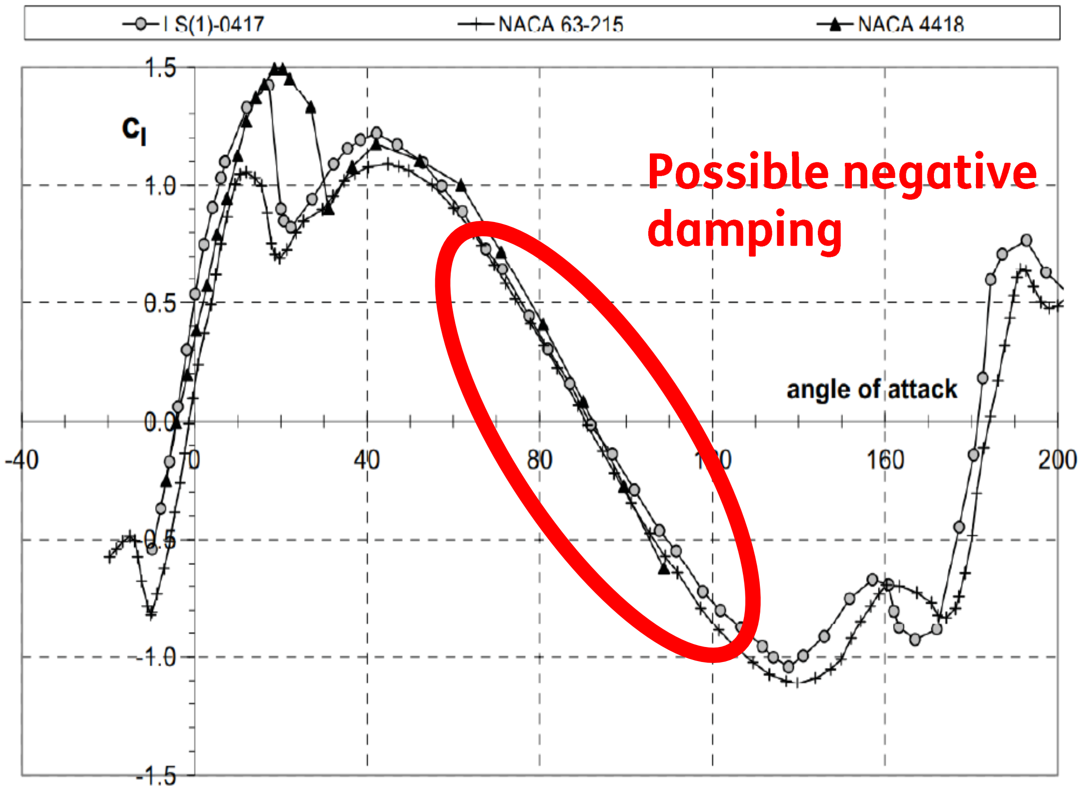
Vortex and Stall induced vibration

Vortex induced



Stall induced



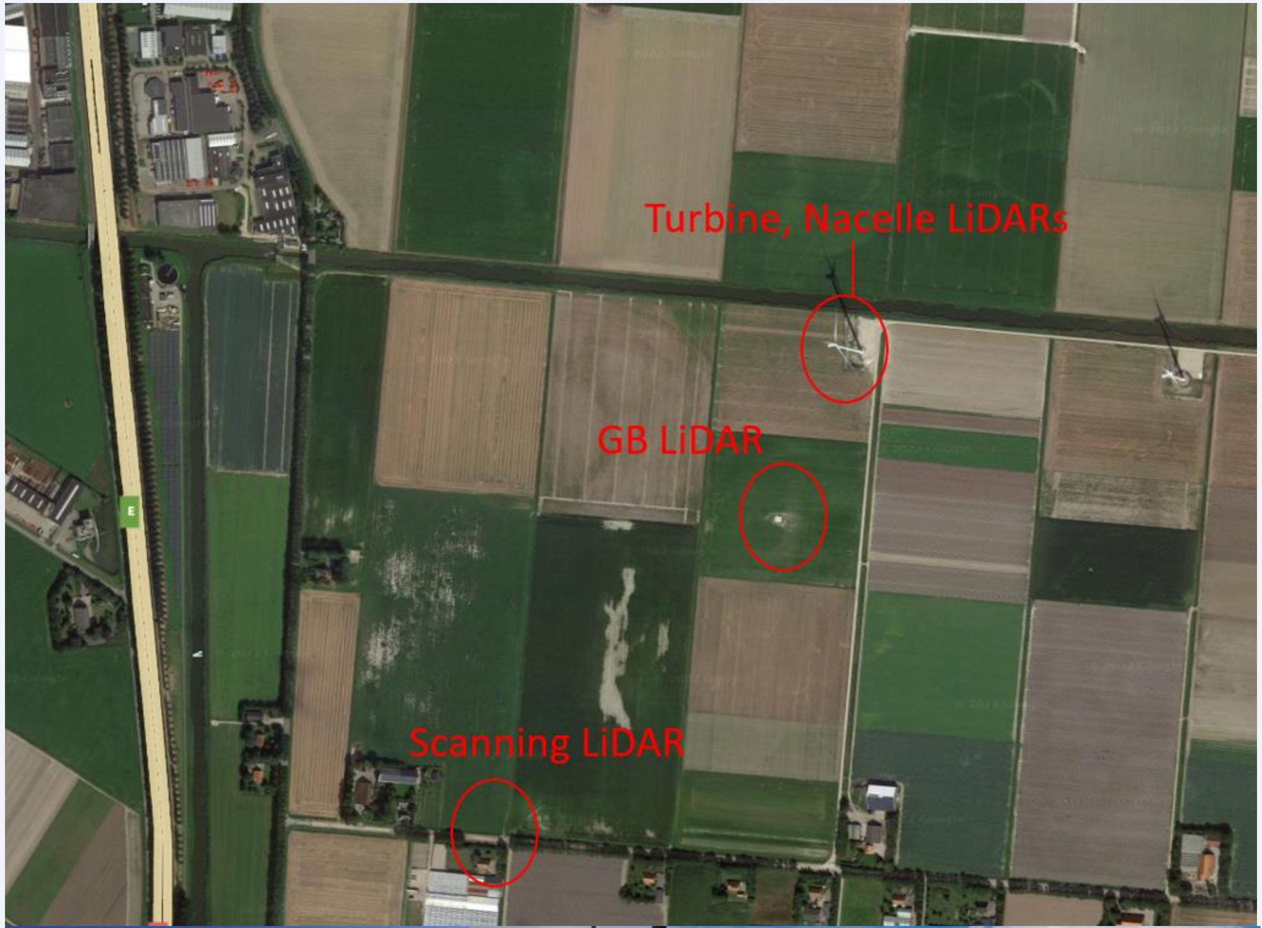
Source: W. A. Timmer. “Aerodynamic characteristics of wind turbine blade airfoils at high anglesof-attack.” In: TORQUE (2010).

Test set-up and measurements

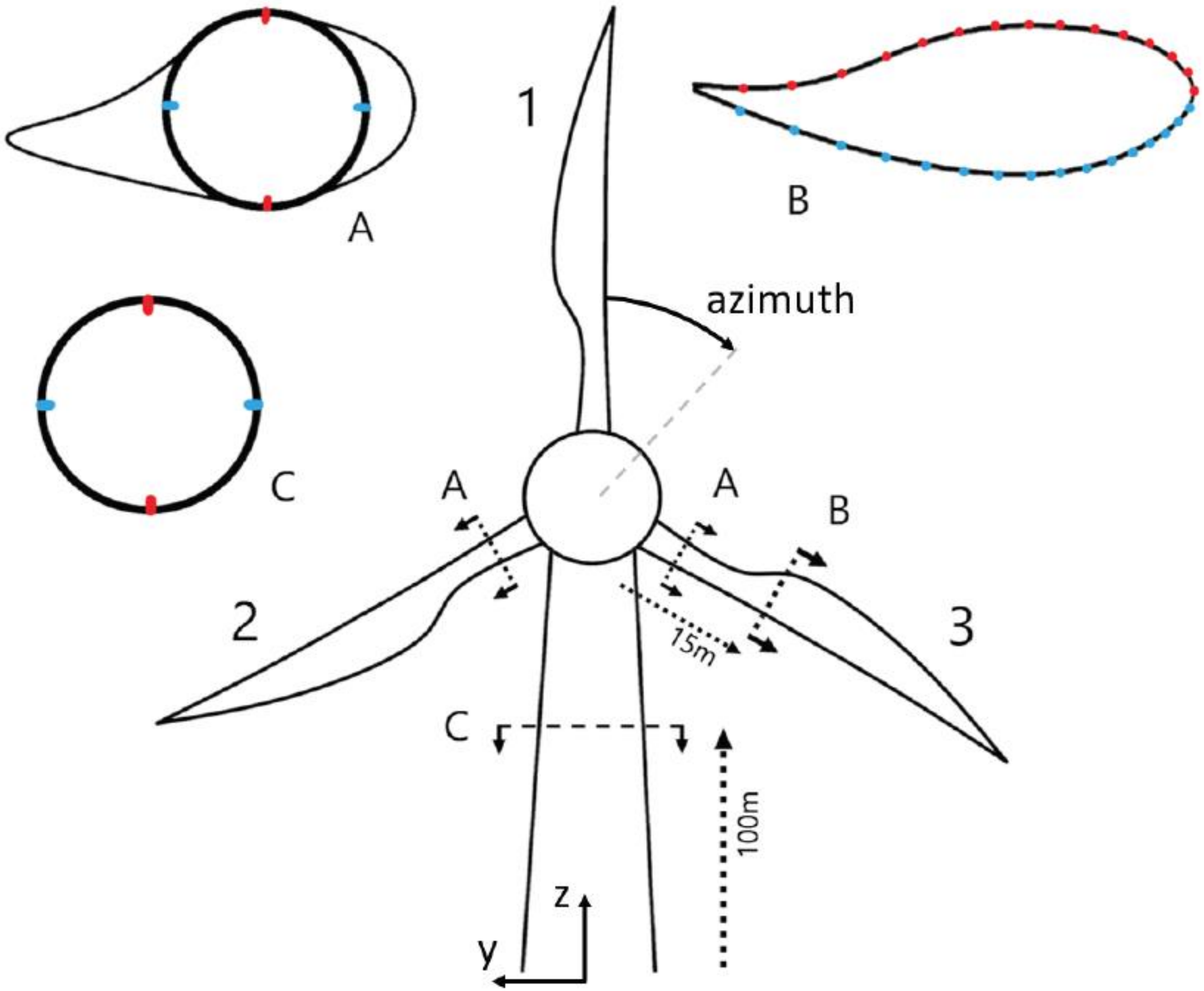
Test set-up

Test site overview

- Turbine type: 3.8MW, 110 m hub height, 130 m rotor diameter
- Ground based Windcube LiDAR @ 11 heights (42 - 188 m)
- 2 Nacelle based fwd looking LiDARs (~0.25D - 5D)
- Meteo mast at 2.0 km from turbine (wind, press, temp, disdro)
- Scanning LiDAR to measure wake at hub height (1D – 5D)



3.8 MW testing turbine



A: Strain gauges

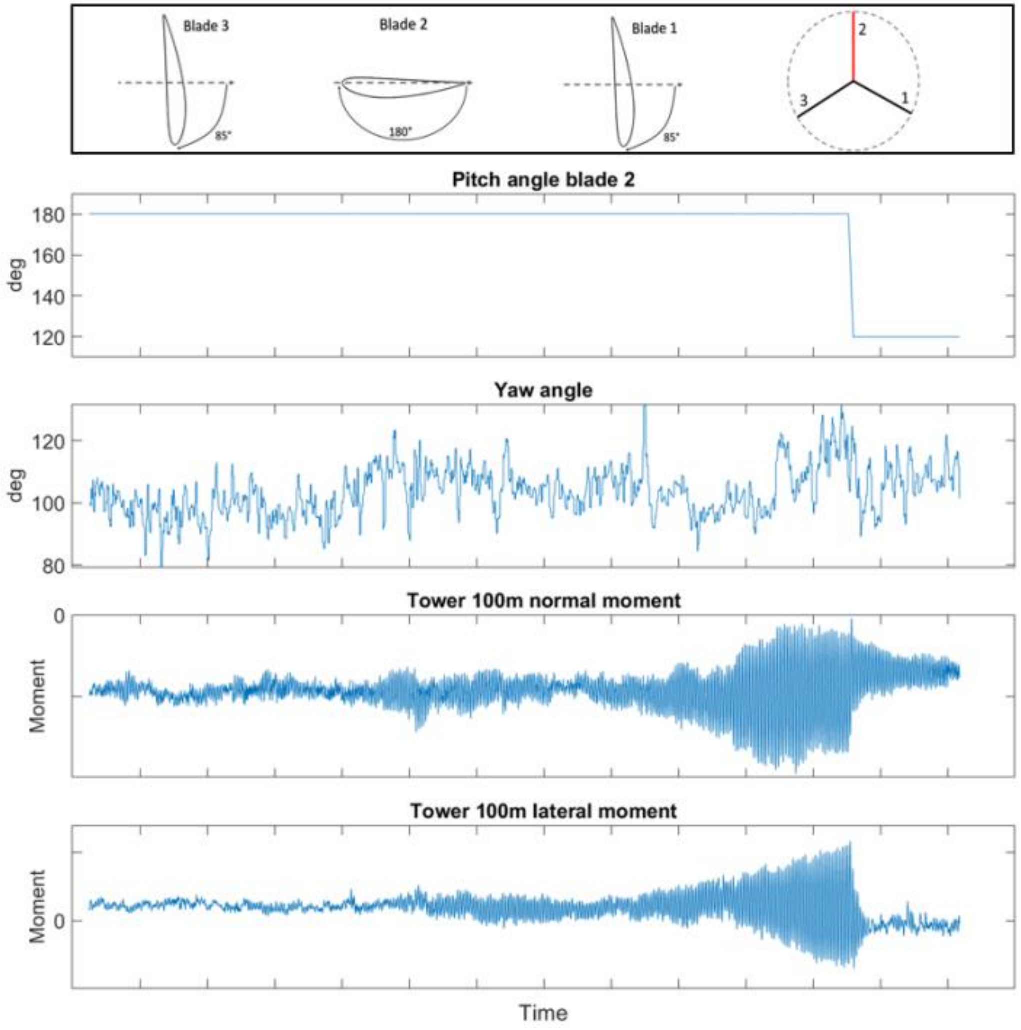
B: Pressure sensor

C: Strain gauges

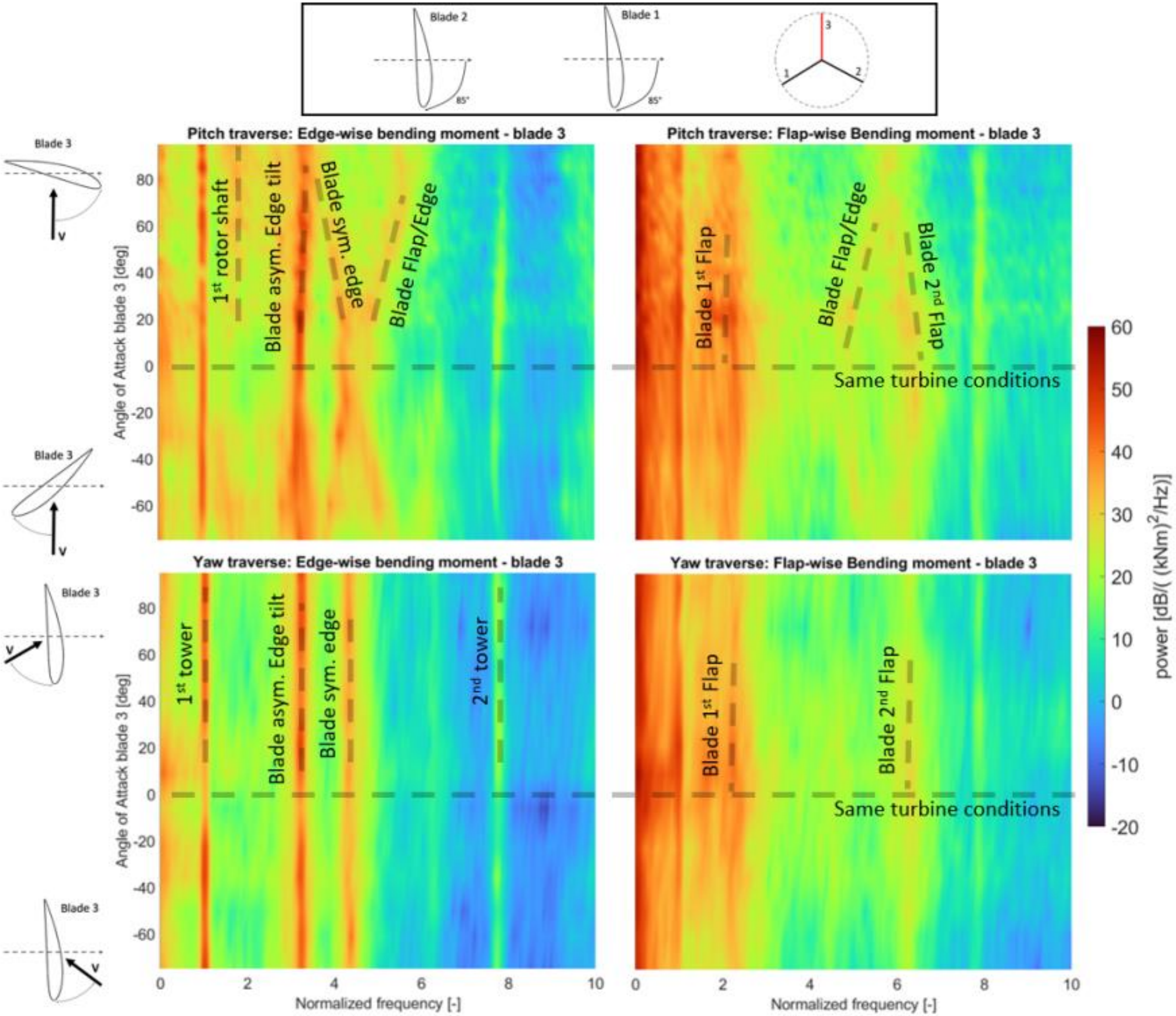
Experiments

#	Pitch angle Blade 1	Blade 2	Blade 3	Yaw misalignment	Rotor azimuth	Wind (std) [m/s]	Ti [%]	Wind dir. Lidar : 210°
1	85°	-15° till 85°	85°	0°	120°	15.9 (2.0)	13%	290°
2	85°	85°	-15° till 165°	0°	240°	14.3 (1.6)	11%	150°
3	85°	85° till 180°	85°	90°	120°	18.8 (2.6)	14%	265°
4	85°	85°	85°	0° till 60°	120°	15.9 (2.0)	13%	290°
5	85°	85°	85°	-130° till 95°	240°	14.3 (1.6)	11%	150°
6	85°	85°	85°	-5° till 200°	240°	19.1 (2.6)	14%	242°
7	85°	85°	85°	-110° till 90°	330°	17.4 (3.4)	19%	270°
8	85°	180°	85°	94° till 113°	120°	19.5 (2.8)	14%	270°
9	85°	85°	180°	117° till 94°	240°	16.6 (1.8)	11%	268°
10	89°	89°	89°	90°	240° till 360°	19.2 (2.6)	14%	256°

Case 8 Extreme vibration observed



Measured power spectral response



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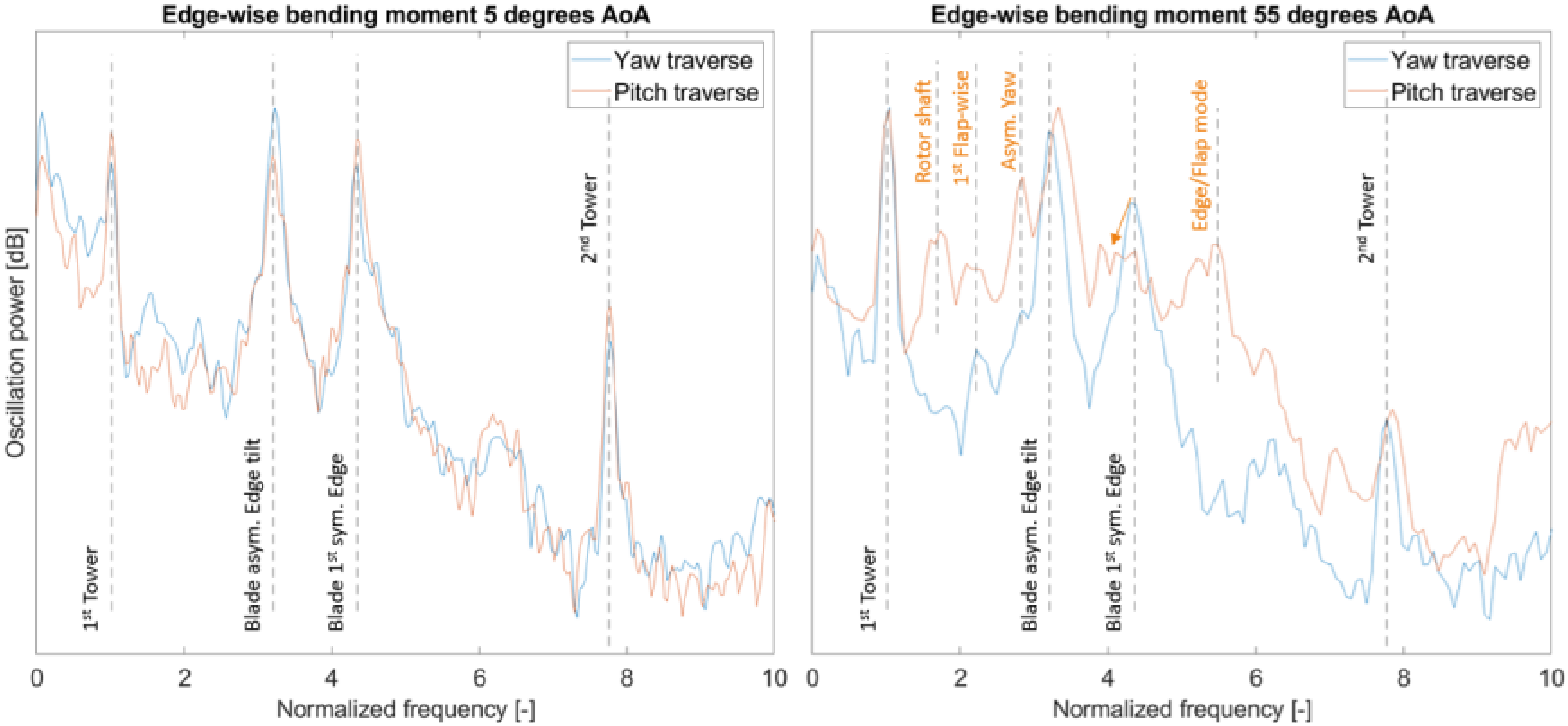
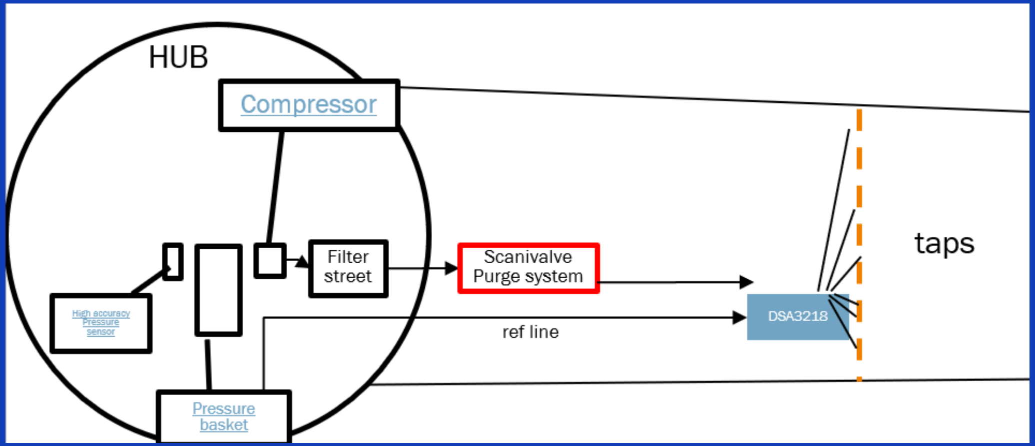
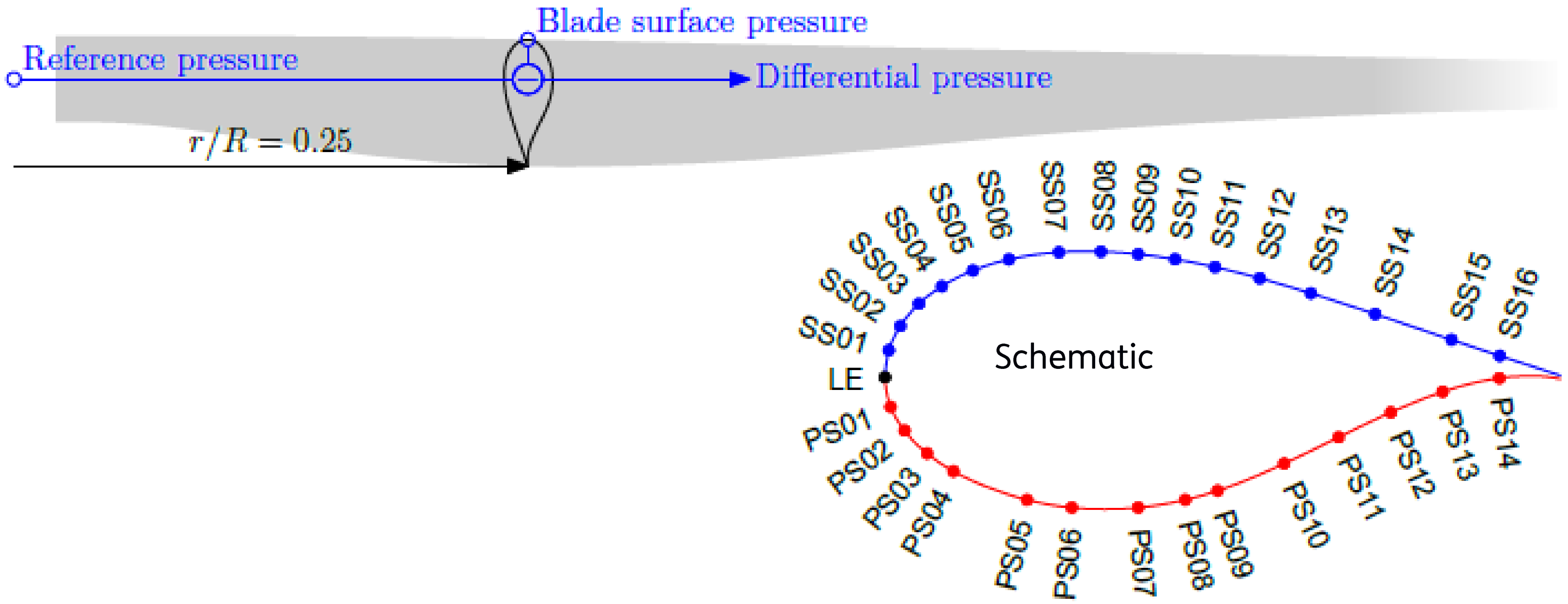
Response spectra at 5 and 55 degree angle of attack



Excitation and pressure measurement

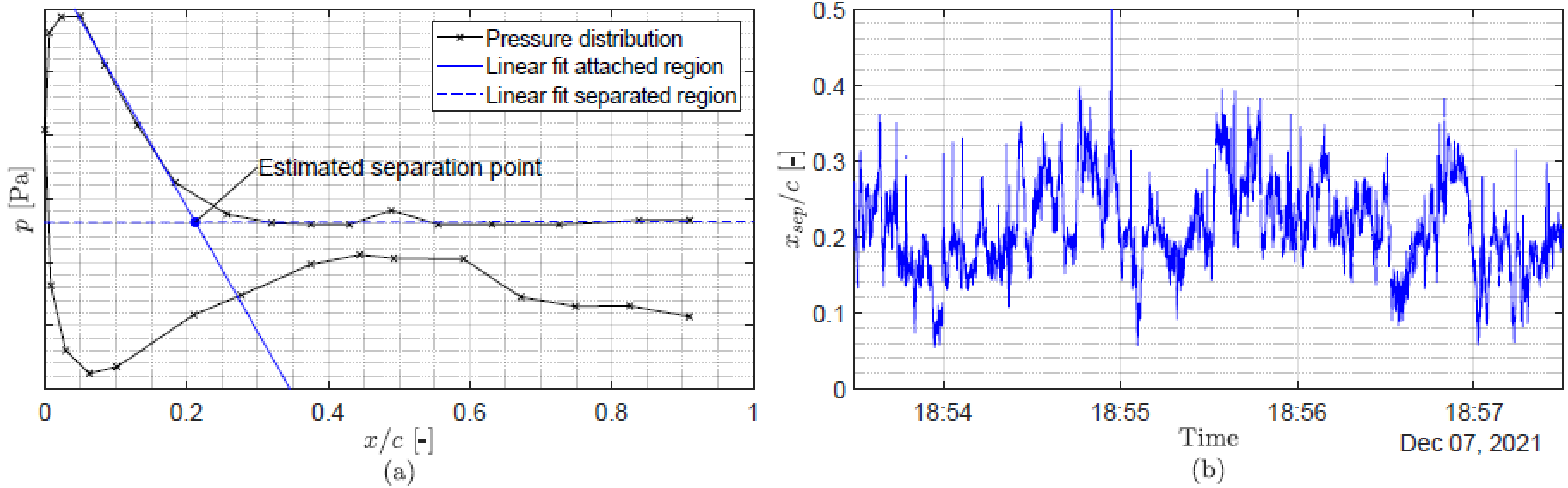


Test set-up

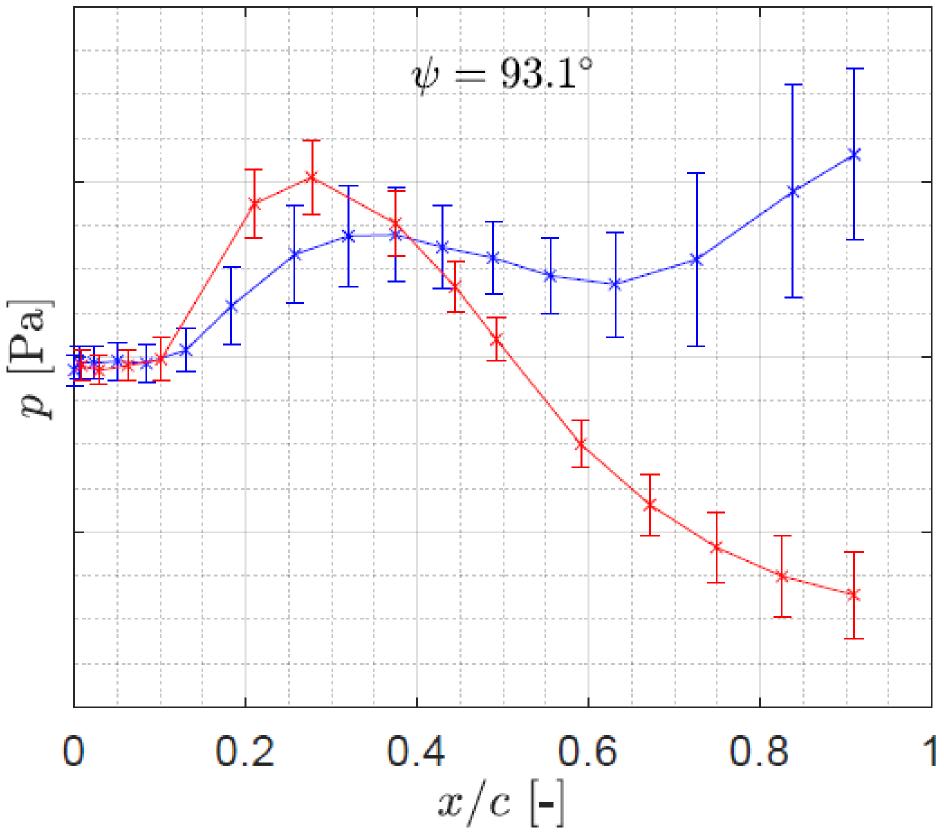


Blade surface pressure
Reference pressure
Differential pressure
$r/R = 0.25$
SS01
SS02
SS03
SS04
SS05
SS06
SS07
SS08
SS09
SS10
SS11
SS12
SS13
SS14
SS15
SS16
LE
Schematic
PS01
PS02
PS03
PS04
PS05
PS06
PS07
PS08
PS09
PS10
PS11
PS12
PS13
PS14

Separation point determination

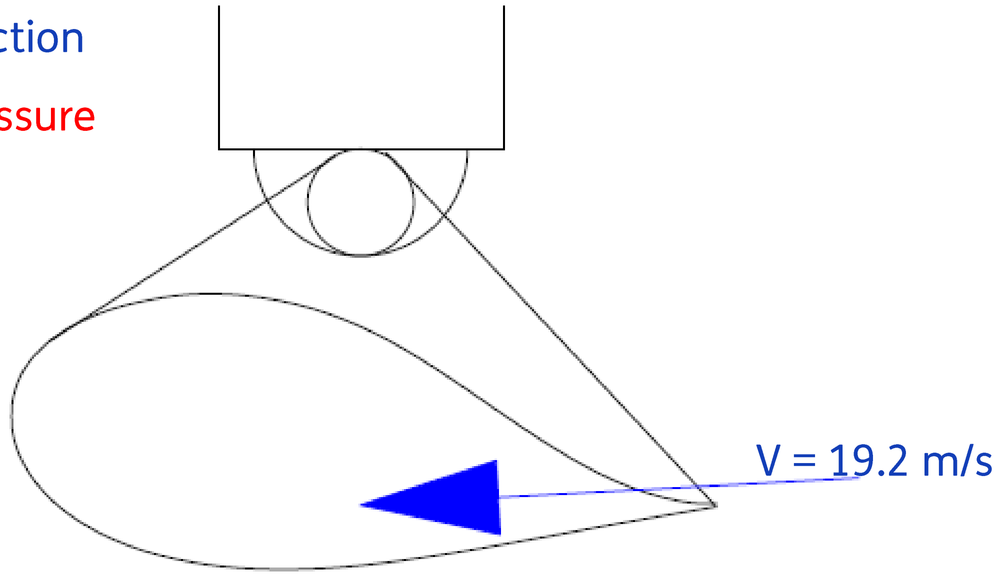


Mean pressure distributions case 9



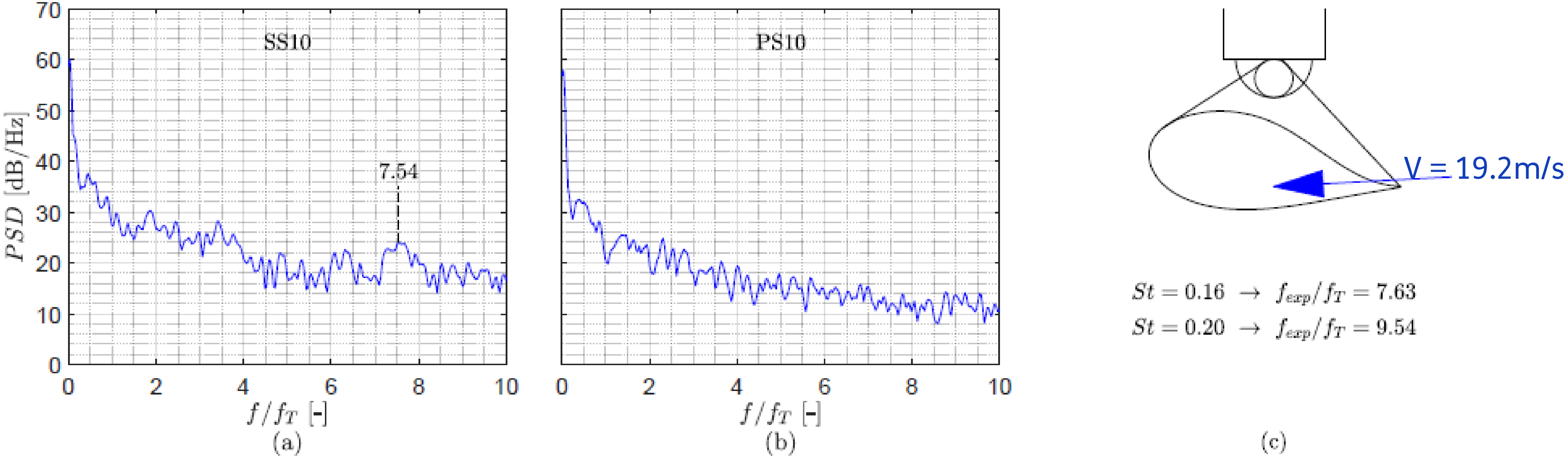
Blue: suction

Red: pressure



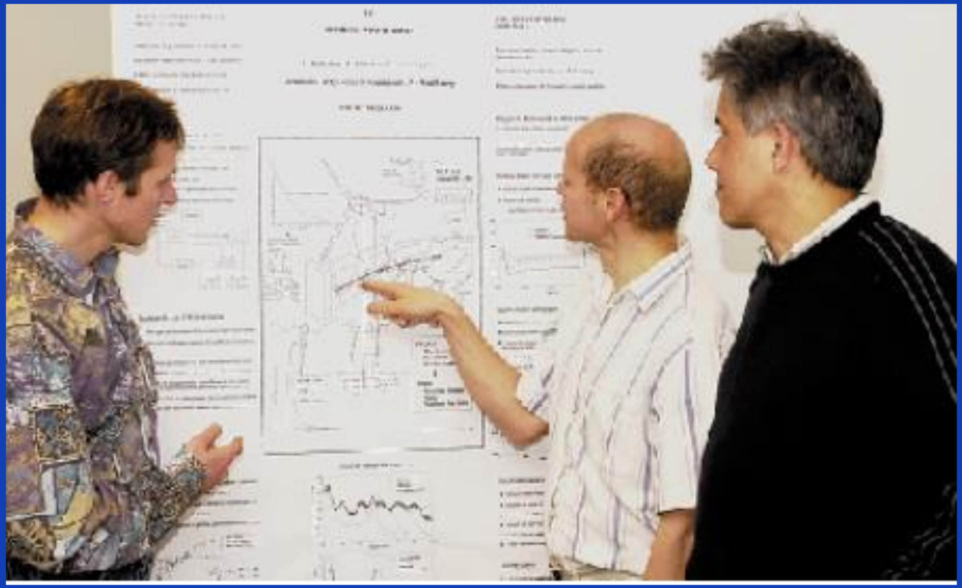
Incoming wind at “trailing edge”.

Power spectral density of pressure sensors SS10 (a) and PS10 (b) case 9



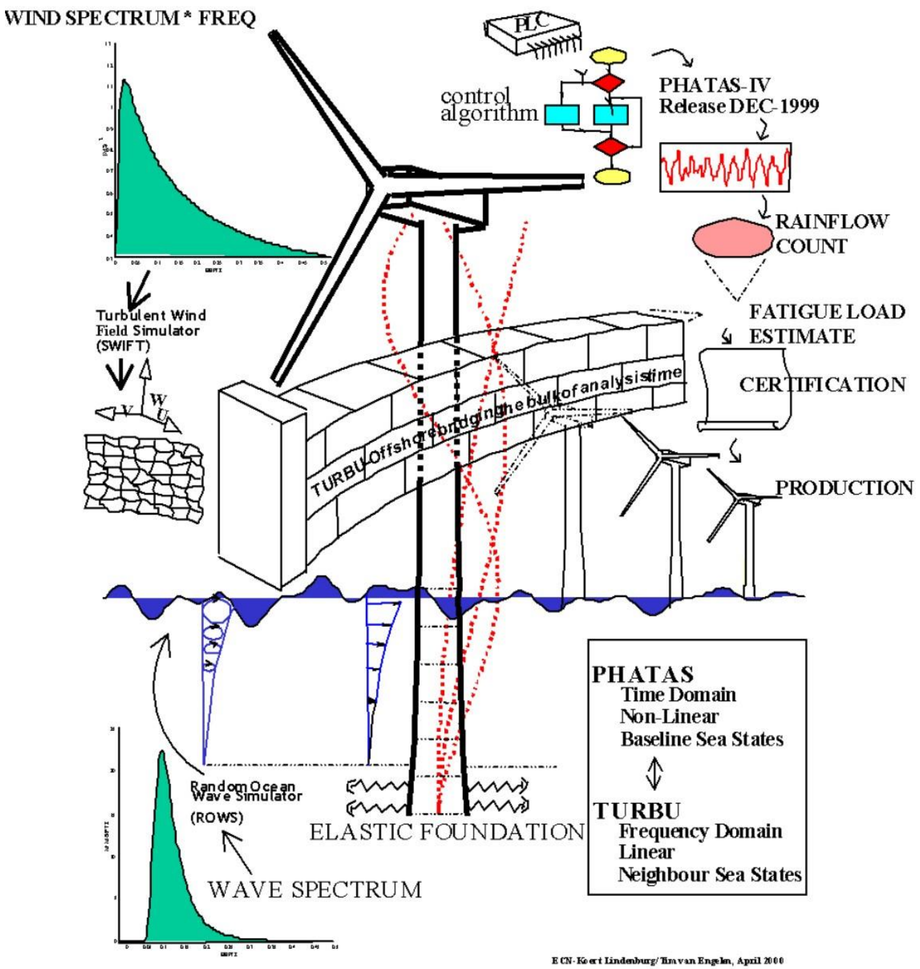
2nd tower mode visible. No vortex induced vibrations observed.

Simulations



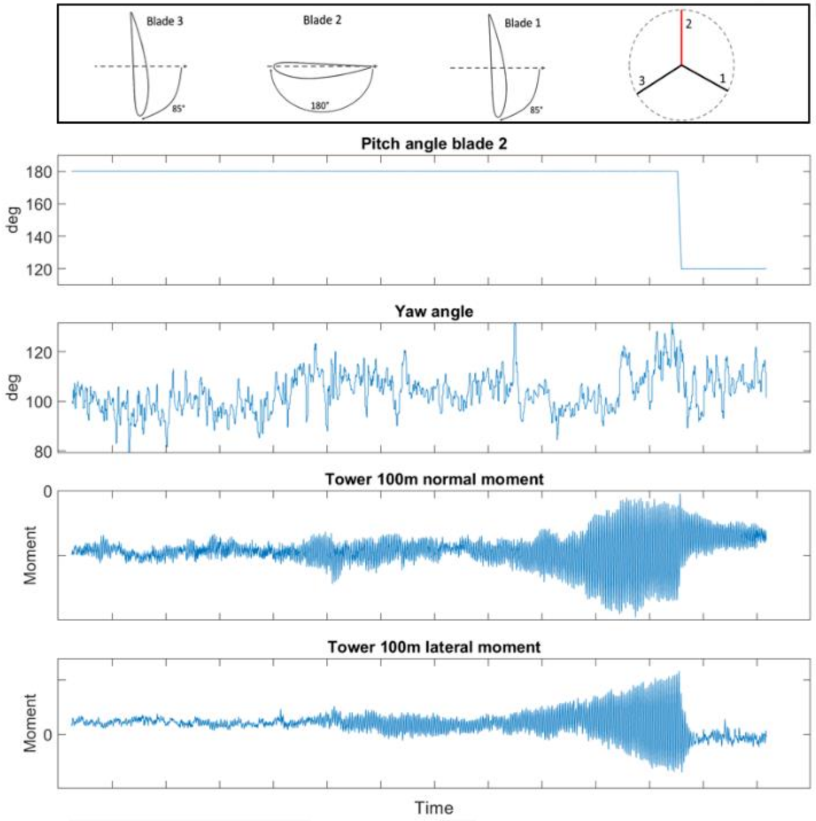
Design codes Turbu and Phatas

- Wind & waves
- Elastic foundation
- Tower
- Nacelle
- Rotor
- Control
- Fatigue and ultimate loads

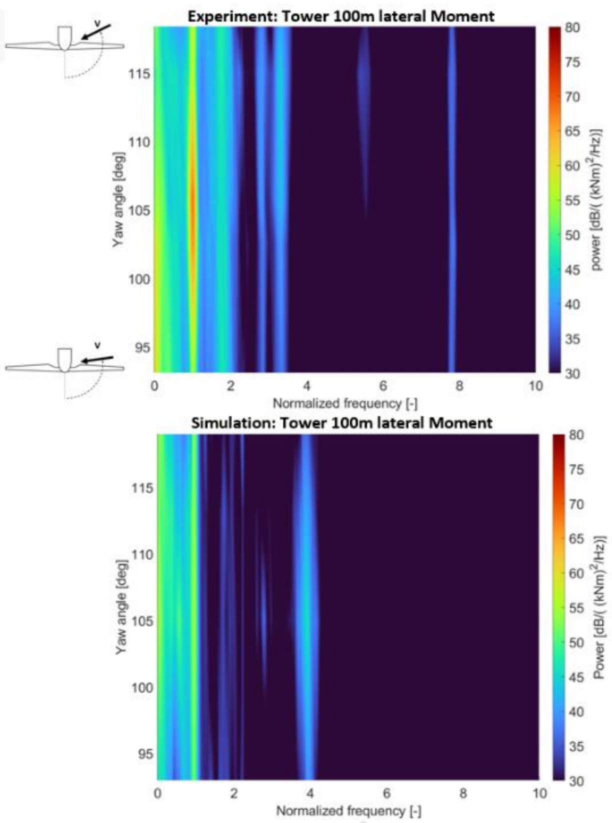


Source: Koert Lindenburg and Tim van Engelen

Validation of models



(a) Time series of standstill vibrations



(b) Visualization of measured (above) and simulated (below) spectra for the yaw traverse

Turbu model

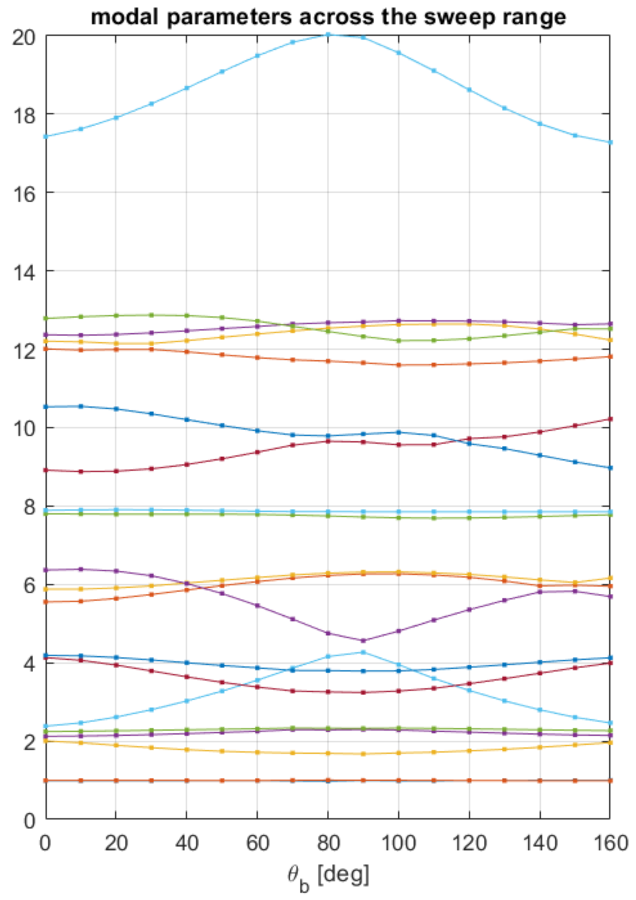
- Linear frequency and time domain analysis of 3-bladed Horizontal Axis WTs
- Full non-linear steady state model (multi-body average deformation)
- Time-invariant linear dynamic model (multi-body, Newton, Coleman)
- Dynamic wake, unsteady aerodynamics
- Reduced order blade and tower models (Hurty [Craig-Bampton])

Turbu analyses

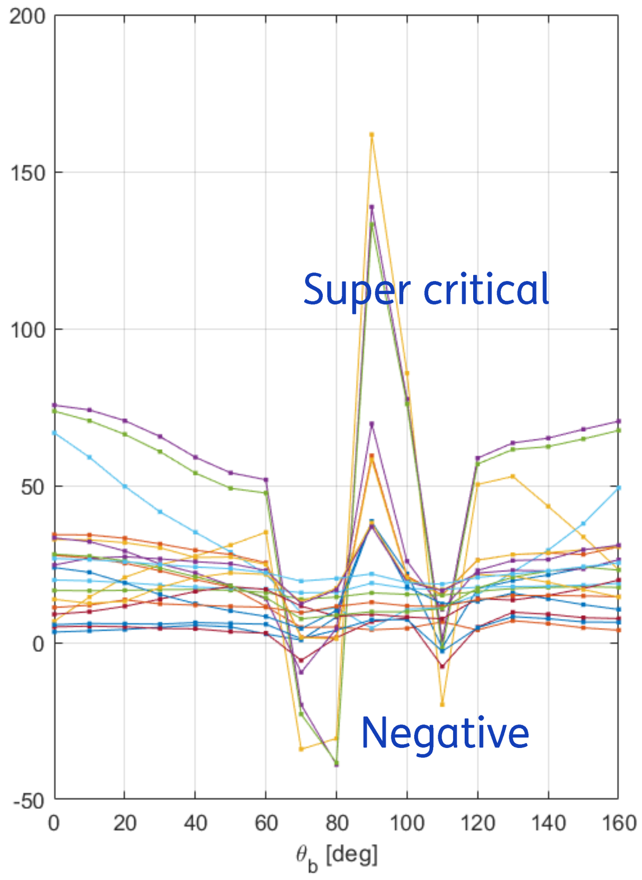
- Aeroelastic stability analysis
- Control design
- Frequency domain load calculations

Pitch sweep modal parameters

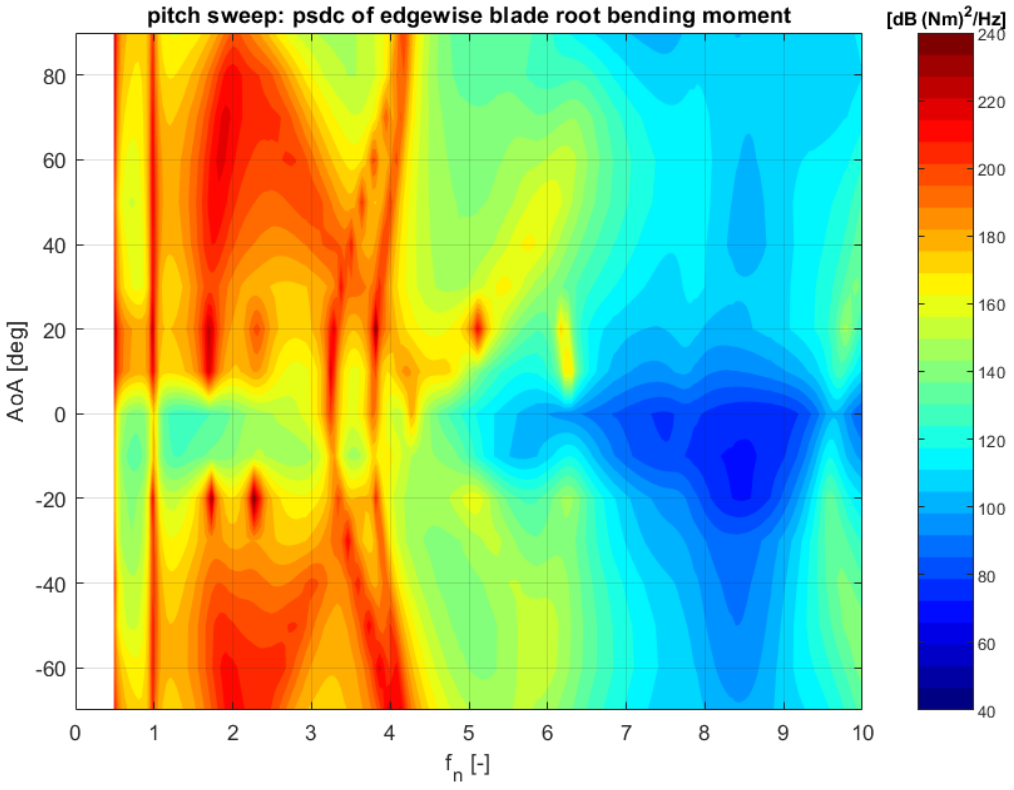
Non dimensional frequency

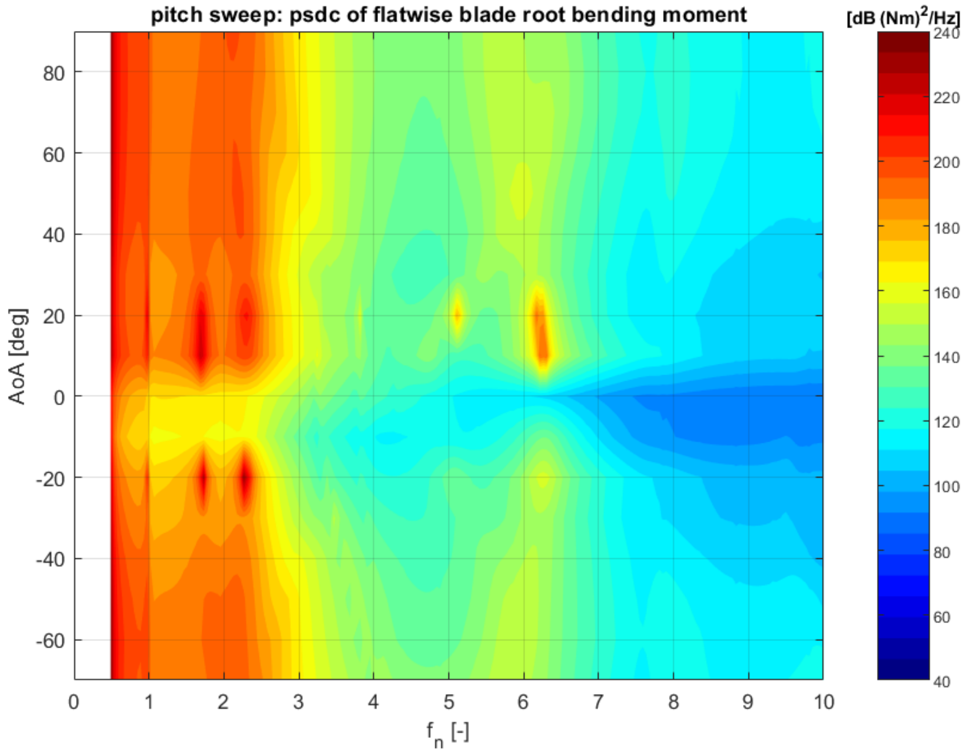


Damping



Power spectral density contour all blades pitched in Turbu!





Conclusions and future research

Conclusions

- The experimental data from the TIADE field campaign, including unique pressure measurements, are a valuable source.
- Measurements:
  - The pitch and yaw traverse are well suited to extract many relevant vibration frequencies of the turbine.
  - Severe vibrations are observed.
  - Analyzing the spectra of the pressure sensors and that of the derived separation point do not indicate the presence of a dominant vortex shedding frequency.
- Simulations:
  - The predicted response under realistic conditions shows similar trends as observed from the measurements.

Future research

- The industry needs more robust, validated design methods and engineering models to take these vibrations into account.
- More pressure sensor in different locations along the blade.
- Pitch multiple blades.
- We need to better understand these vibrations at stand still and idling and their potential causes.
- A dedicated wind tunnel test in controlled environment is proposed to accelerate on these topics.