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Numerical and Experimental Results of a Passive Free Yawing Downwind Wind Turbine

David R.S. Verelst

DTU Wind Energy
Department of Wind Energy

The WINDFLOWER project

- EU Marie Curie Industry Academia Partnerships and Pathways (IAPP) co-funded PhD project consisting out of the following consortium:
  - 3E/XANT (Brussels, renewable energy consultant)
  - DTU Wind Energy (formerly known as Risø)
  - TU Delft (Netherlands)
- Focus of the PhD research:
  - Numerical investigation of the feasibility of the free yawing downwind concept
  - Wind tunnel tests at the TU Delft Open Jet Facility (OJF):
    - Comparing different degrees of blade flexibility
    - Free yawing, downwind turbine
  - Comparison HAWC2 simulations with wind tunnel tests
  - Close link with industry
- This PhD project contributed to:
  - PhD thesis and presentation
  - Patent application (3E/XANT), wind turbine in development
  - Three conference papers on free yawing and the wind tunnel experiments
  - Technical Risø report on blade sweep for the NREL 5MW reference turbine
  - Journal publication as co-author on extreme load extrapolation techniques

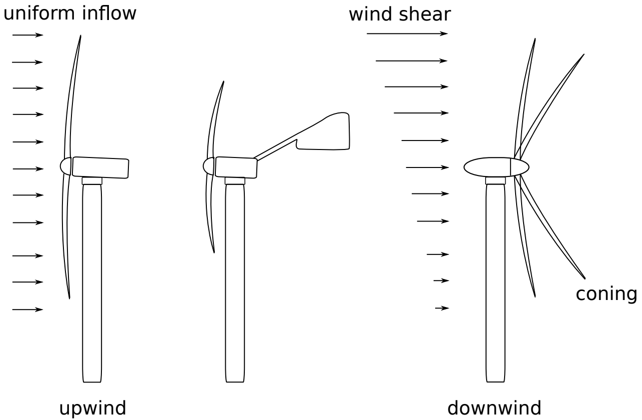
Acknowledgements

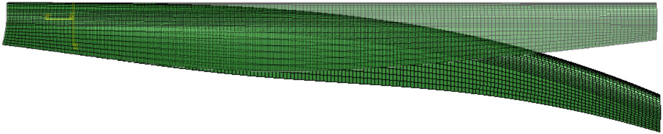
- Funding: EU Marie-Curie IAPP, Dutch NWO Veni grants
- Supervisor Torben Larsen, and co-supervisor Helge Madsen
- TU Delft OJF support: Jan-Willem van Wingerden, Roeland De Breuker, Kees Slinkman, Hans Weerheim
- Colleagues from AED
- The Office
- Friends and family

Presentation Overview

- Numerical studies: static and free yaw stability for a 140kW wind turbine
- Small 300 Watt experimental wind turbine:
    - Wind Tunnel experiments: design, production, measurement techniques
    - Measurements and results
    - Simulation input data: a numerical representation of the experiment in HAWC2
    - Comparing numerical and experimental results
- Conclusions and future work

The Basics



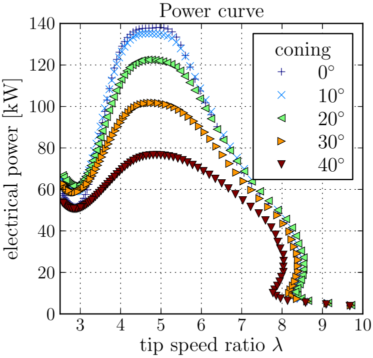


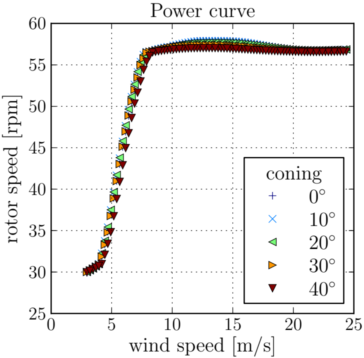
Numerical Studies with HAWC2

- Coupled aerodynamic-structural time domain wind turbine simulation code
- Structure:
  - Multi-body formulation
  - Flexible bodies with Timoshenko beam elements
  - Orthotropic material properties: no structural couplings
- Aerodynamics:
  - Blade Element Momentum theory
  - Tip correction: Prandtl
  - Dynamic stall: Beddoes-Leishman
  - Dynamic inflow
  - Skewed and sheared inflow corrections

Numerical Studies: Baseline Design

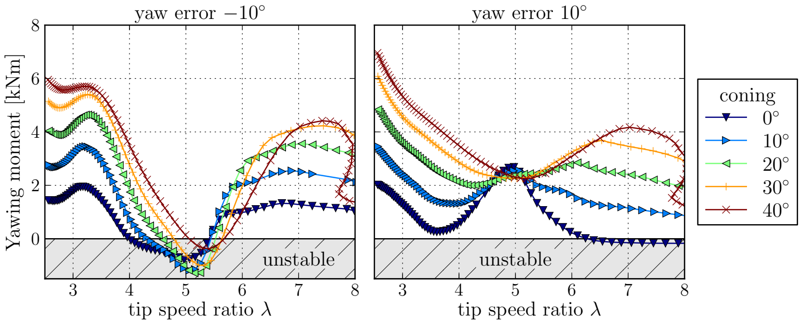
Configuration	3 blades, downwind, stall controlled	Cut in, cut out wind speeds	3–25 m/s
Rated power	140 kW	Rated wind speed	12 m/s
Blade length	10 m	Hub radius	0.5 m
Tower height	30 m	Rated rotor speed	57 RPM





Yaw Moments and Rotor Coning

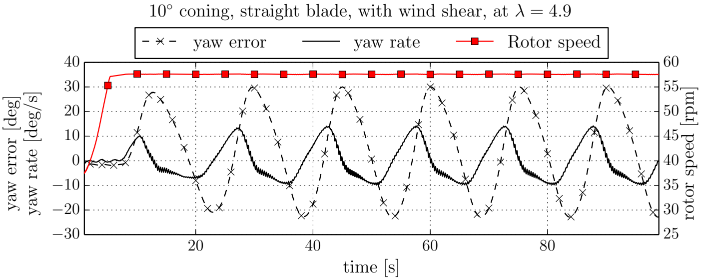
- Static yaw stability
- Sheared inflow conditions

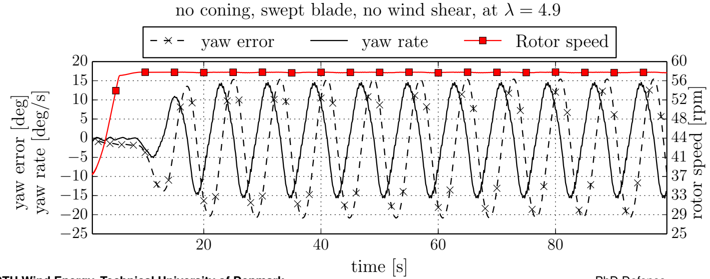


Varying Rotor Configurations in Free Yaw

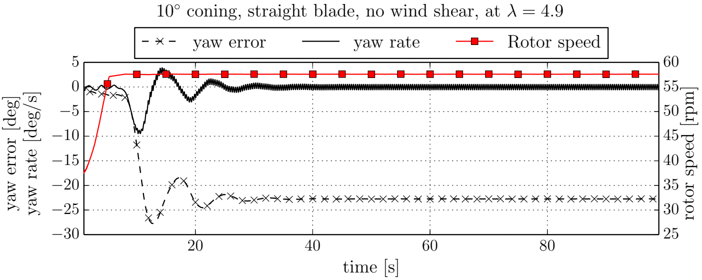
- A practical and applied approach
- Standard: straight blade, no coning angle
- Coned: straight blade with a 10° coning angle (coned downwind)
- Swept: swept blade, no coning angle
- Swept and coned: swept blade with a 10° coning angle (coned downwind)
- Uniform and standard sheared wind profiles
- Blade sweep curve: $x = a\left(\frac{z-z_0}{z_e-z_0}\right)^b$
- Evaluate both static and dynamic yaw stability

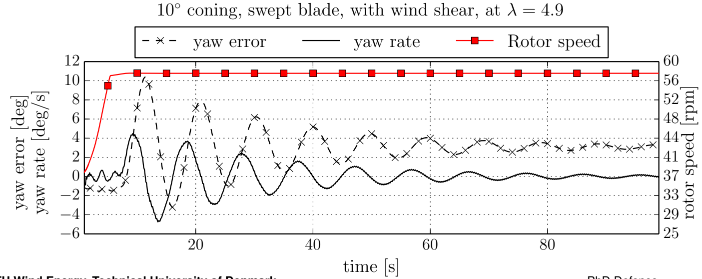
Free Yaw Response



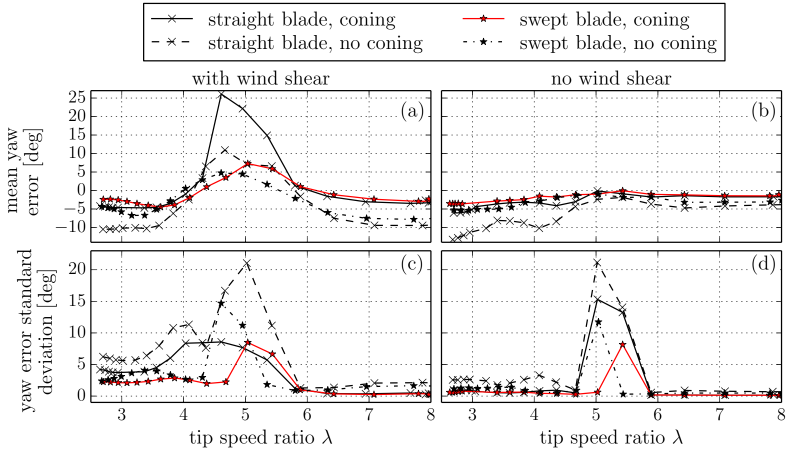


Free Yaw Response





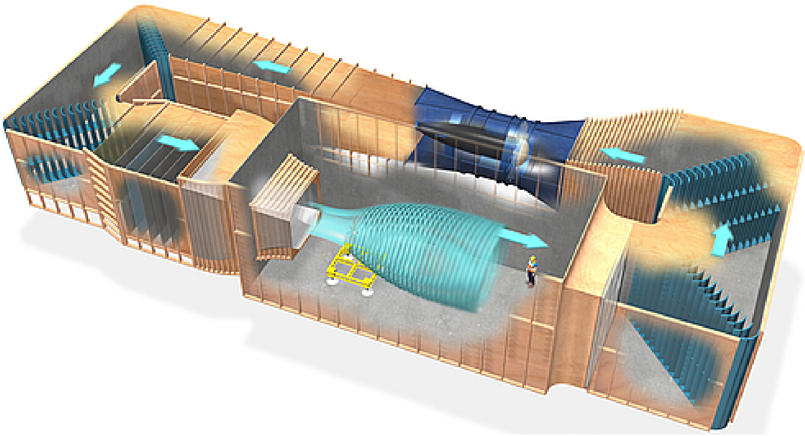
Free Yaw Response Overview



Wind Tunnel Experiments

The TU Delft Open Jet Facility

- Wind speeds: 3 - 35 m/s (wind force 11, 70 knots)
- 500 kW fan
- 2.8m by 2.8m exit nozzle



Scaling: Blade Length from 12m to 1m

- Full scale starting point (XANT)
  - rated power: 100kW
  - 24m rotor diameter
  - Optimal tip speed ratio (TSR) $\approxeq 6$
  - Typical Reynolds numbers at optimal TSR $\approxeq 0.50e6 - 1.50e6$
- Scaled down model, very simple scaling rules:
  - Rotor diameter $\leq$ 1.8m (wind tunnel size restriction)
  - Maintain TSR, consequently optimal RPM's / wind speeds are:
    - 300 RPM @ 4 m/s
    - 750 RPM @ 10 m/s
  - Typical Reynolds number similarity is not maintained $\approxeq 0.10e6 - 0.15e6$
- High rotor speeds result in significant centrifugal stiffening. Achieving blade flexibility is challenging.

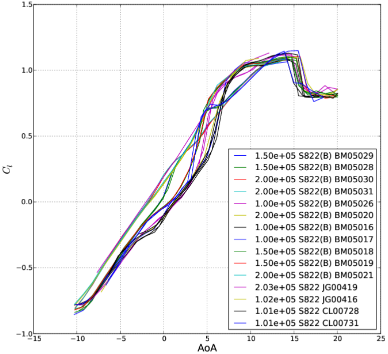
Practical Design Constraints

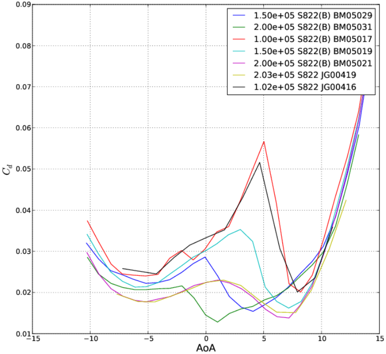
- Platform: small 300 Watt turbine, designed and assembled in Canada (vpturbines.com)
- Refitted with custom build and in-house designed blades

Aerofoil Selection

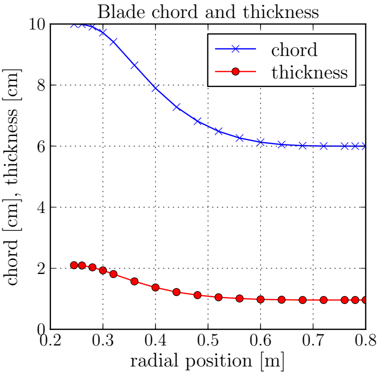
- source: University of Illinois Low Speed Aerodynamic test database (UIUC LSATs)
- aerofoil aerodynamic characteristics: uncertainties with measured data

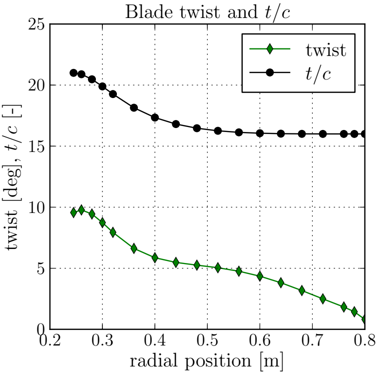
	region	t/c	Re_{design}	Re_{data}	$C_{L_{max}}$
NREL S823	inboard	21%	$4e5$	$1e5$	1.184
NREL S822	outboard	16%	$6e5$	$2e5$	1.100



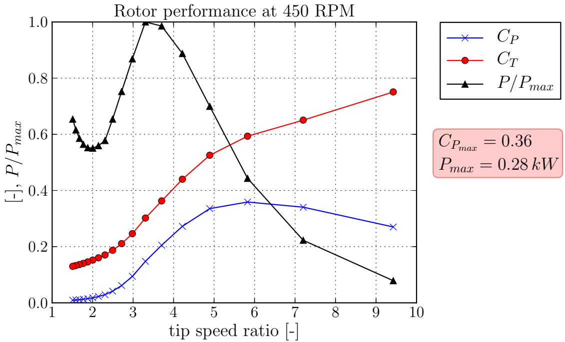


Aerodynamic Rotor Design with HAWTOPT



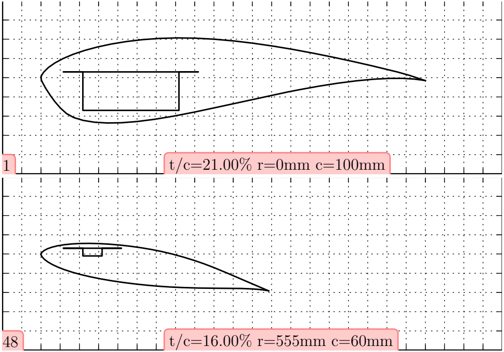


Aerodynamic Rotor Performance (HAWTOPT)



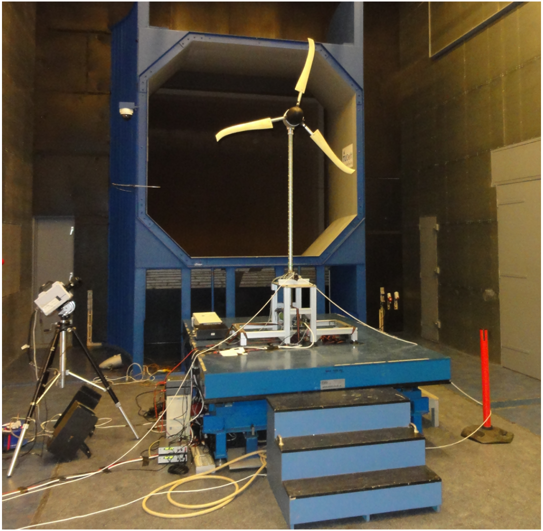
Blade Structural Design

- Using steady state averaged HAWC2 simulations
- Maximize tip deflection $\geq 10\%$ of rotor radius. Difficult duo to rotational stiffening
- Basic cross sectional modeller TU Delft
- Basic failure criteria based on cross sectional area and HAWC2 loads

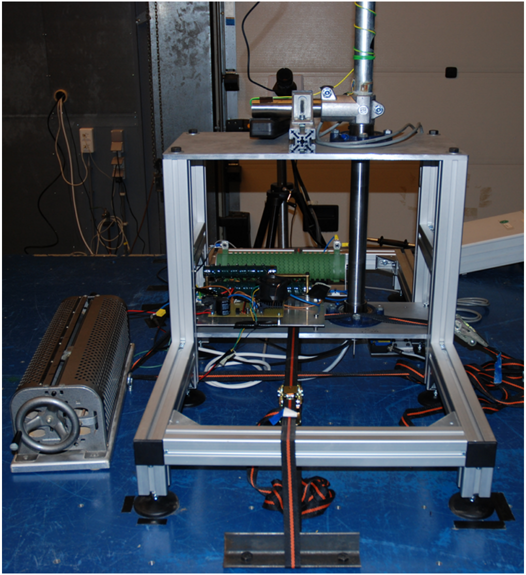


Test Setup Overview

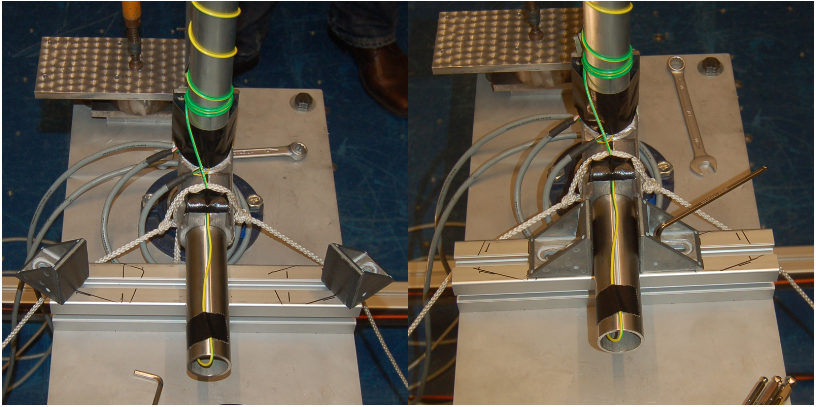
- Blade tip trajectory (HS camera)
- 3D accelerometer tower top
- Fixed data acquisition dSPACE
- Free yawing (tower base), control with wire
- Limited generator torque control (no active tracking of rotor speed)
- Blades made from injected PVC foam, internal glass fiber stiffener
- Rotor speed measurements
- Tower base strain FA, SS
- Blade strain (flapwise), wireless transmitted
- Yaw angle (laser)



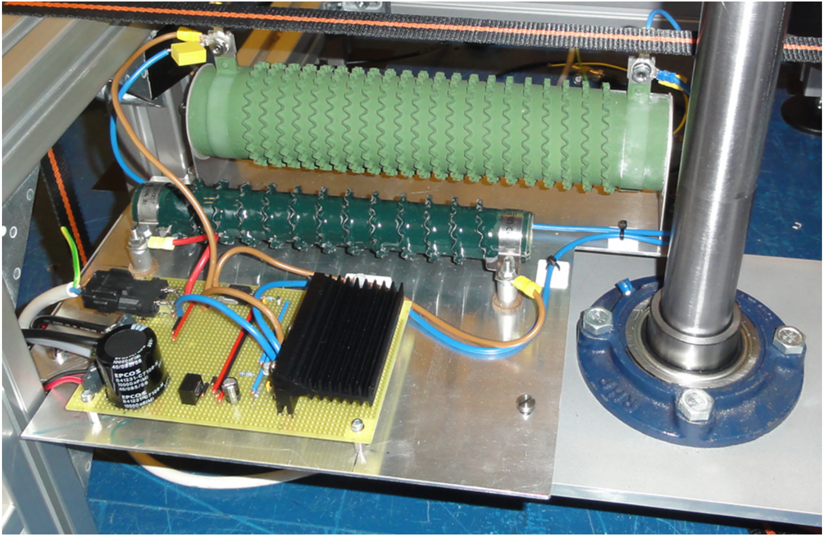
Tower Support Structure



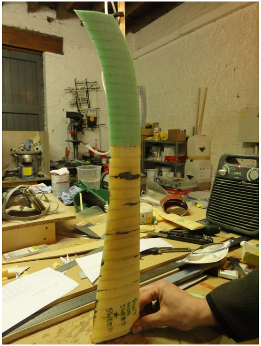
Free Yaw: Locking and Range Limits

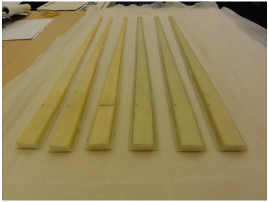


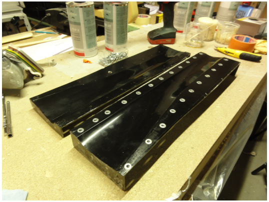
Yaw Bearing and Generator Load



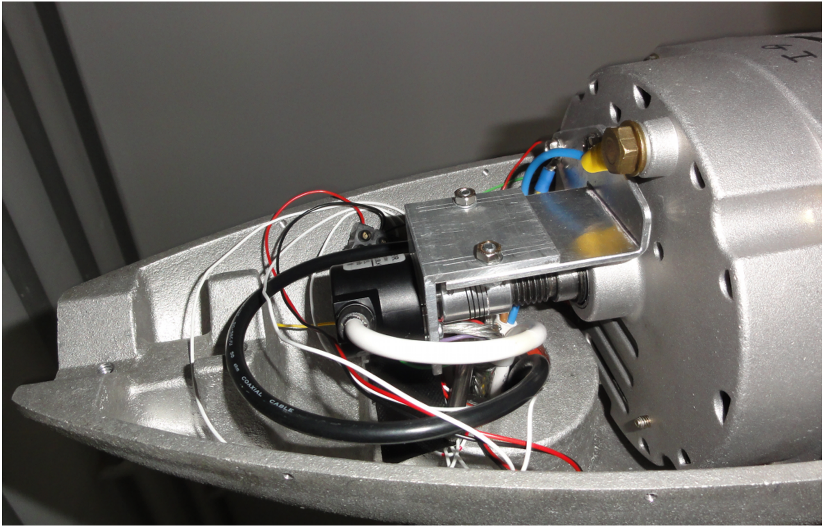
Blades made from injected PVC foam



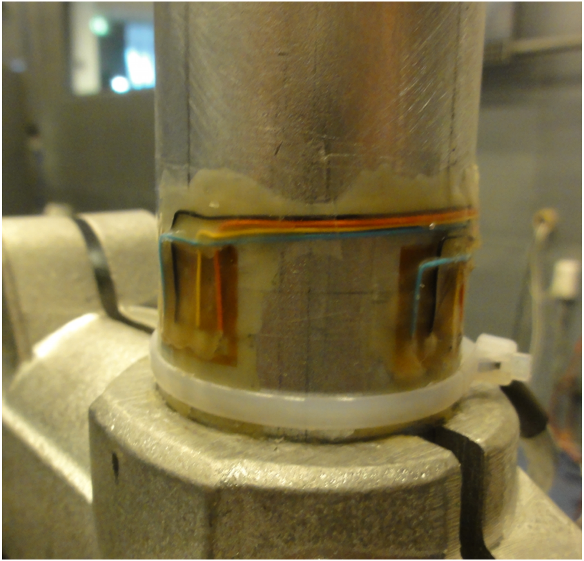




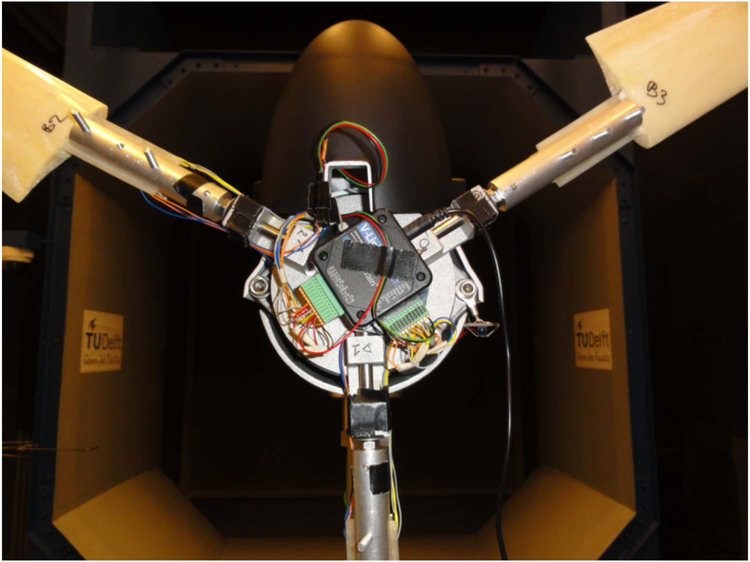
Rotor Speed on Extended Shaft



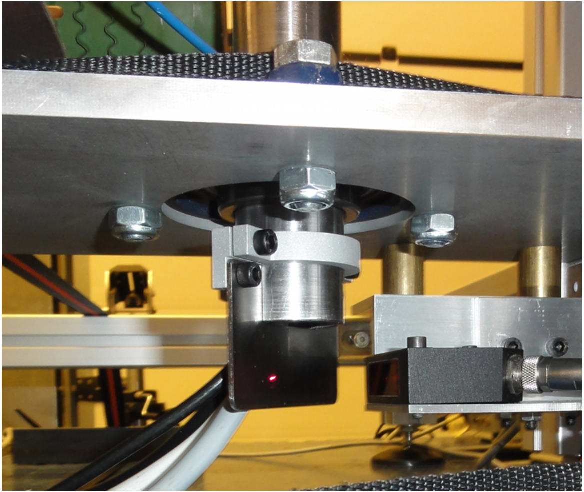
Tower Strain Gauges



Wireless Blade Strain Transmitter



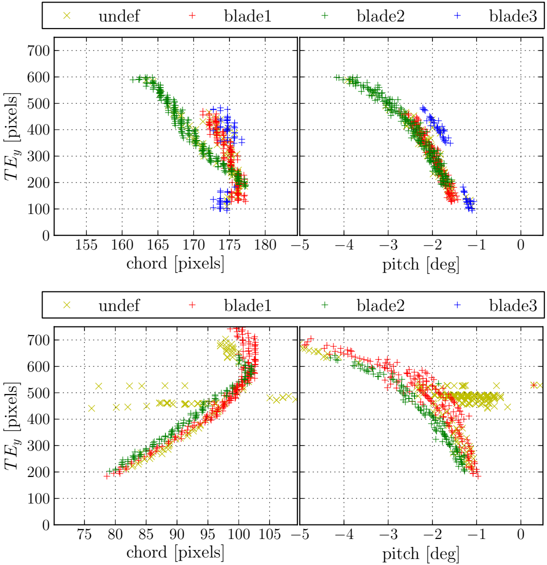
Yaw Angle with Laser Distance Meter



Measurements and Results

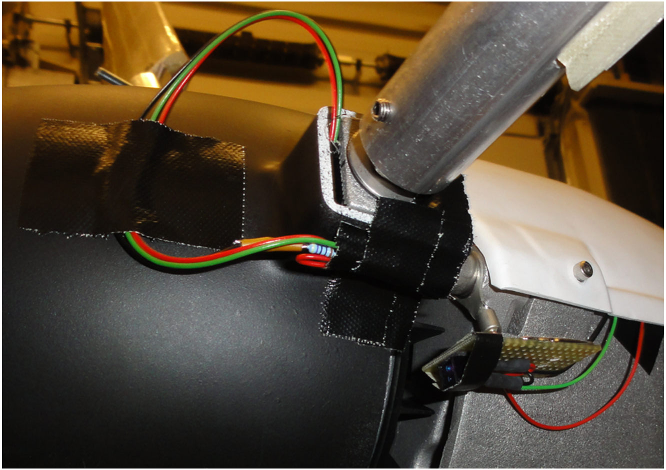
High Speed Camera Data Processing

High Speed Camera Processing Results

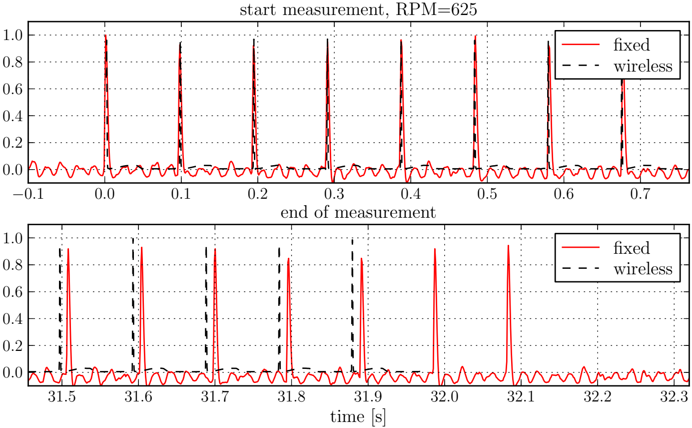


- Trailing Edge (TE) coordinates function of position on the lens: perspective deformation.
- February, April results: camera positions slightly different, other lenses and lighting conditions
- Results used to establish coning imbalances, and blade pitch angles

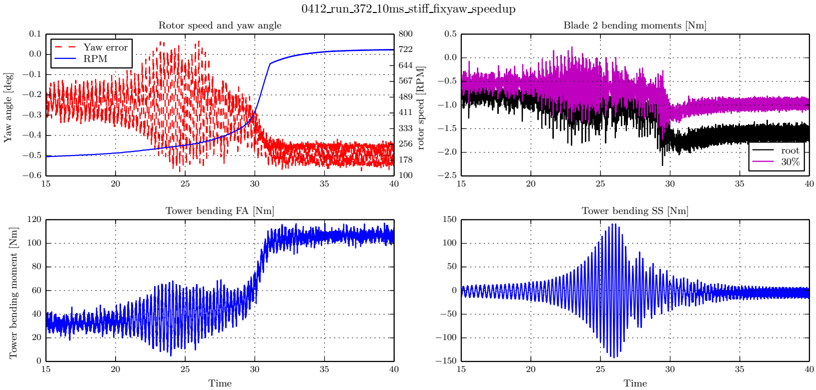
Synchronizing dSPACE and Wireless Strain



Synchronizing dSPACE and Wireless Strain



Trailer Time: Tower Eigenfrequency Passage



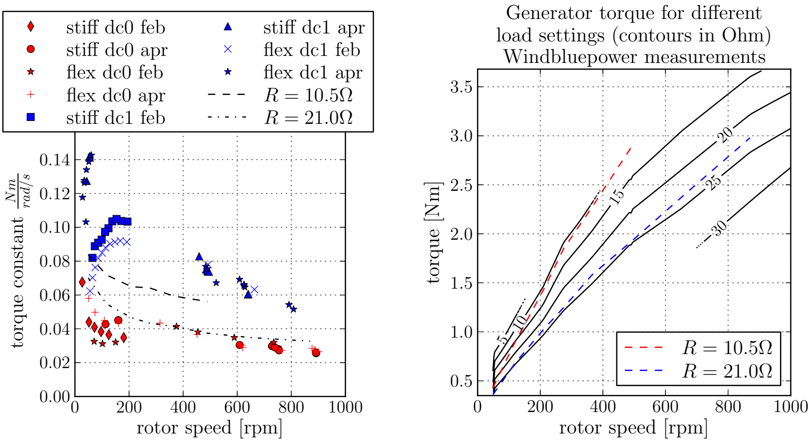
Trailer Time: Free Yaw Stability

Simulation Input Data

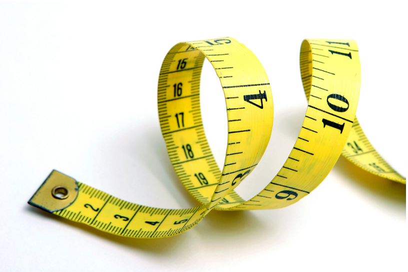
Model Properties, System Identification

- Create a numerical model that corresponds to the experimental setup
- Blade structural properties (static, non rotating):
  - complex varying cross section geometry
  - optimize stiffness distribution to match measured static deflection curves
  - optimize mass distribution to match measured center of gravity, and eigenfrequency
  - optimize damping to match measured frequency response decay tests
- Tower structural properties (static, non rotating):
  - simple tubular constant cross section geometry
  - stiffness affected by clamping at the yaw bearings
  - optimize stiffness to match measured eigenfrequency
  - optimize damping to match measured frequency response decay tests
- Nacelle and hub are assumed stiff compared to the tower and blades
- Blades stiff in torsion: no measurable blade tip twist deformations (rotating, HS camera)
- Yaw bearing friction not measured, but very low
- Lacking: accurate generator torque-rpm curve, no torque measurements

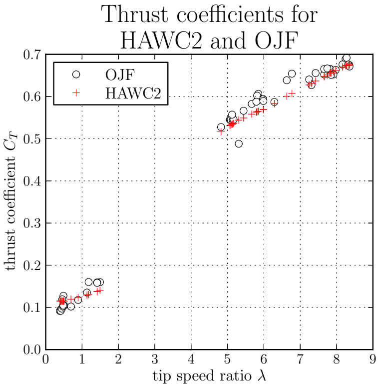
Linear Generator Model



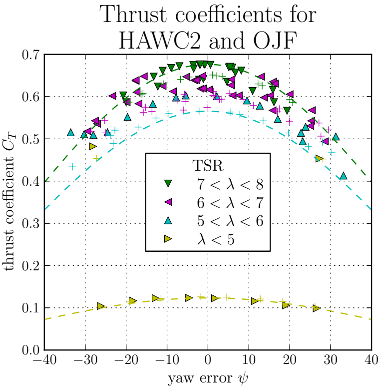
Simulations vs Measurements



Rotor Thrust Coefficients

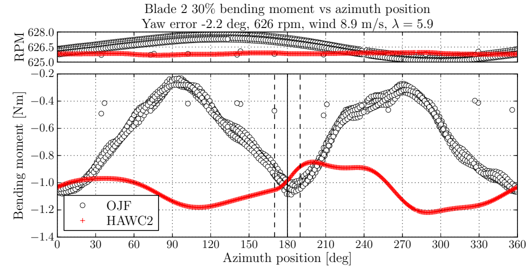


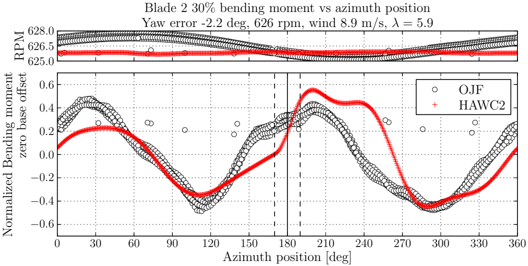
(a) Aligned flow



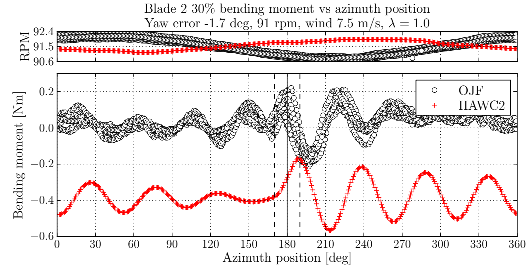
(b) Yawed flow. Triangles refer to measurements, crosses to simulations. Dotted lines are proportional to $cos^2\psi$.

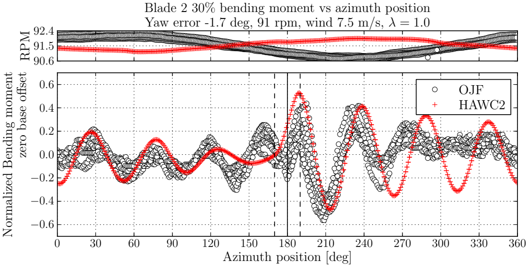
Flapwise Blade Root Moment (high RPM)



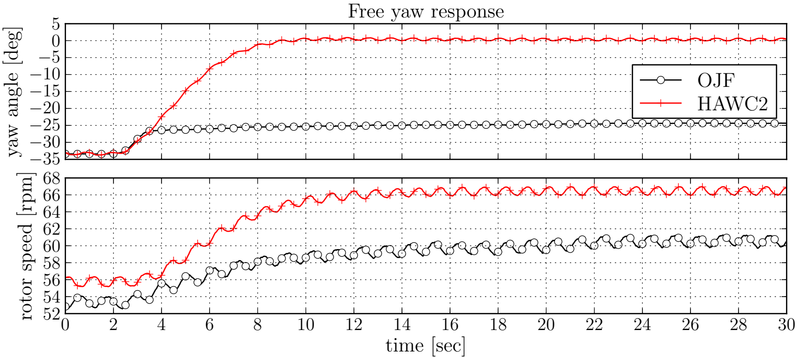


Flapwise Blade Root Moment (low RPM)

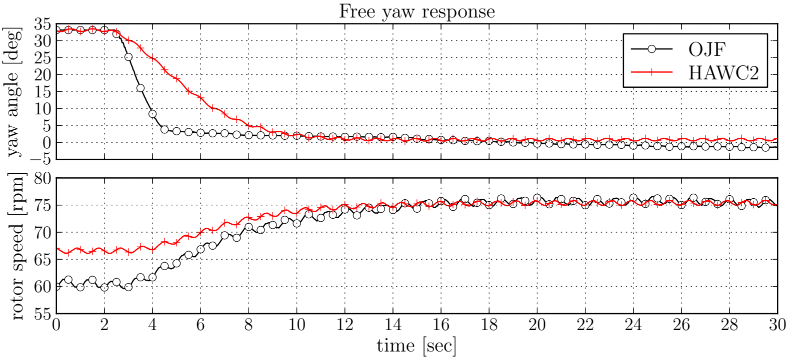




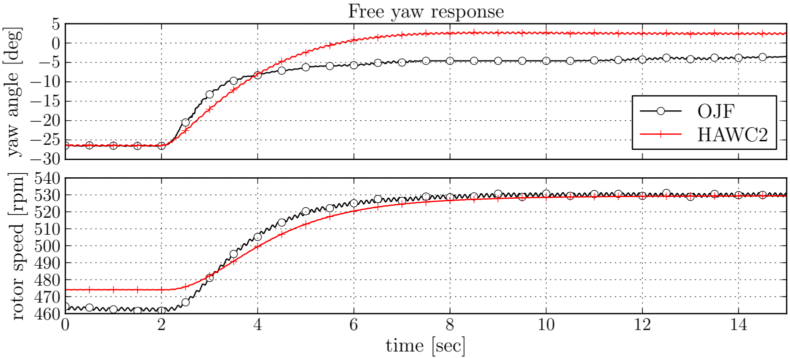
Free Yaw Response: Deep Stall



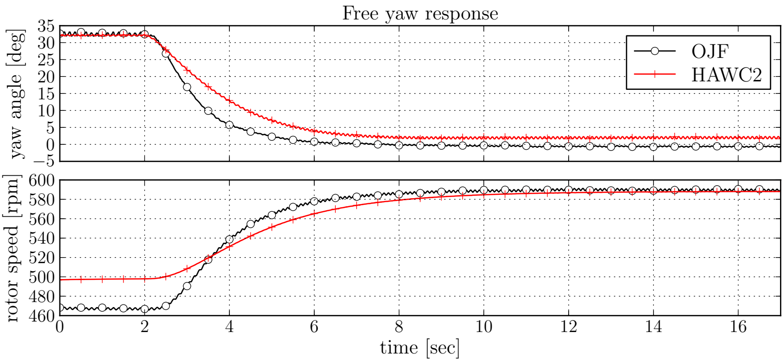
Free Yaw Response: Deep Stall



Free Yaw Response: Optimal TSR



Free Yaw Response: Optimal TSR



Conclusions

- Numerical studies for a 100 kW wind turbine:
  - Unstable in free yaw when blade close to maximum lift point
  - Combining blade sweep and rotor coning angle minimizes unstable operating points
- Wind tunnel experiments:
  - High blade flexibility failed due to centrifugal stiffening
  - Hardware and sensor limitations (generator and control, torque measurements, synchronisation)
  - Documentation
  - Verified free yaw stability
  - Unstable regions not reached due to limited generator control
  - Recorded azimuthal blade load dependency for various inflow angles
- Simulations vs experiments:
  - Matching thrust coefficients for varying inflow angles
  - Data synchronisation issues
  - Similar trends for blade load azimuthal dependency for varying inflow angles
  - Comparable free yaw dynamics
  - Difference in steady state free yaw angle while operating

Future Work

- Detailed aerodynamic assessment of yaw moment contributions from different radial stations along the blade, and under varying operating conditions
- Blade design: formulate strategy which includes free yawing behaviour
- Yaw moment sensitivity to aerodynamic profile coefficient data, and modelling (3D stall delay)
- More data remains to be analysed/compared with simulations:
  - Improving high speed data footage analysis
  - Synchronization issues
  - More accurate generator model, better torque estimates?
  - Other blade configurations (sweep, coning)
- Follow up experiment:
  - Use practical experience gained to improve the experiment (measurements techniques and test definitions)
  - Use more extensive and robust/redundant system identification strategies
  - Sufficient torque control to test unstable free yawing conditions
  - Design and built a truly flexible blade
  - Focus on yawed flow
  - Influence of wind shear

The End.

Thank you for your attention.