Experimental Investigation of a Downwind Coned Wind Turbine Rotor under Yawed Conditions

Christian Schulz

Supported by
Stefan Netzband
Klaus Wieczorek
Moustafa Abdel-Maksoud

christian.schulz@tuhh.de
Institute for Fluid Dynamics and Ship Theory
Hamburg University of Technology

MOTIVATION

Particular needs for new experimental investigations

- Only few investigations at higher yaw angles
- Focus on power and thrust

Support of new wind turbine concepts

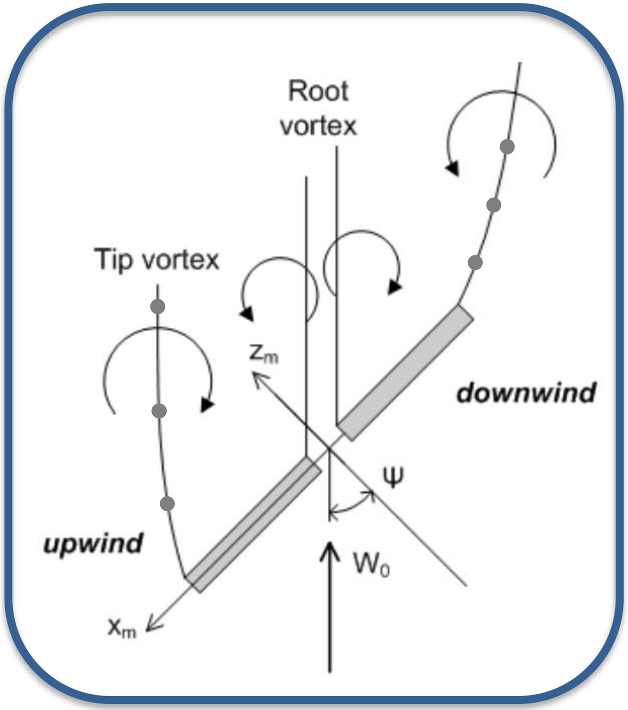
- Free-yawing wind turbines
- **Self-aligning floating offshore wind turbines (SFOWT)**
  - Higher yaw angle
  - Self-aligning dependent on yaw moment

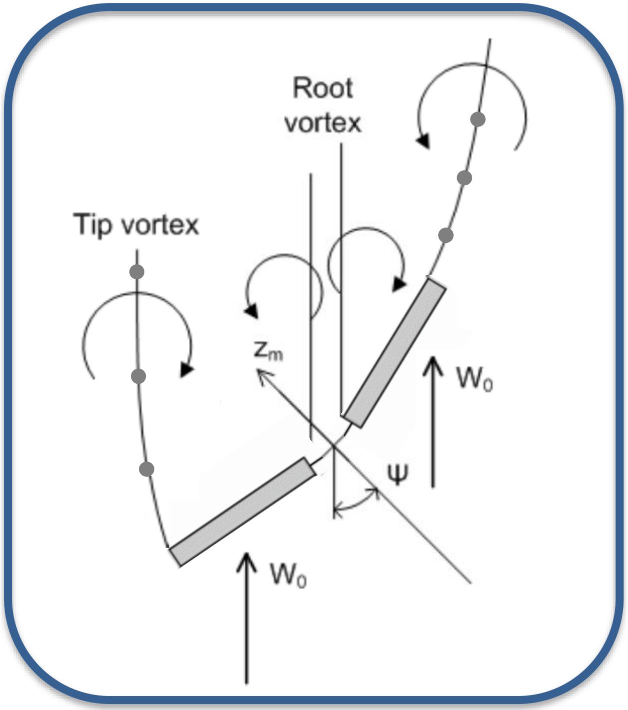
→ **Detailed investigation of yaw moment and power up to 55° yaw angle**

OVERVIEW: EXPERIMENTAL INVESTIGATION OF A DOWNWIND CONED ROTOR

Experimental Investigation of a Downwind Coned Rotor

Background: Origin of the Yaw Moment





1. Lower induction at the upwind side

2. Higher inflow angle on the upwind side

[W. Haans, Wind Turbine Aerodynamics in Yaw – Unravelling the measured Rotor Wake (slightly modified)]

BACKGROUND: PREVIOUS EXPERIMENTS

Previous experiments of under yawed conditions

- MEXICO
- NREL UAE Phase VI
- Sant and Haans, TU Delft
- …

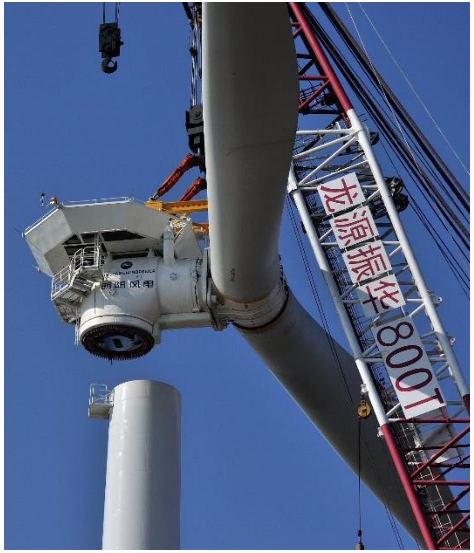
Only very few measured the yaw moment

Downwind coned rotor was only considered by NREL

- Extremely high cone angle or teeter dampers used, strong tower effects

aerodyn SCD 6MW

9° downwind cone



[AERODYN ENGENEERING]

[M. HAND, D. SIMMS, S. LARWOOD: Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns]

OVERVIEW: EXPERIMENTAL INVESTIGATION OF A DOWNWIND CONED ROTOR

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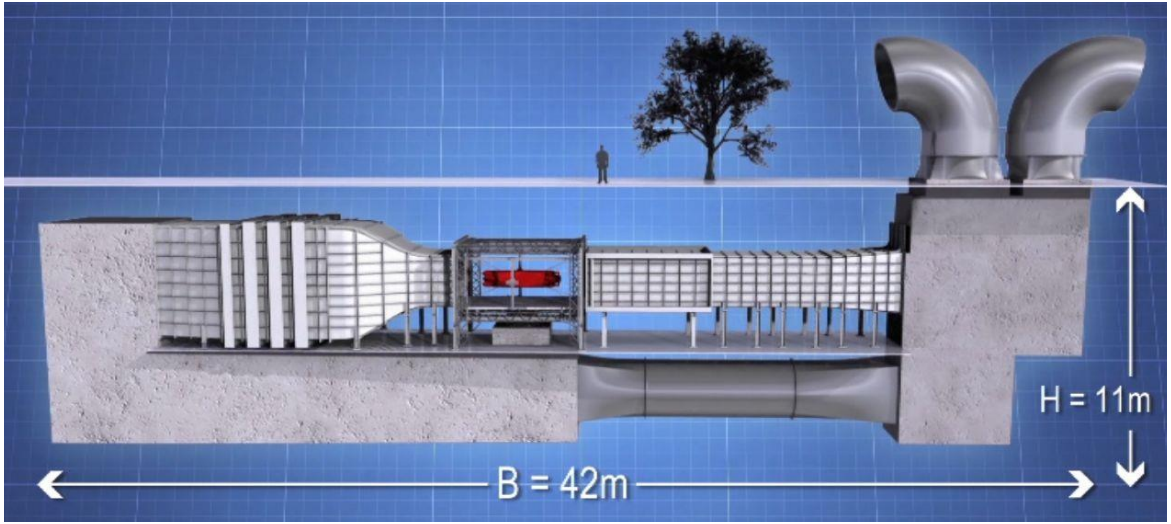
Wind Tunnel at TUHH

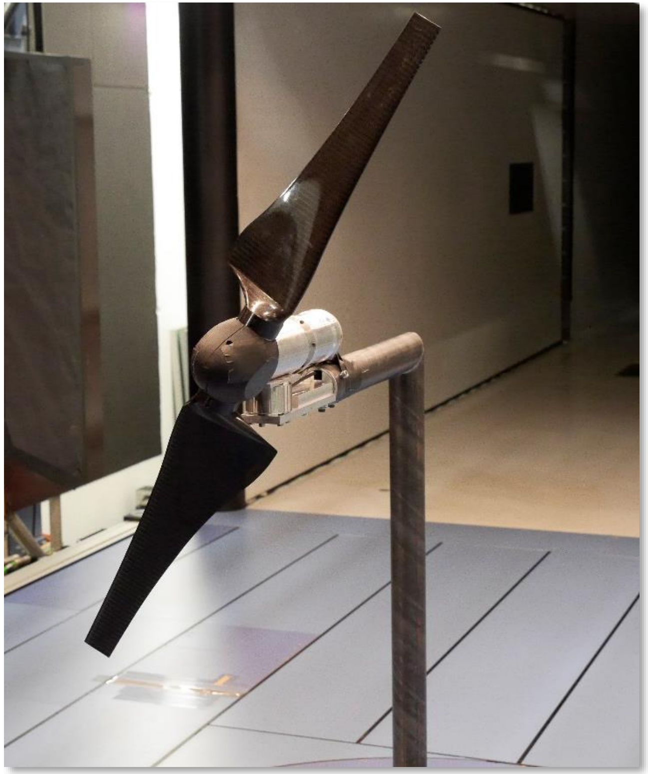


TUHH Wind Tunnel	
Max. wind speed:	40 m/s
Turbulence degree:	< 0.2%
Measuring section (L X B X T)	5 x 3 x 2 m

Operational Modes:
closed circuit (Göttingen – mode)
open circuit (Eiffel – mode)
integrated 6-component balance

Wind Tunnel Model: Overview

TUHH Experimental Wind Turbine	
Rated power	130 W
Rotor diameter	**0.925 m**
Number of blades	2
Downwind cone angle	**5°**
Rated wind speed	9.3 m/s
Rated rotational speed	**1200 RPM**
Wind tunnel size	2 x 3 m
Blockage ratio	**11.2 %**
Sensor	6C - balance



Wind Tunnel Model: Blade Design

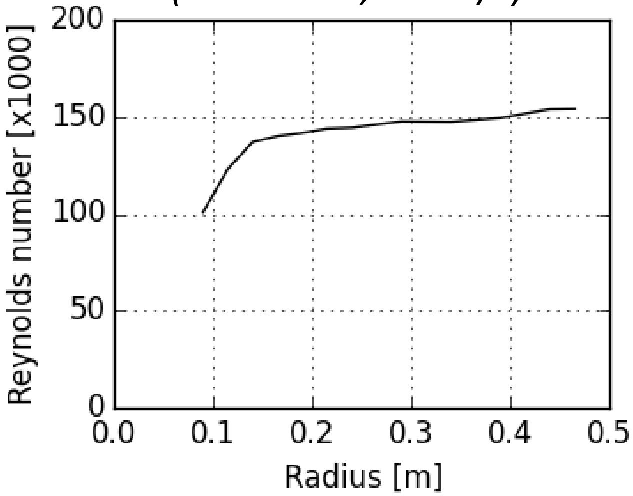
Design goals

- Validation case for simulations
    - Low Reynolds number dependency
    - No Stall
    - Availability of measurement data for airfoil
    - High power coefficient
    - Low blade deformation

Properties

- SD7062, 14% thickness (Experimental data available for Re 100,000 and 200,000)
- Nearly constant Reynolds number of 150,000 at 1200 RPM

Estimated geometrically at rated conditions (1200 RPM, 9.3 m/s)



Wind Tunnel Model: Blade Manufacturing and Quality

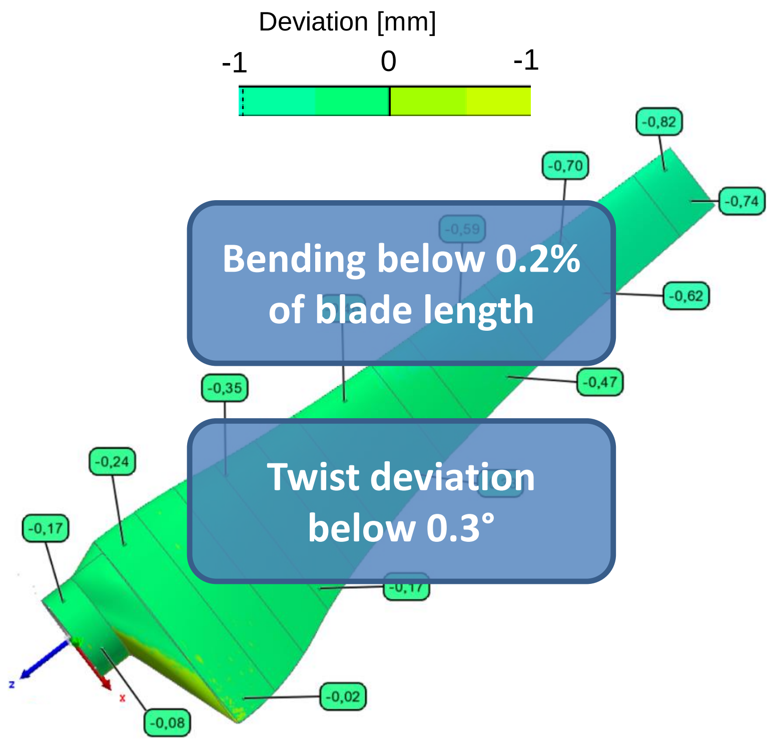
Choice of material driven by

- Manufacturing accuray
- High interia forces
    - Acceleration: 400 g at 50 % of radius
    - Induce bending moments due to cone angle

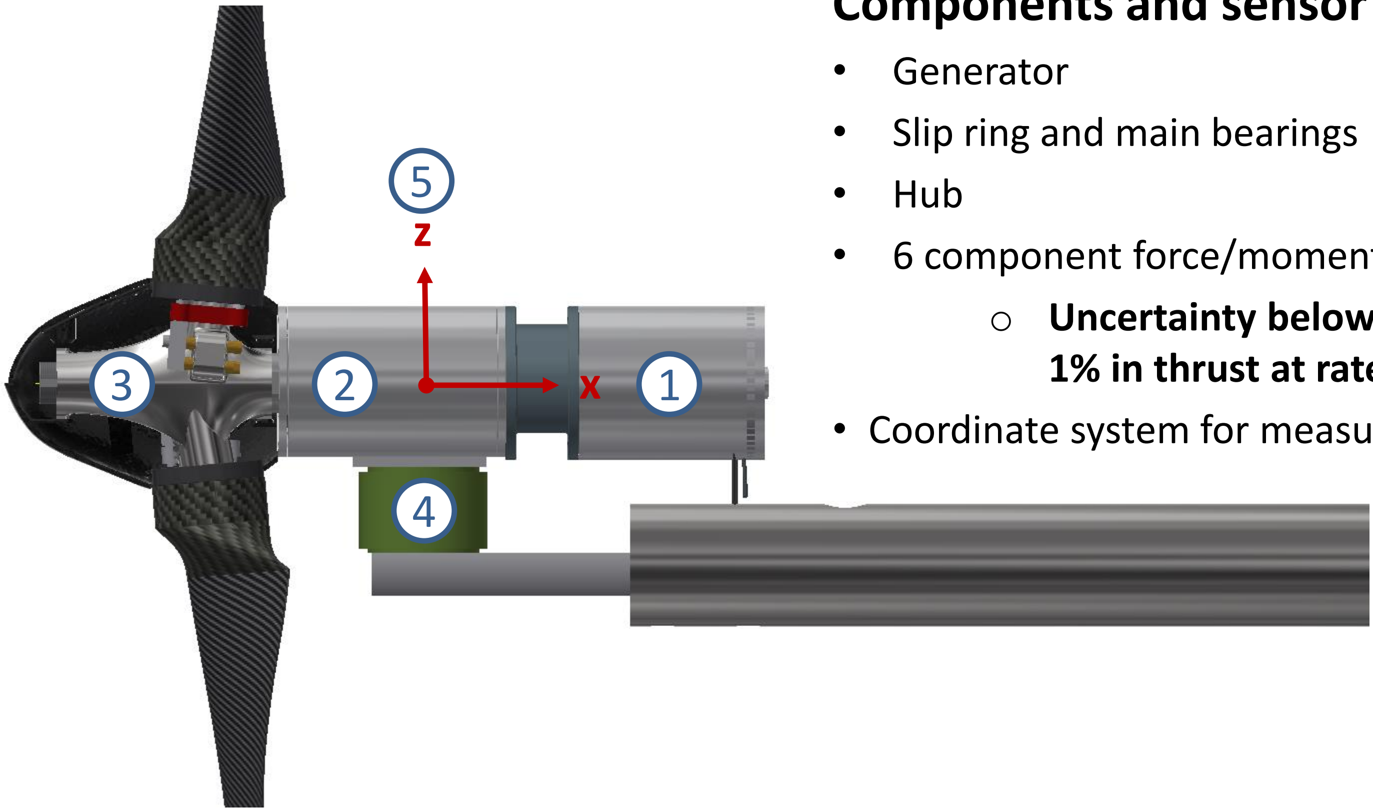
Rigid and lightweight structure needed

- Prepreg carbon fiber
- Shear web
- Hard resistance foam core
- High risk of undesired twisting

3D scan performed



Wind Tunnel Model: Nacelle, Sensor and Coordinate System



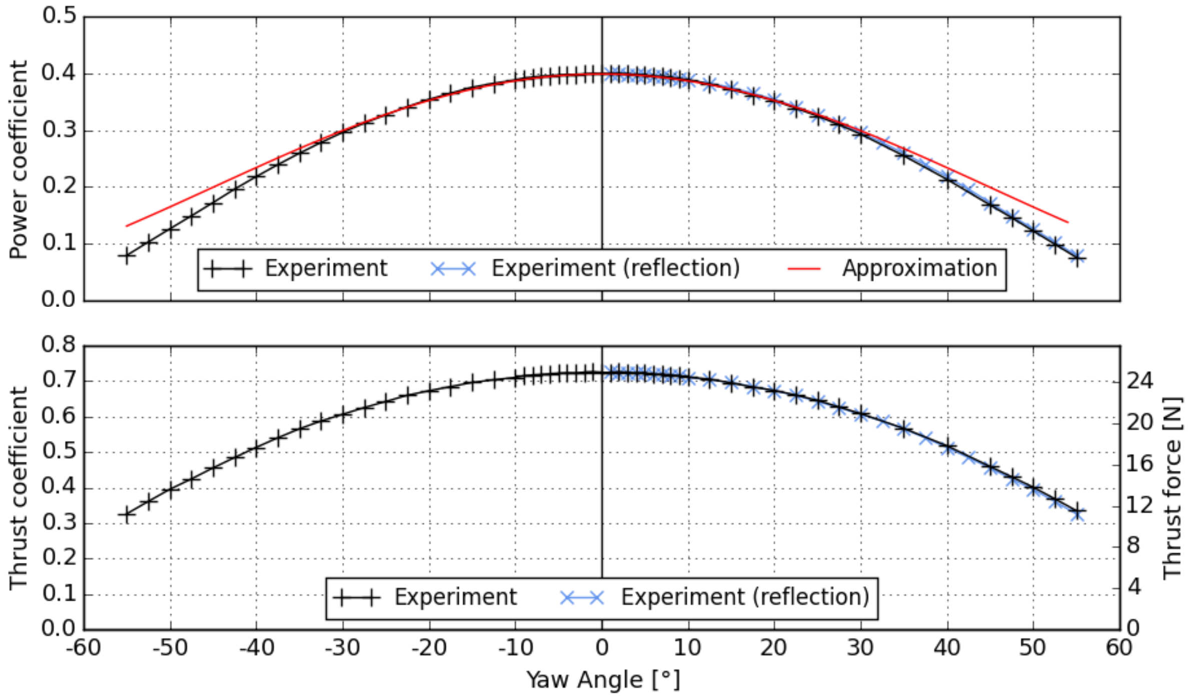
Components and sensor

1. Generator
2. Slip ring and main bearings
3. Hub
4. 6 component force/moment sensor
   - **Uncertainty below 2% in torque and 1% in thrust at rated conditions**
5. Coordinate system for measurements

Overview: Experimental Investigation of a Downwind Coned Rotor

Experimental Investigation of a Downwind Coned Rotor

Results: Power and Thrust coefficients (Mean Values)

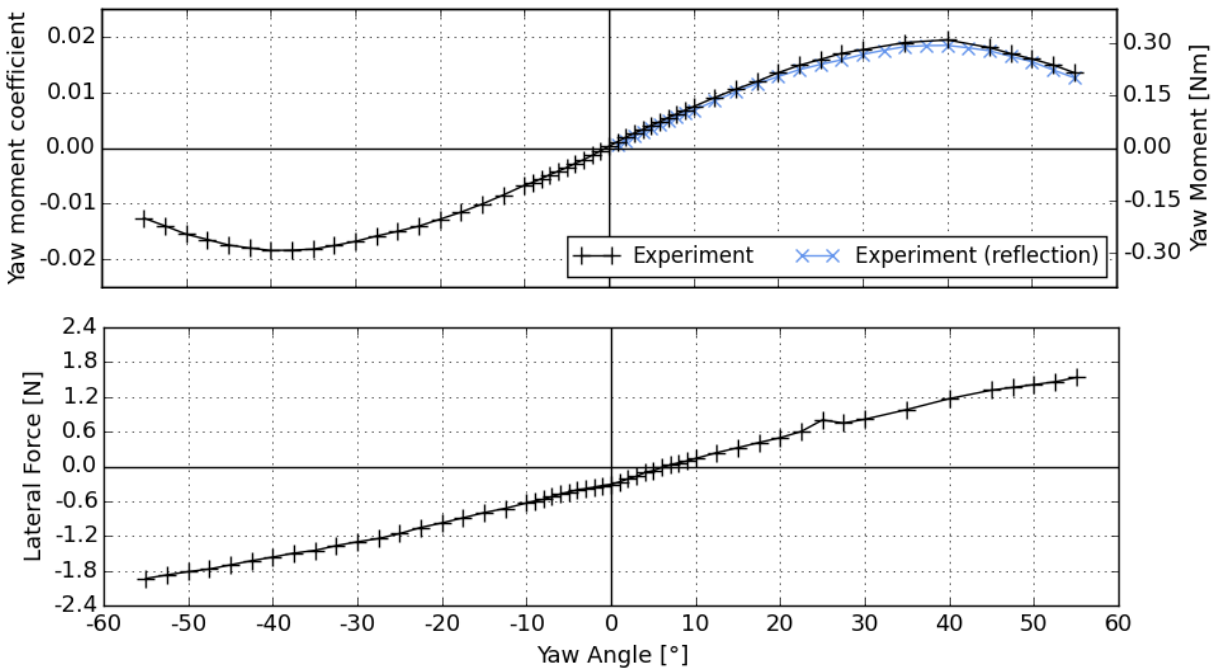


Results

- Power coefficient of 0.4
- Very smooth curves for power coefficient and thurst
- Nearly symmetric behaviour
- $cos^2\gamma$ fits well up to 30°
- Strong deviation at higher yaw angles

Results: Yaw Moment and Lateral force (Mean Values)

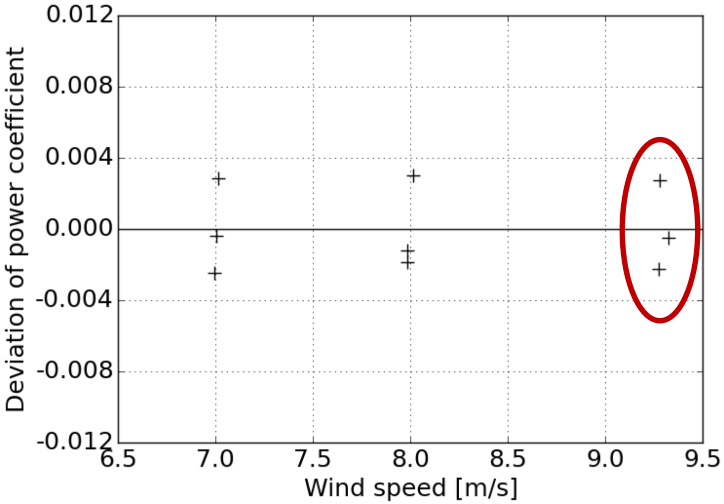
$$C_{m,yaw} = \frac{M_{yaw}}{{}^{1}/_{2}\,\rho\, v^2 A_{rotor} R_{rotor}}$$

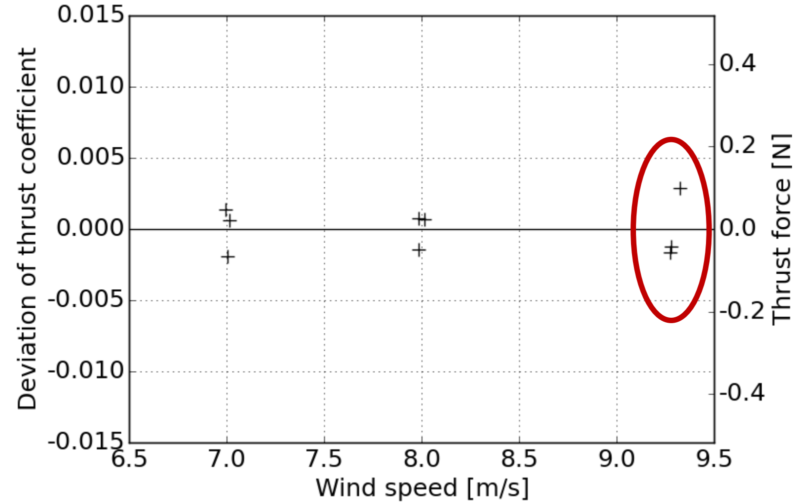


Results

- **Yaw moment**
  - Maximum yaw moment at 40°
  - Smooth curve
  - Slight deviation to symmetric copy
  - Zero crossing nearly exactly at 0°
  - Low uncertainty in yaw angle
- **Lateral force**
  - Slight offset in Lateral force (ca. 1% of thrust)
  - Mainly caused by nacelle drag force

RESULTS: REPEATABILITY OF TORQUE AND THRUST





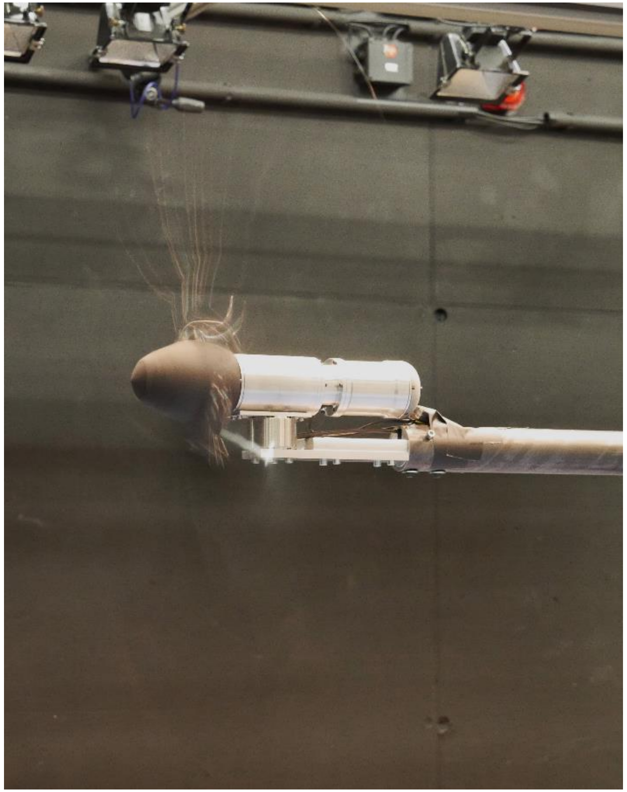
- **Repeatability checked on three different days**
- **Cables were moved**
- **Deviation between repetitions below 1% in C_p and 0.5% in C_t at rated conditions**

Results: Critical Issues

Aspects that need to be considered

- Small offset in lateral force
- Yaw moment deviated by nacelle drag force and unknown lever arm
- Vibration induced periodic forces up to 2% of thrust
- Deviations in rotational speed up to 1% (considerd in C_p calculation)
- Low pass filter was applied (40 Hz corner frequency)
- Small deviations due to cables‘ stiffness

→ **No serious issues were observed**



Overview: Experimental Investigation of a Downwind Coned Rotor

Experimental Investigation of a Downwind Coned Rotor

CONCLUSION

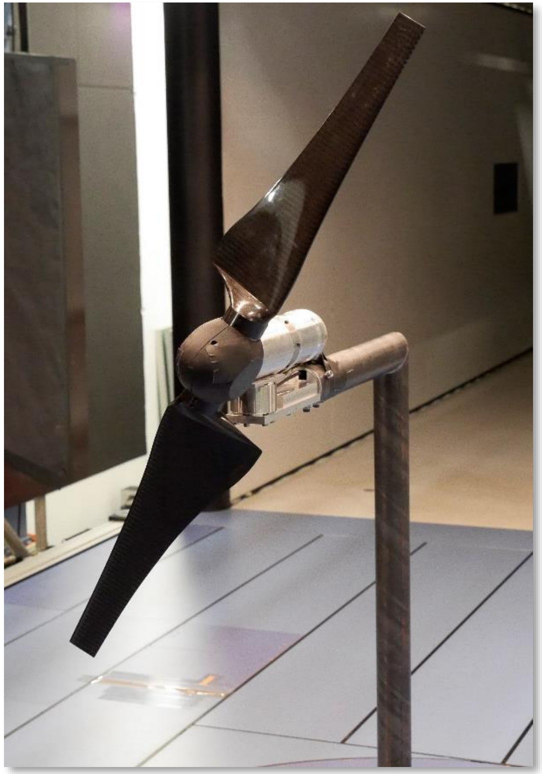
Conclusion

- High repeatability and low measurement uncertainty were achieved
- $cos^x\gamma$ approach is not suitable for higher yaw angles
- Yaw moment increases up to 40°
- **Rare data for the yaw moment is now available for validation**
    - Validity of Blade Element Momentum Method for Self-aligning Floating Wind Turbines can be investigated

Invitation to Simulate

Every researcher is invited to validate his tool with the presented experiment!

- A detailed description will we published in the **conference proceedings** (if paper will be accepted)
- **Data sets or CAD models** may be handed out on request
- Publications welcome



Acknowledgement

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Thank You for your Attention

Christian W. Schulz