TWEET-IE
Twin Wind tunnels for Energy & the EnvironmenT
INNOVATIONS - EXCELLENCE

Wind Energy Institute

Grand Opening Event TWEET-IE

Measurement technique at the Wind Energy Institute

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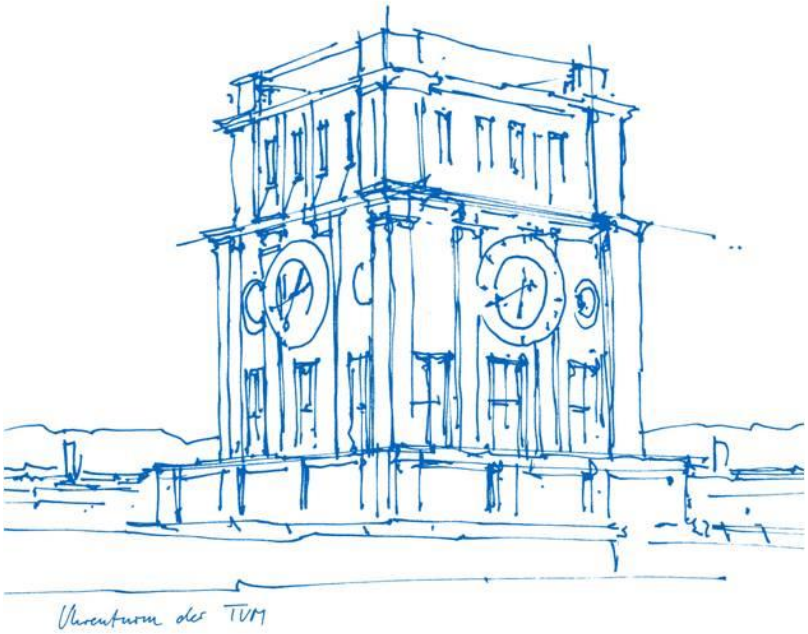
Wind Energy Institute



Athens, 25th January 2023

The Importance of Wind Tunnel Experiments

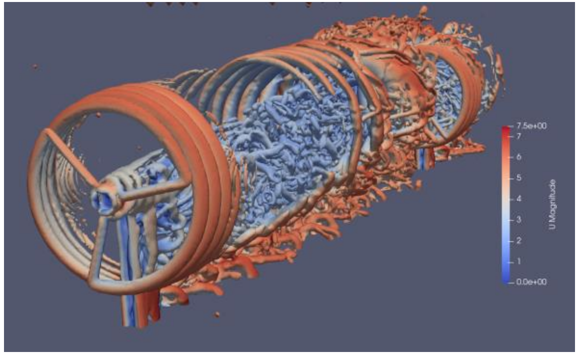
Full-scale measurements

Alpha ventus, Source: Martina Nolte,

Prediction

Scaling
Blockage

Computational Fluid
Dynamics (CFD)



Validation &
Calibration

Wind tunnel experiments

Source: Geir Mogen, NTNU

TUM Scaled Wind Farm Family

G0.6 **(2017)**

G1 **(2013)**

G2 **(2007)**

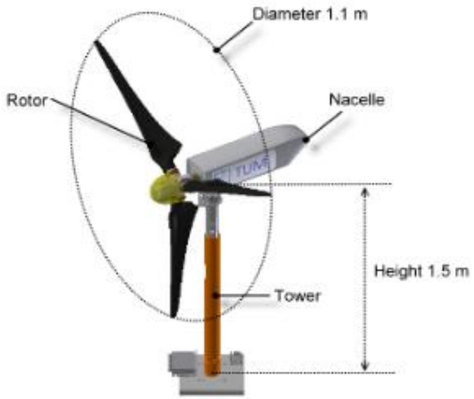
Control hardware (Bachmann M1)
Supervisory control & safety loops
Pitch, torque and yaw control

All:

- Real-time individual (G1 & G2) blade pitch, torque & yaw control
- Fully sensorized: shaft and/or blade loads, shaft torque, tower loads, blade pitch and rotor azimuth, nacelle acceleration

From single WT analysis to multiple wake interactions and complex terrains

G1 – Generic Scaled Wind Turbine



$\eta_L = 1:155$

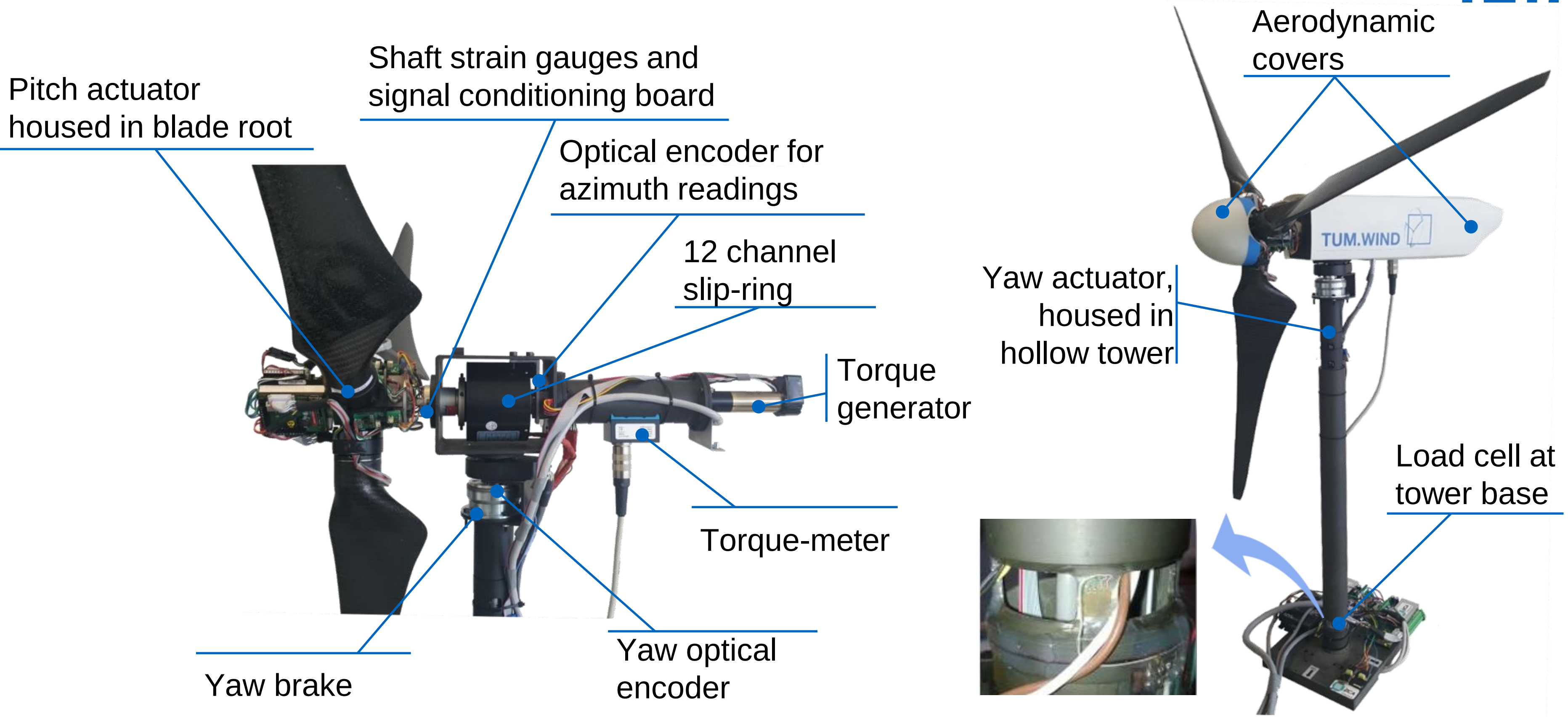
$\eta_T = 80:1$

Parameters	Scaled Model	Samsung S7.0-171
Rotor Diameter [m]	1.1	171.2
Hub Height [m]	0.80	110
Rotor Speed [rpm]	850	10.4
Nominal Power [W]	46	7.70e6
Nominal Torque [Nm]	0.511	7.07e6
Reynolds number [-]	85’000	25.0e6

Basic design requirement:

- Testing of **wind farm control** strategies

G1 – Generic Scaled Wind Turbine



Rotor Aerodynamic Design

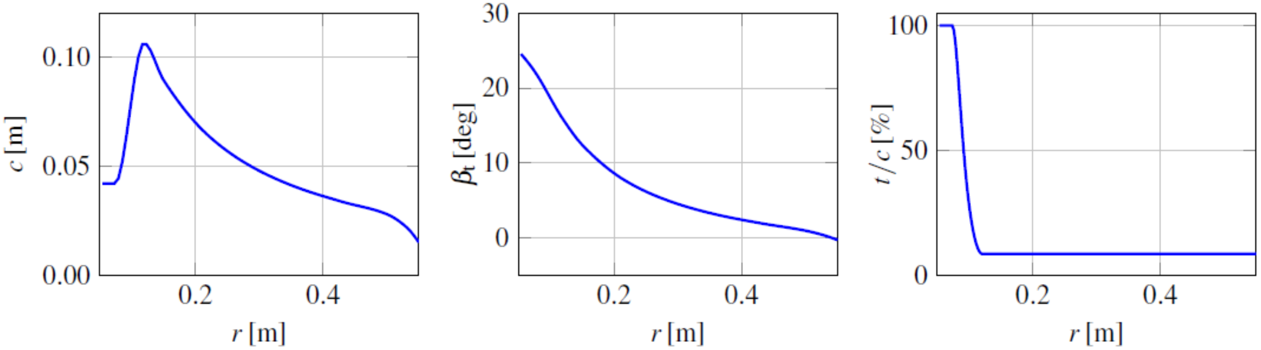
Blade Geometry

Optimal rotor

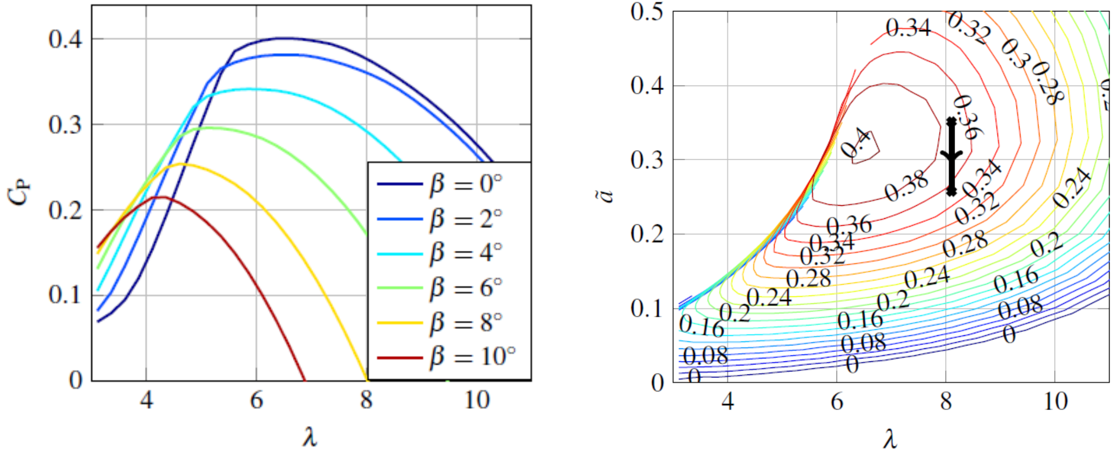
C_P = 0.40

λ = 8.1

Re = 85000

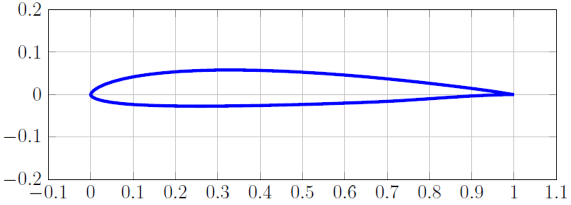


Rotor performance

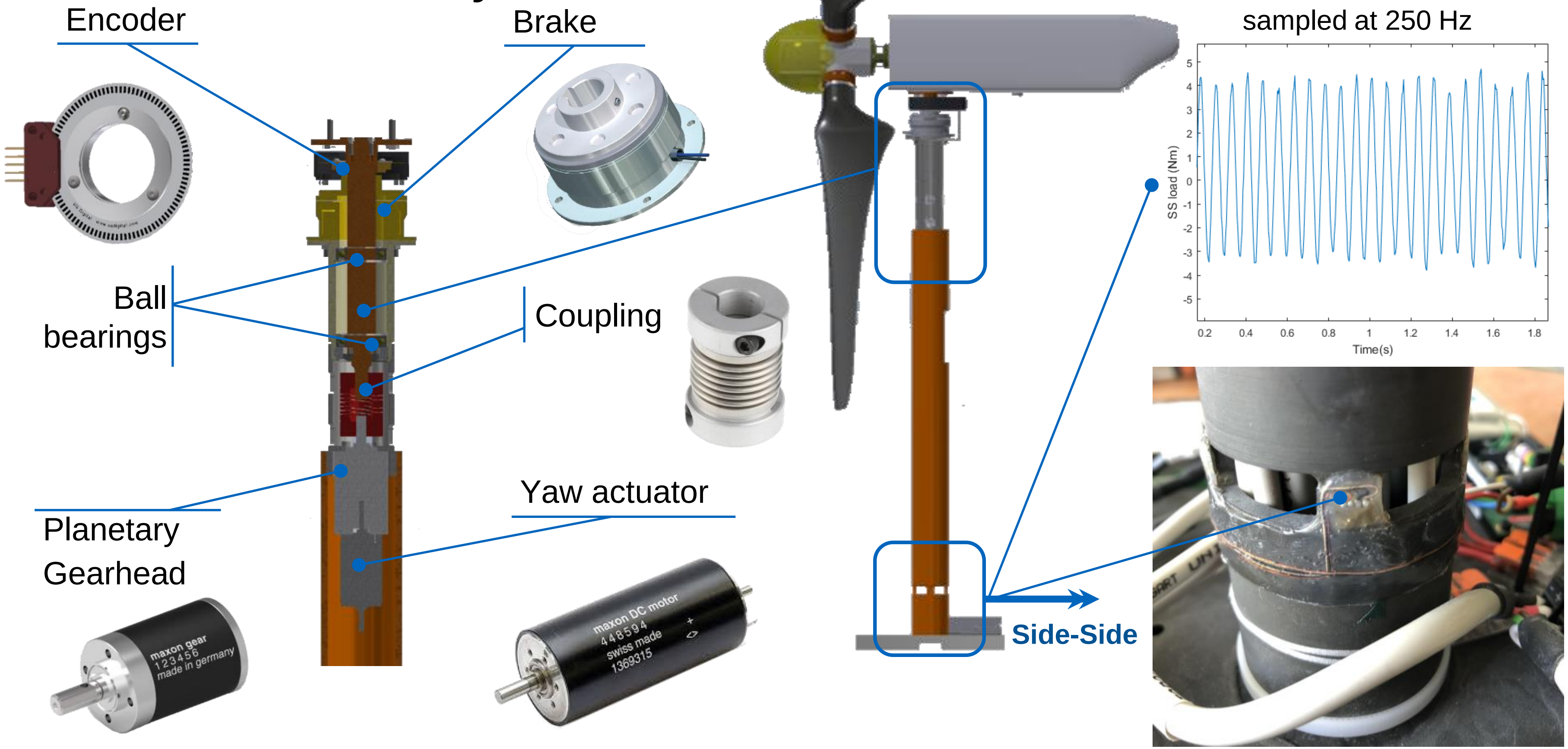


RG-14 airfoil

Low Reynolds, low cambered



Tower and Yaw system

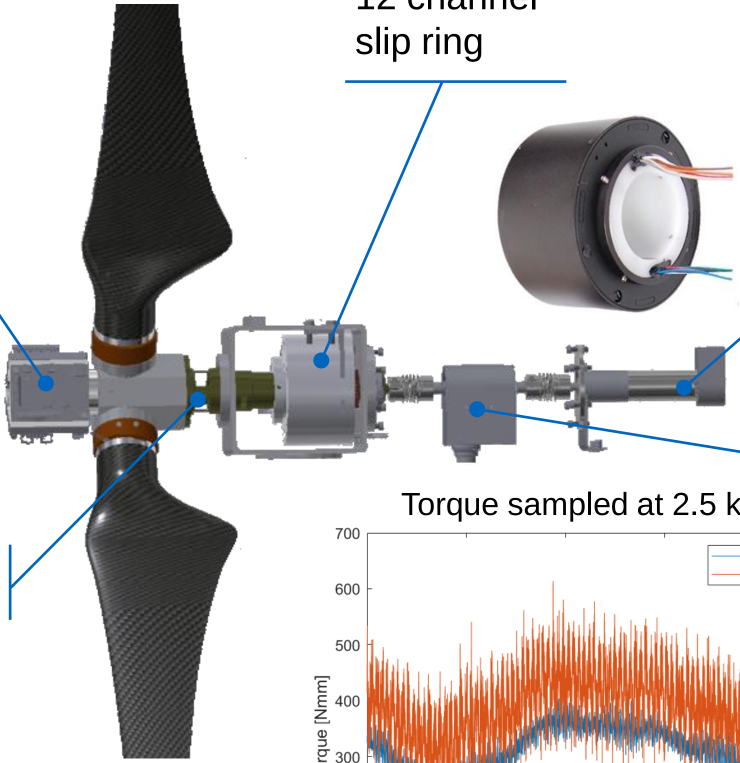


Nacelle

12 channel
slip ring

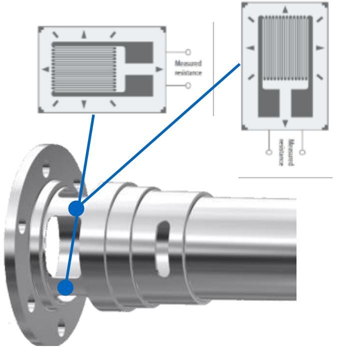
Conditioning
boards

Generator unit

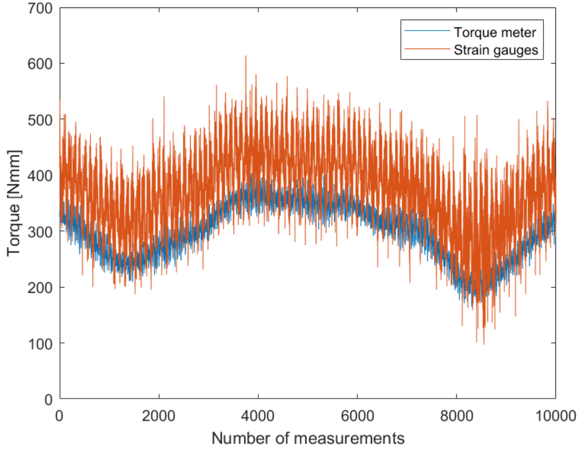


Torque-meter

Shaft with strain gauges



Torque sampled at 2.5 kHz



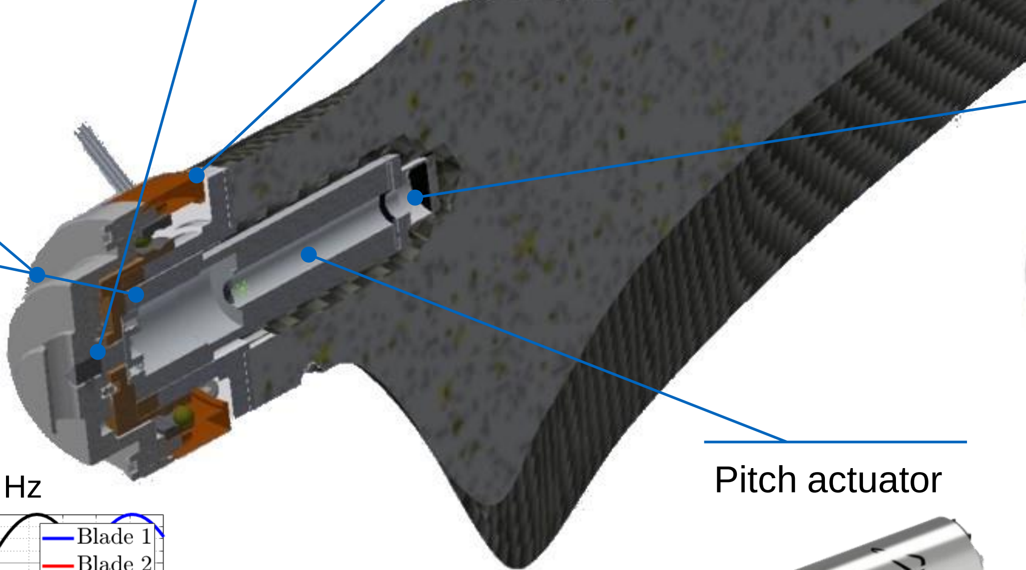
Blade / Pitch

Torsion spring

Bearings

Hall sensor

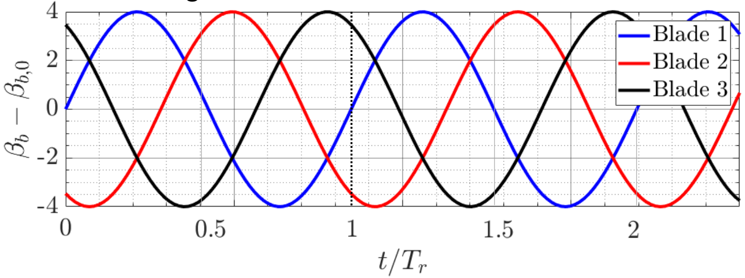
Planetary Gearhead



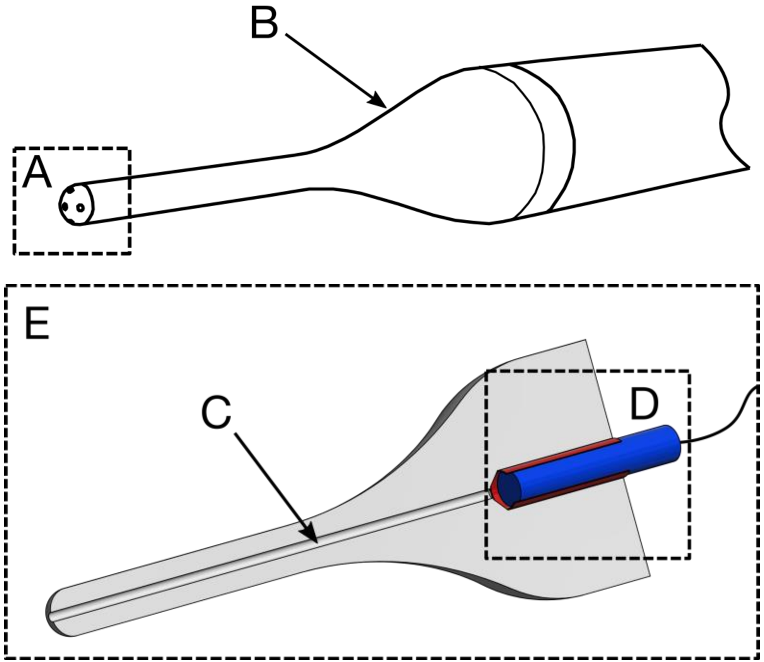
Motor encoder

Pitch actuator

Pitch signal for IPC actuation at 14 Hz



Multi-Hole Pressure Probe Introduction



A Probe tip shape (spatial calibration and resolution)

B Additive manufactured tip (mechanical restrictions)

C Line-cavity system (temporal calibration and resolution)

D Piezo-resistive pressure sensor (Characterization)

E Pressure probe assembly and technical requirements

Calibration and Reconstruction: Spatial Characteristics

Goal: Correlation between the **mean free-stream flow conditions** and the **measured pressures** at the probe

Calibration step

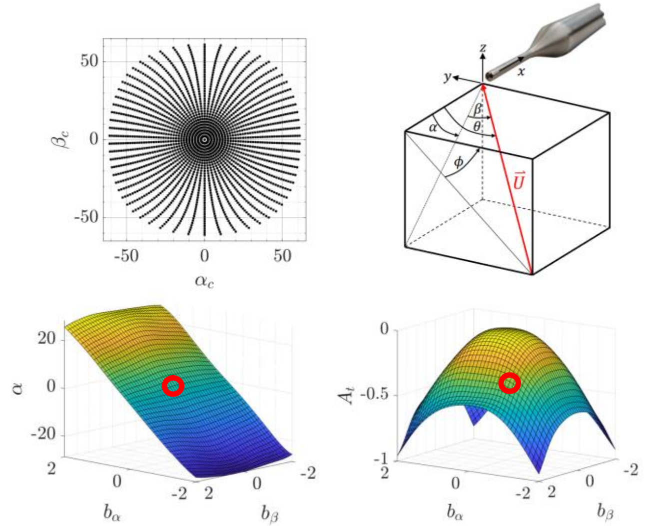
Processing step

Reconstruction

set in W/T: $U_\infty, \alpha, \beta|_{cal}$ → measure: $p_1 \dots p_5$

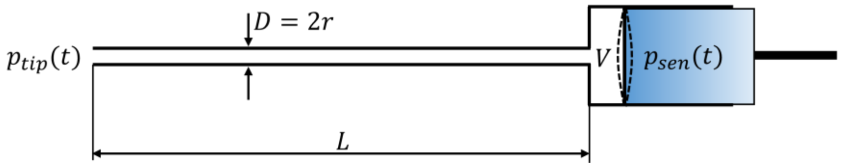
Cal. data

measure: $p_1 \dots p_5$ → ⊕ → reconstruct: $U_\infty, \alpha, \beta|_{recon}$



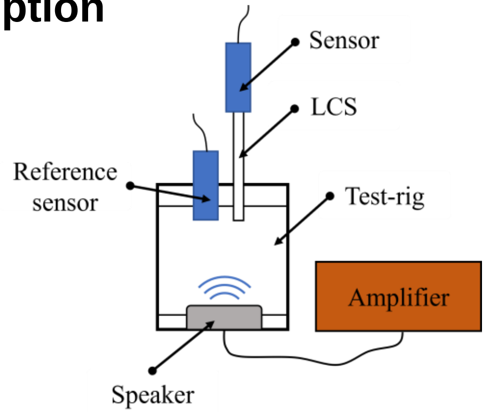
Calibration and Reconstruction: Temporal Characteristics

Determination of the **Transfer Function** of the Line-Cavity-System:



Theoretical Description

Application

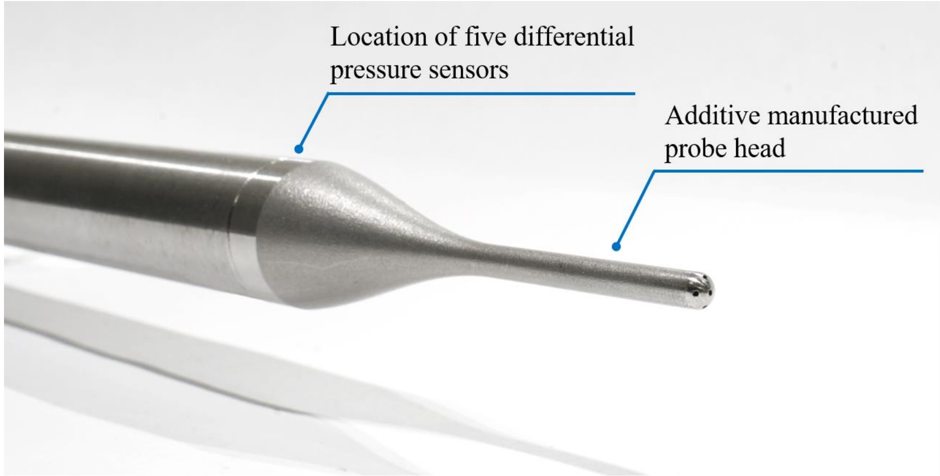


$$H(\omega) = \frac{P_{sen}(\omega)}{P_{tip}(\omega)} = \boxed{\frac{\hat{p}_{sen}(\omega)}{\hat{p}_{tip}(\omega)}} \cdot \boxed{e^{i\omega t+\varphi(\omega)}}$$

Attenuation and Resonance

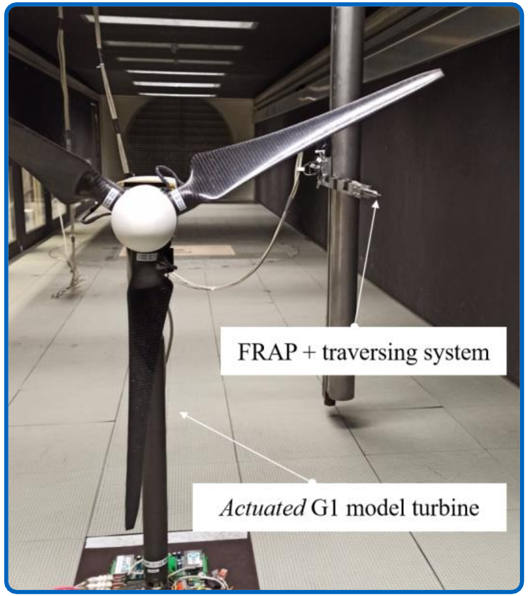
Phase Shift

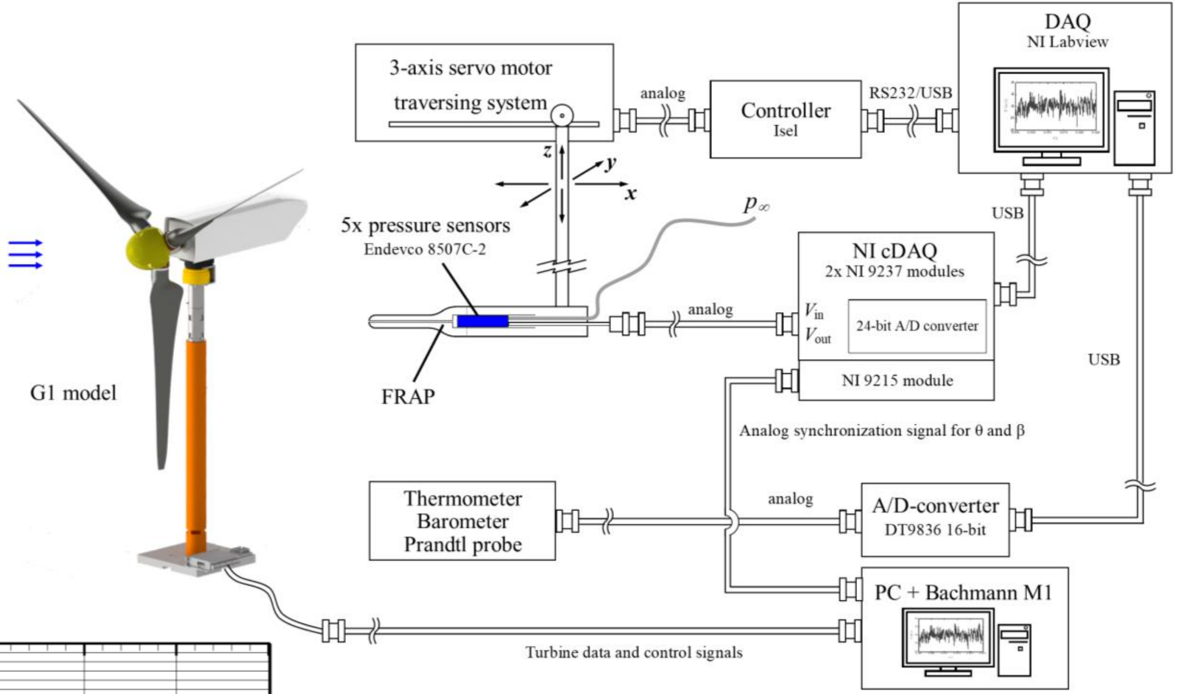
Fast-response aerodynamic pressure probe (FRAP)

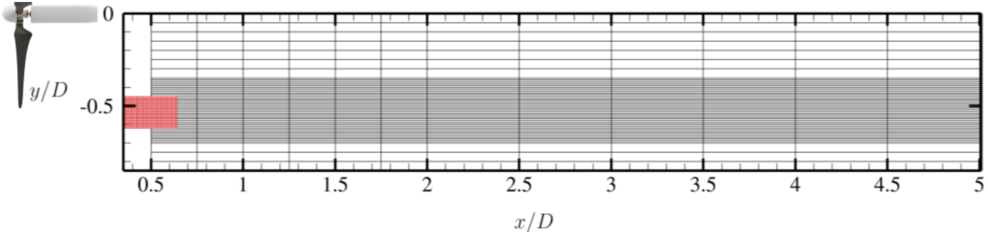


Tip diameter	$3\ mm$
Channel diameter	$\leq 1\ mm$
Sensor type	Differential, piezo-resistive
Sensor gauge pressure range	$2\ psig$
Sensor diameter	$2.3\ mm$
Spatial/angular calibration	$\pm 60°$
Temporal calibration	$10\ kHz$

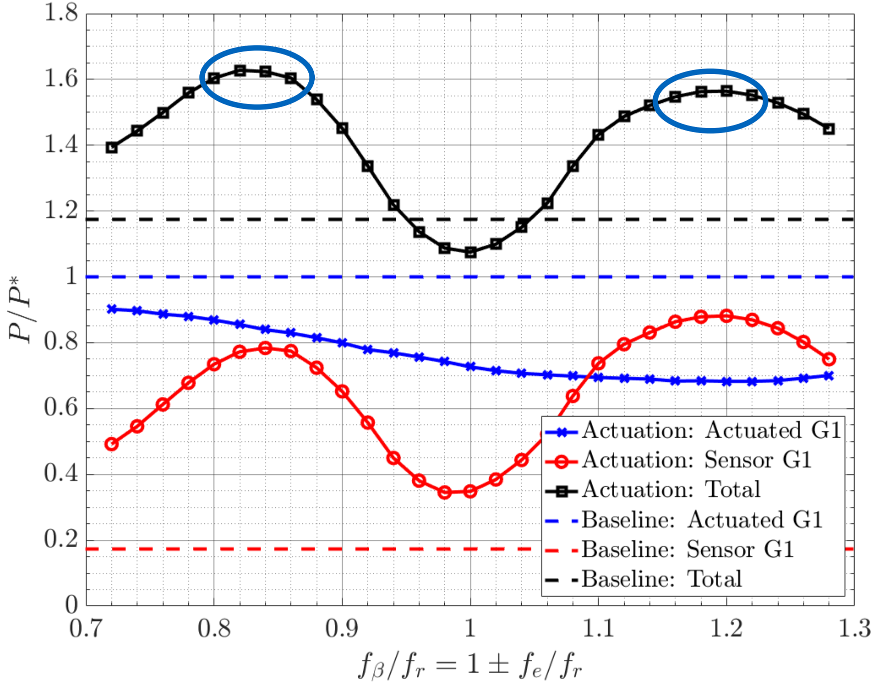
System communication

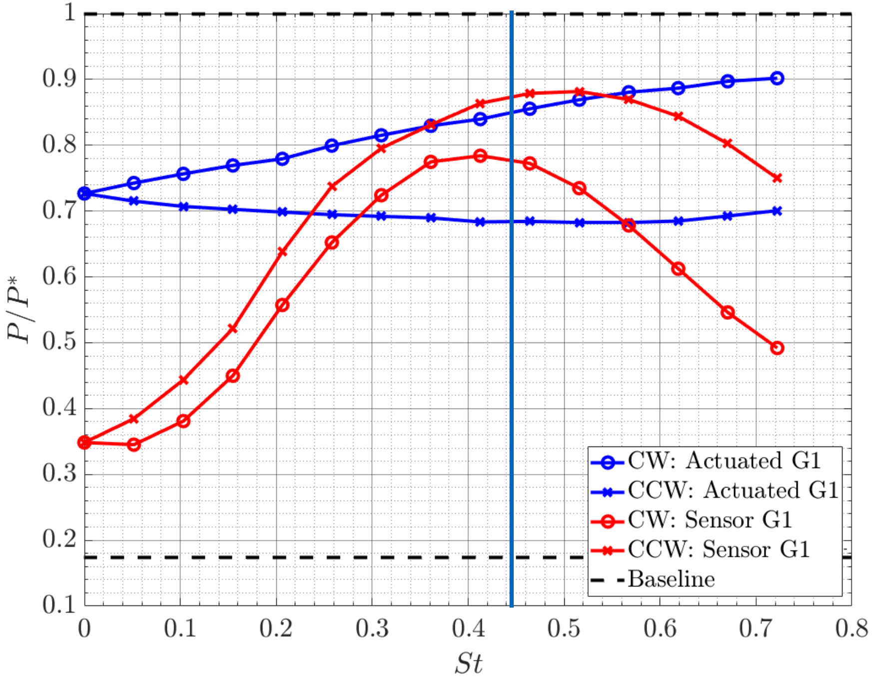




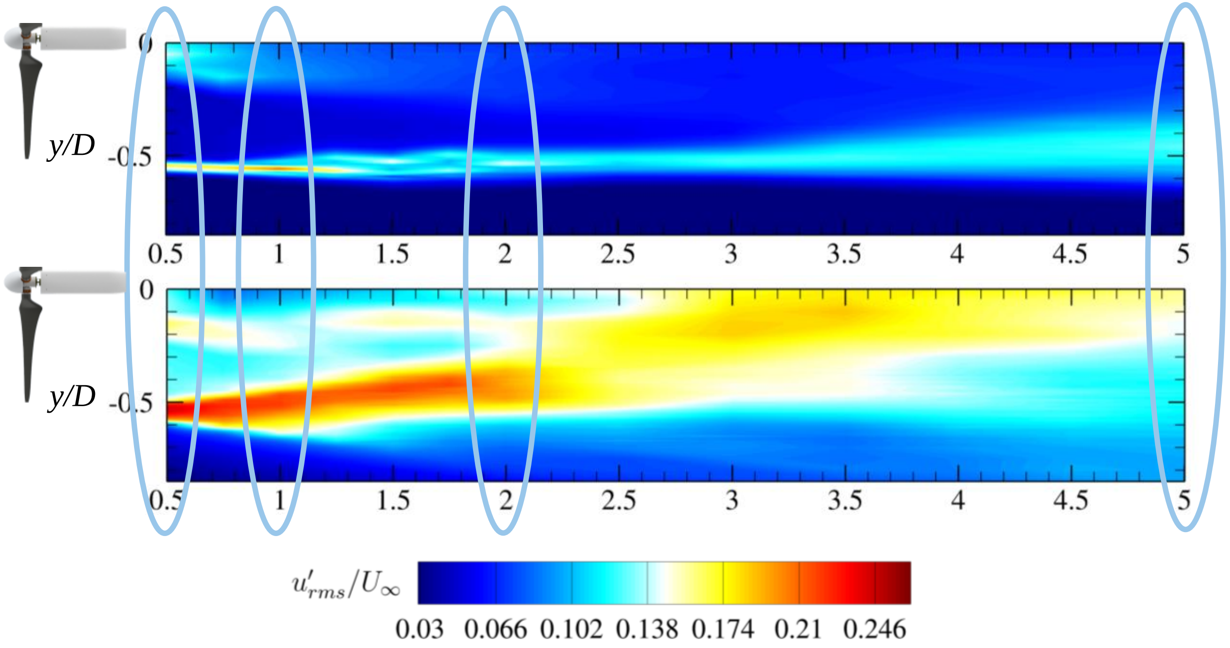


Results: Extracted Power





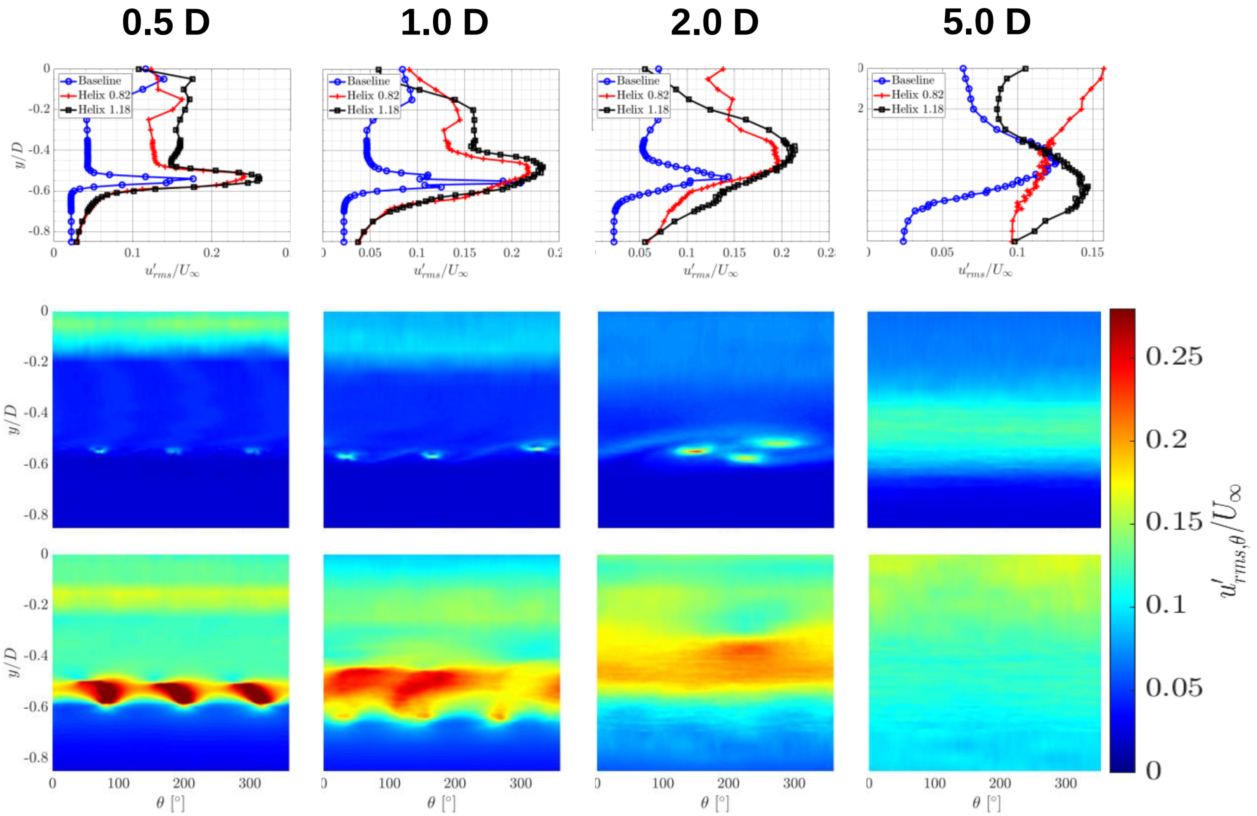
Results: Time-averaged wake u'_{rms}/U_∞



Baseline: $f_\beta/f_r = 0.00$

Helix 0.82: $f_\beta/f_r = 0.82$

Results: phase locked u'_{rms}/U_∞



Time averaged data

Baseline: $f_\beta / f_r = 0.00$

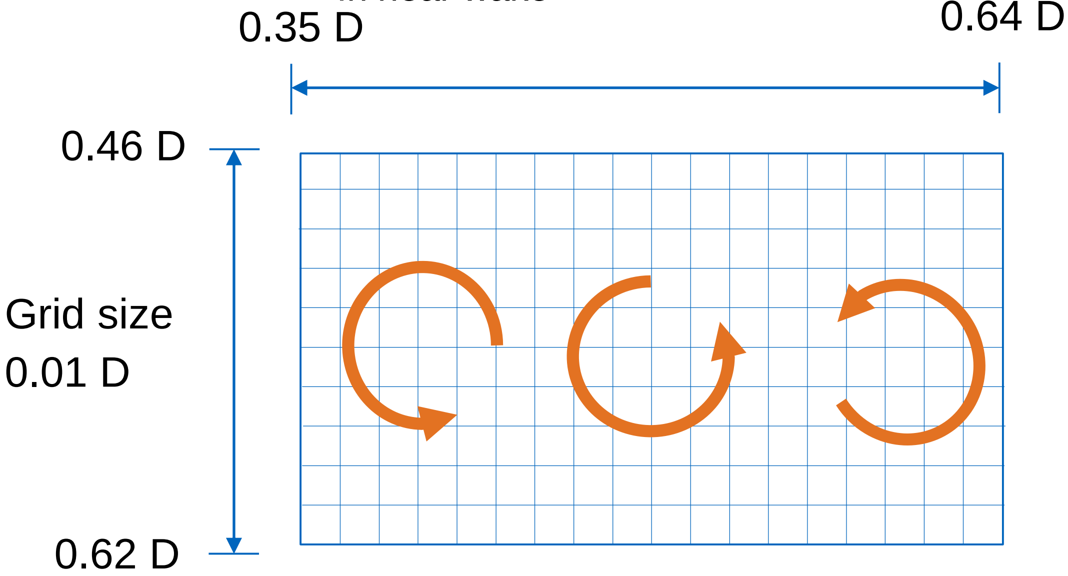
Helix 0.82: $f_\beta / f_r = 0.82$

Tip Vortices

Refinement

Tip vortices

In near wake



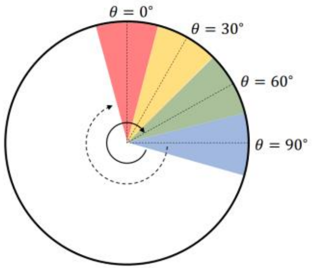
Tip Vortices

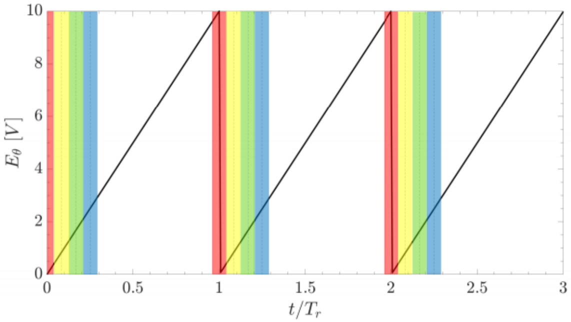
Vorticity

Synchronized
with Azimuth

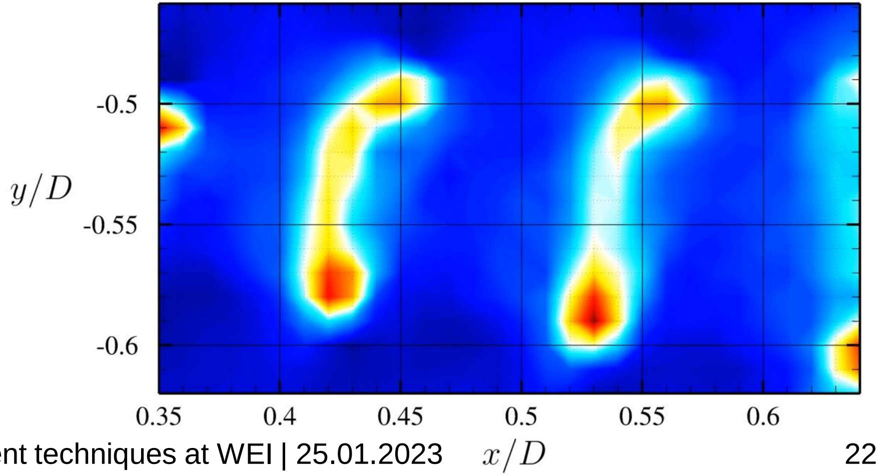
Phase-locking

with the rotational frequency:





Helix 0.82: $f_\beta / f_r = 0.82$



Tip Vortices

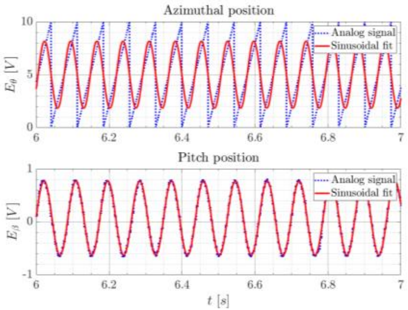
Vorticity

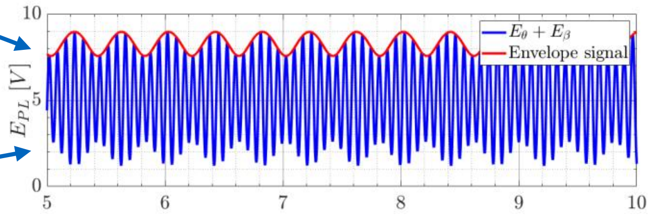
Synchronized with
Envelope frequency

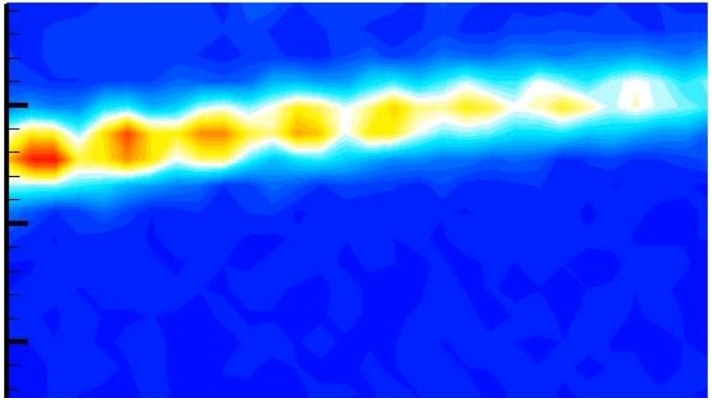
Helix 0.82: $f_\beta / f_r = 0.82$

Phase-locking

beat/envelope frequency:







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Thank you for your attention!