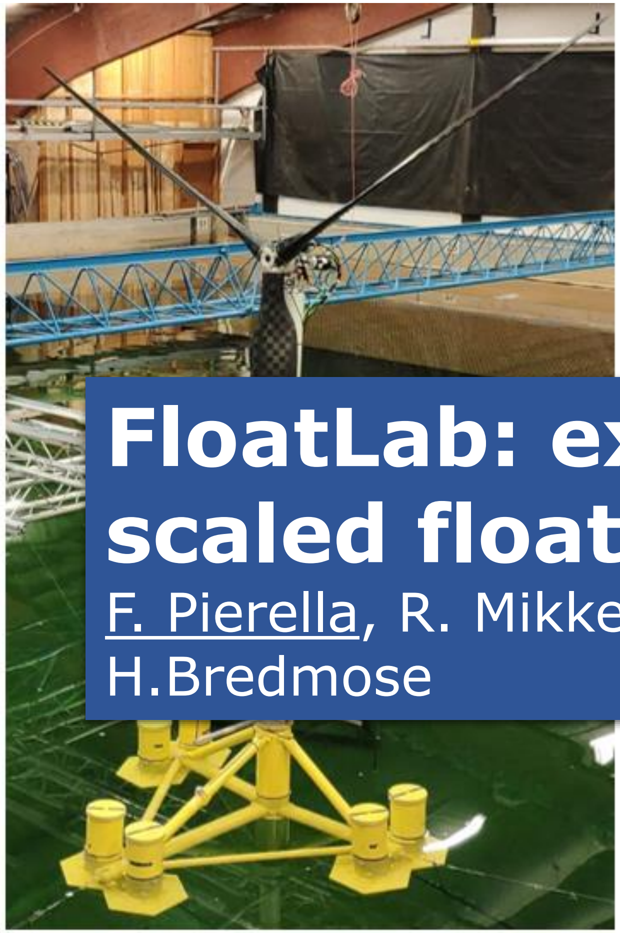
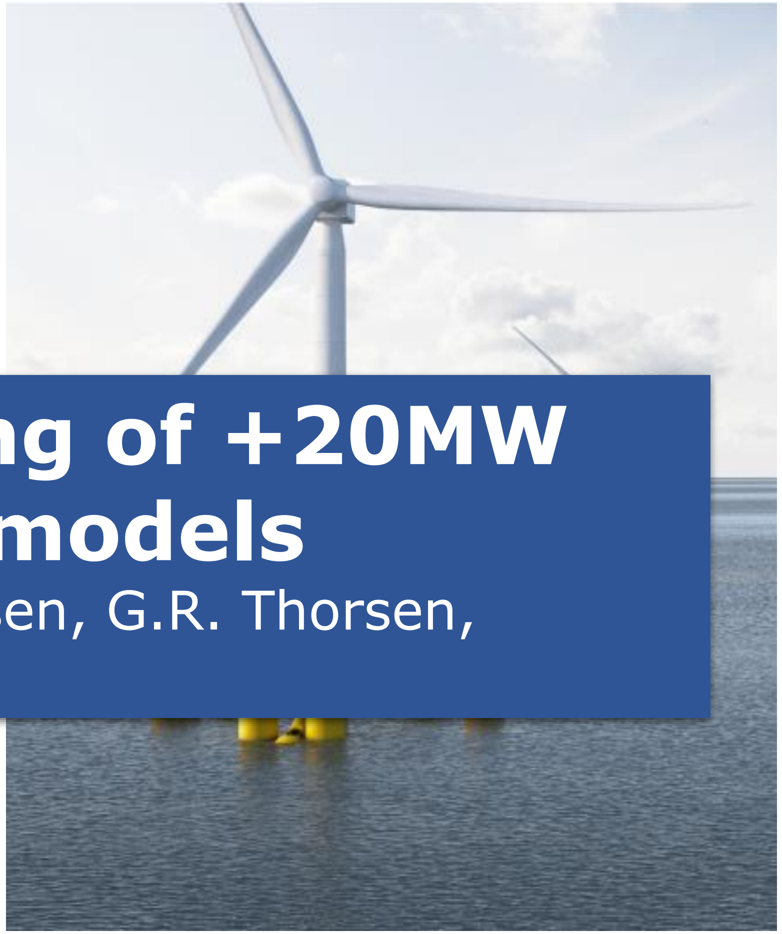
Innovation Fund Denmark





FloatLab: experimental testing of +20MW scaled floating wind turbine models

F. Pierella, R. Mikkelsen, K. Lønbæk, K. Enevoldsen, G.R. Thorsen, H.Bredmose

DTU

DHI

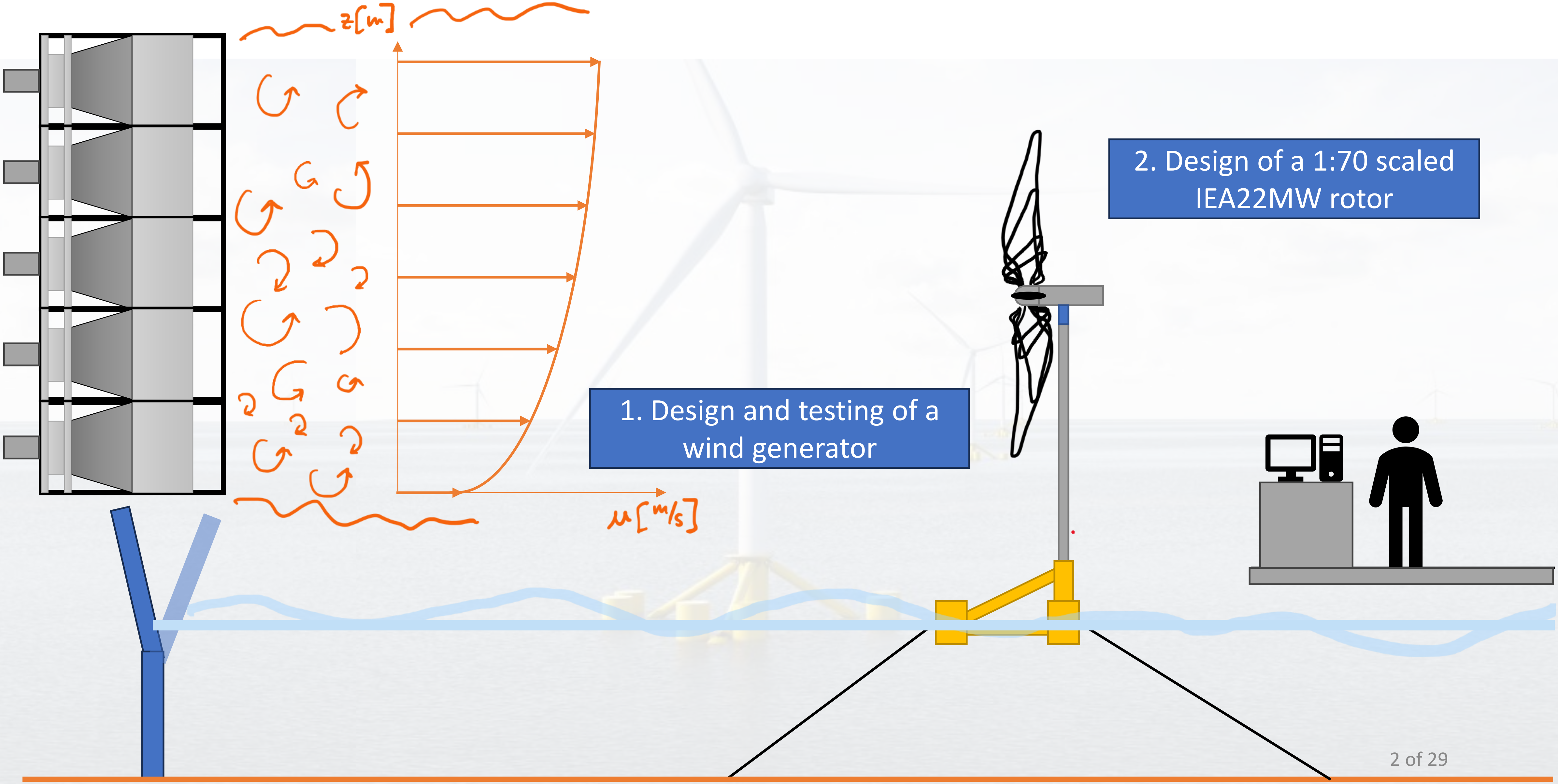
SIEMENS Gamesa RENEWABLE ENERGY

Stiesdal Offshore

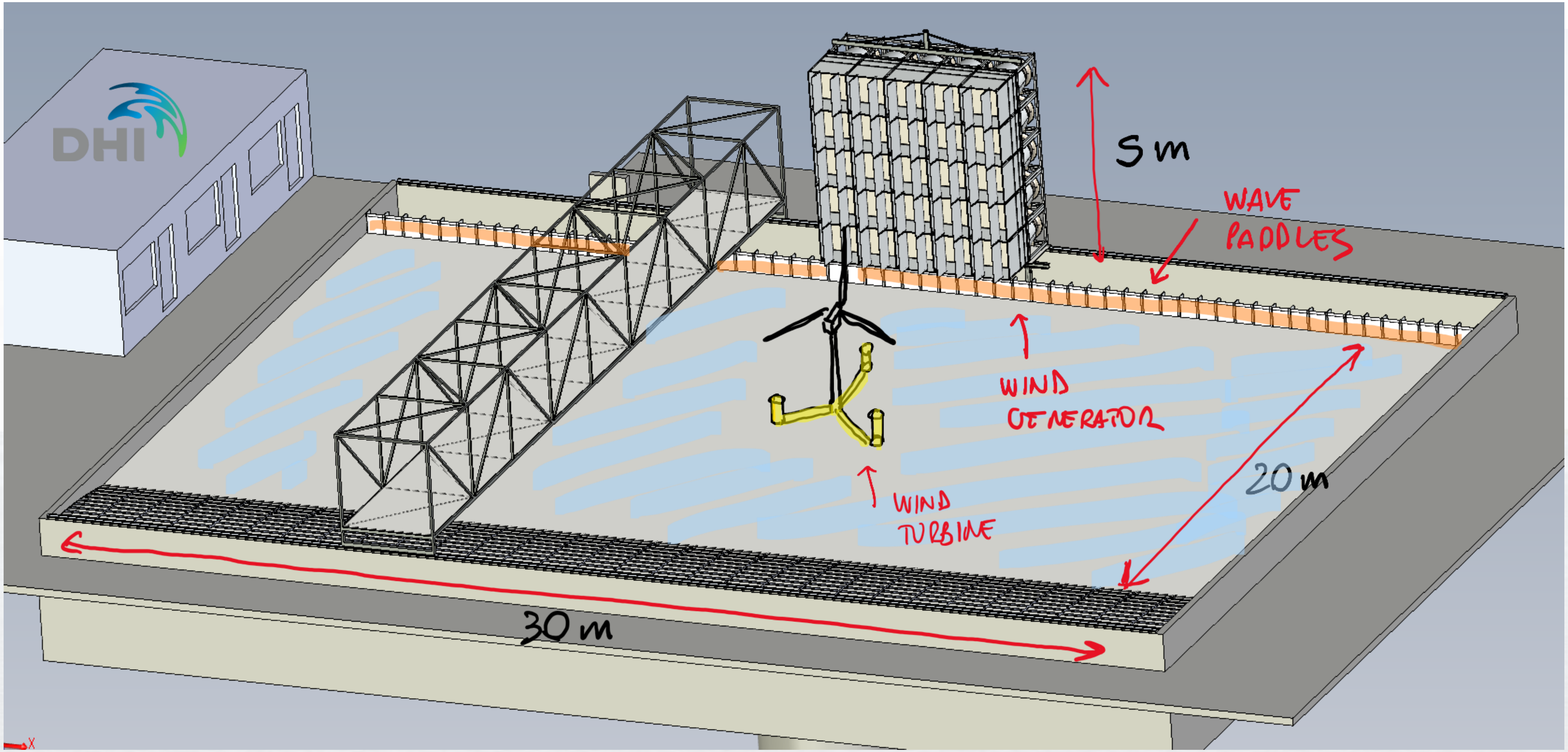
Ørsted

STROMNING

What are you going to see today?



A more realistic view of the experimental setup



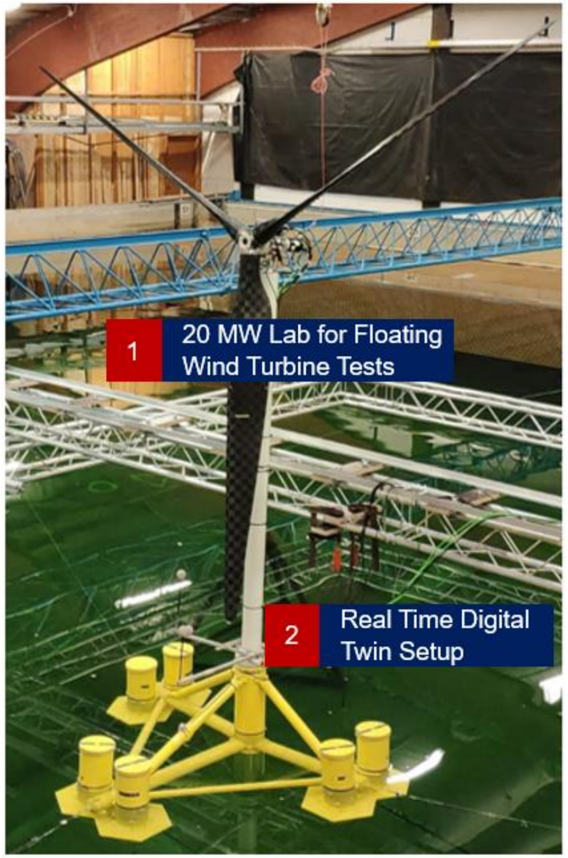
The FloatLab Project

Innovation Fund Denmark

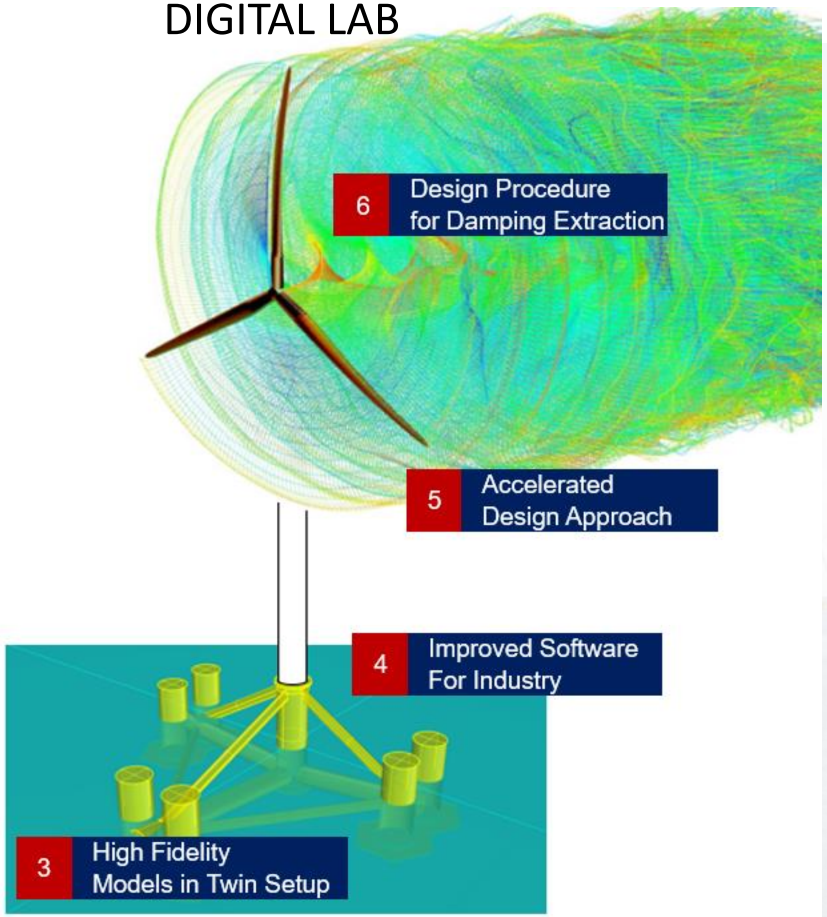
- Danish Innovation Fund
  - 2024-2028
  - Budget 22.3 MDKK (3M€)

- Twinned physical and Digital lab for +20MW floating wind turbine design

PHYSICAL LAB

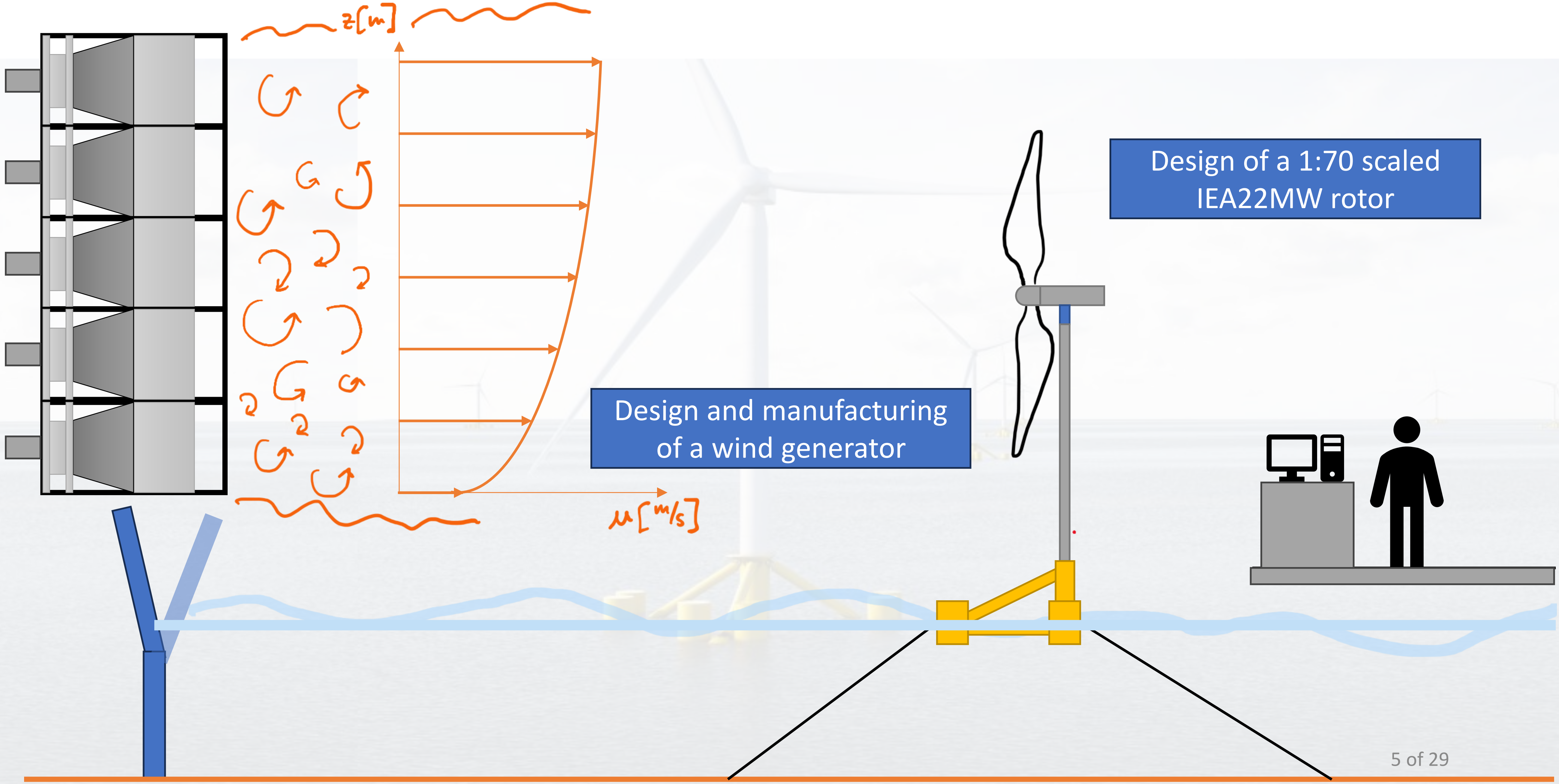


DIGITAL LAB



STROMNING DHI Stiesdal DTU Ørsted SIEMENS Gamesa RENEWABLE ENERGY

Part 1: the wind generator



Design of the wind generator

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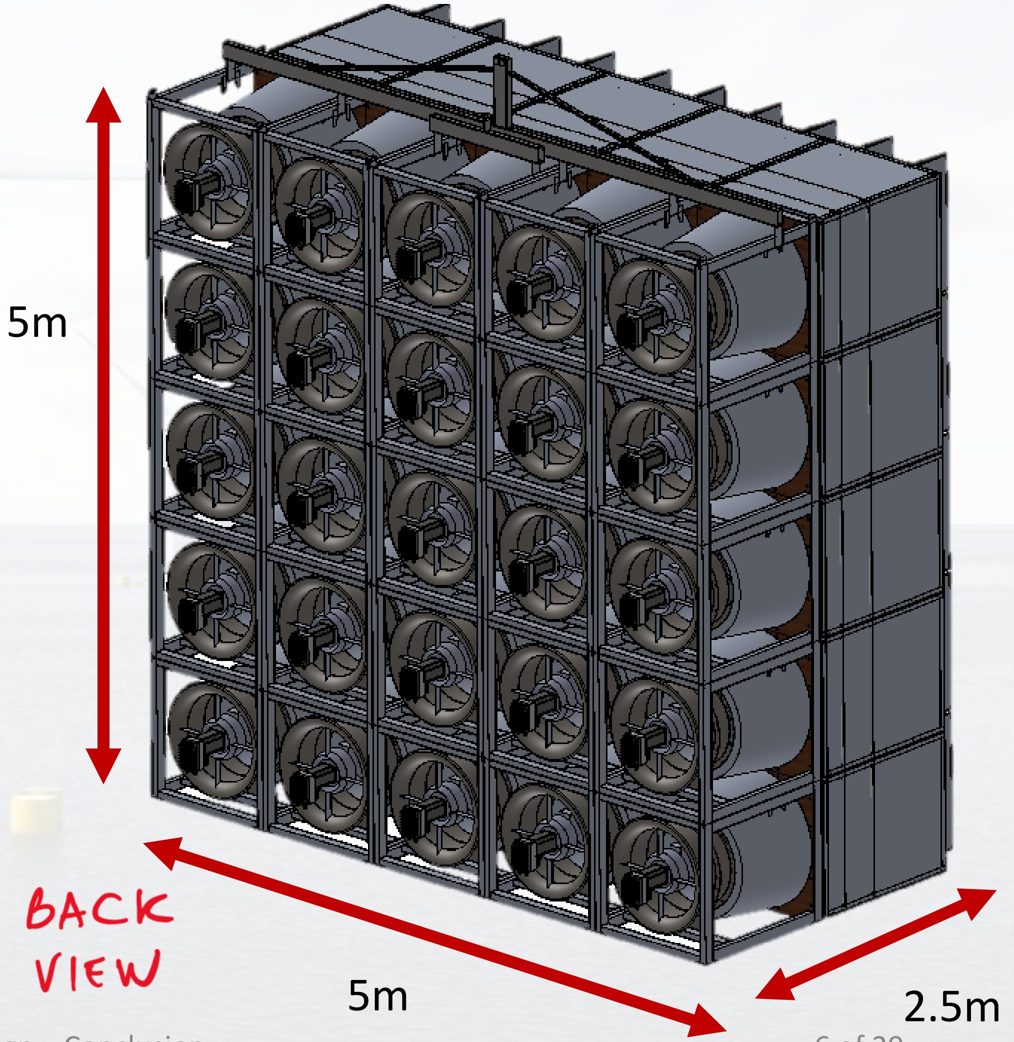
- Specifications
  - Mass≈5t , P≈50 kW @ 5 m/s
  - Max speed 5 m/s
  - Frequency response up to ca. 0.5 Hz

- Complex wind features
  - Shear
  - Turbulent scales of varying size
  - Wind coherence



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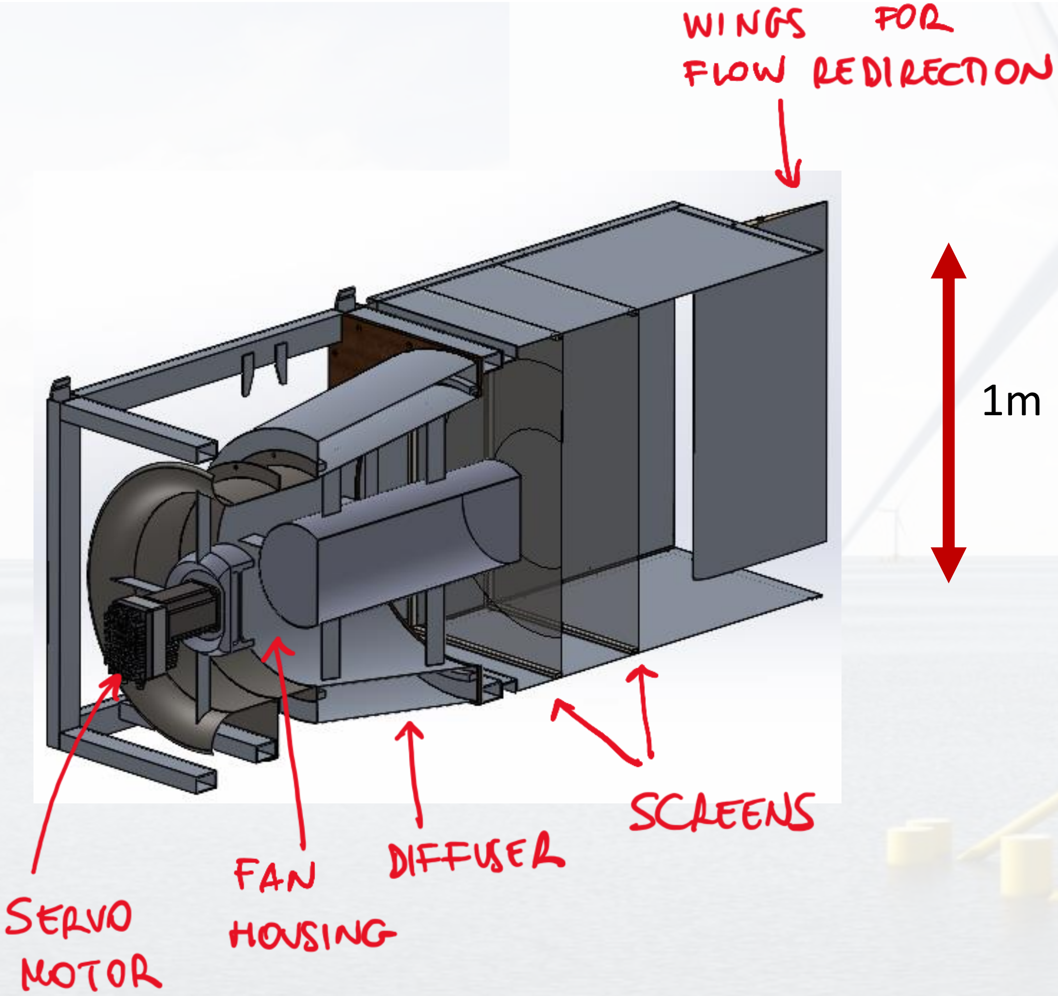
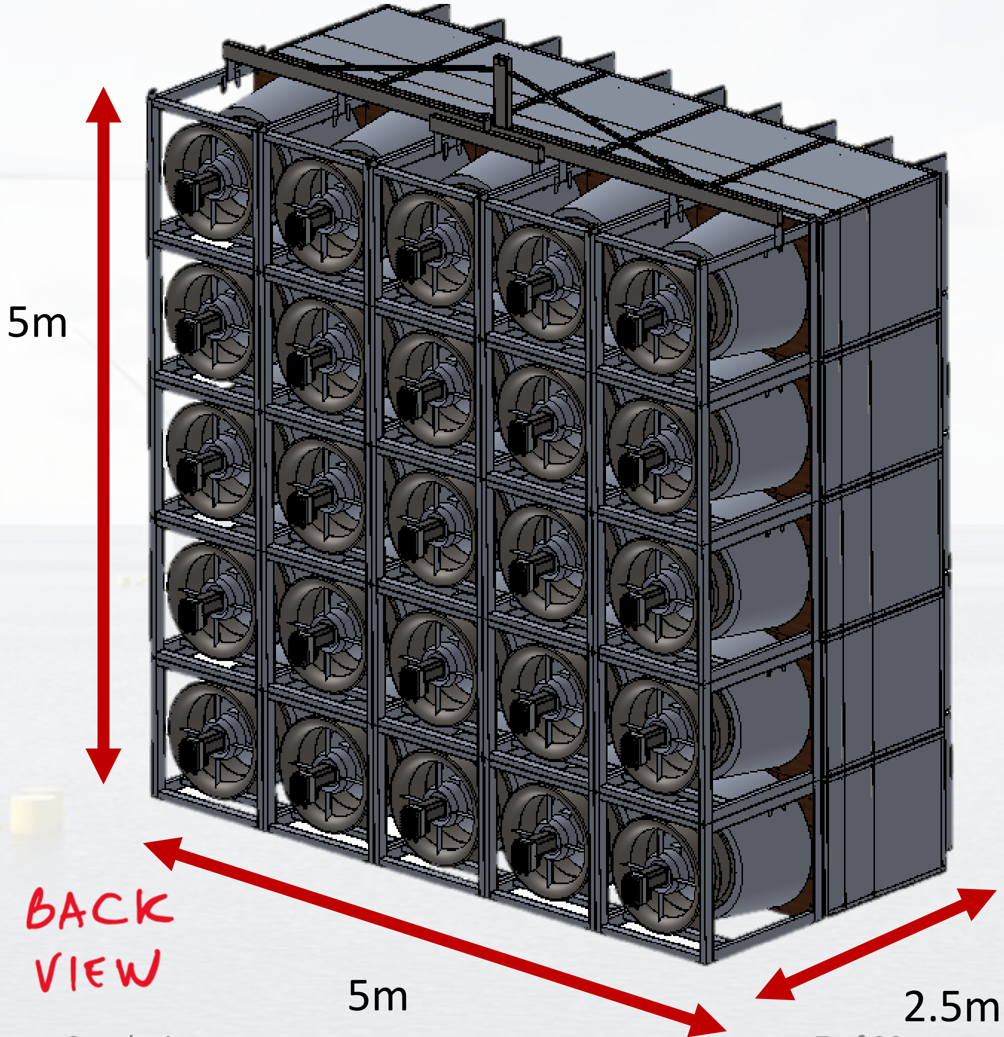
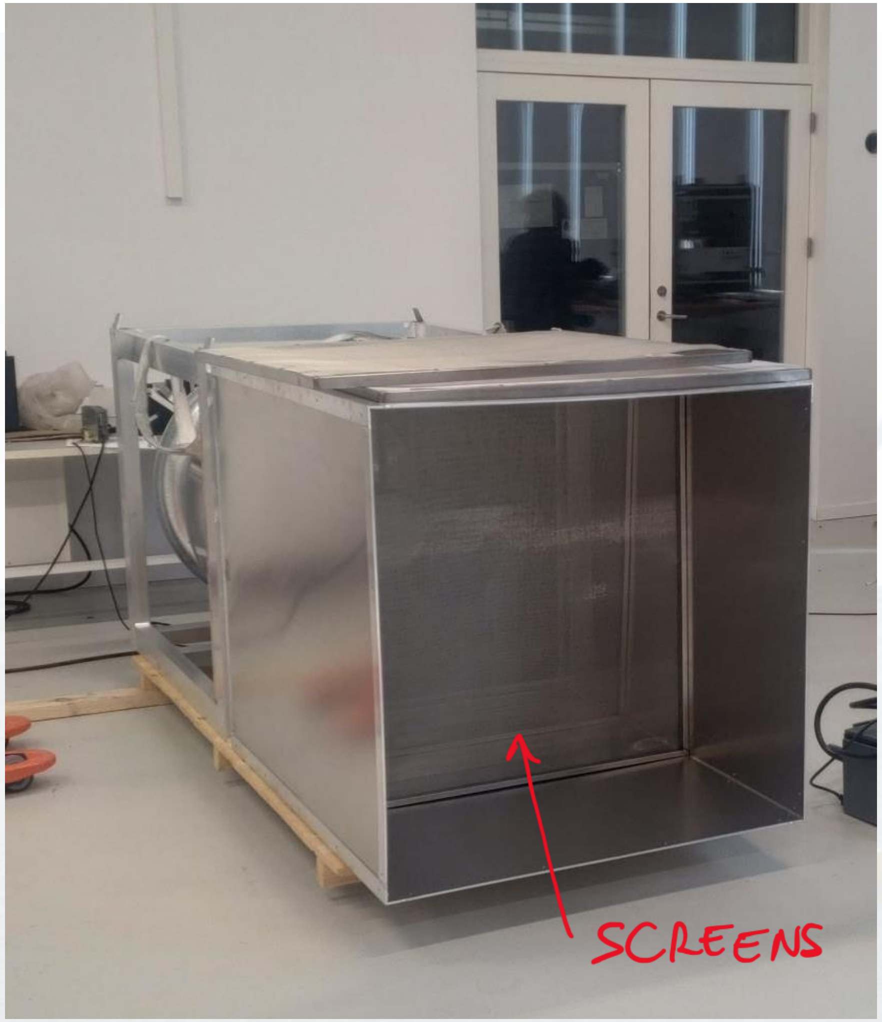
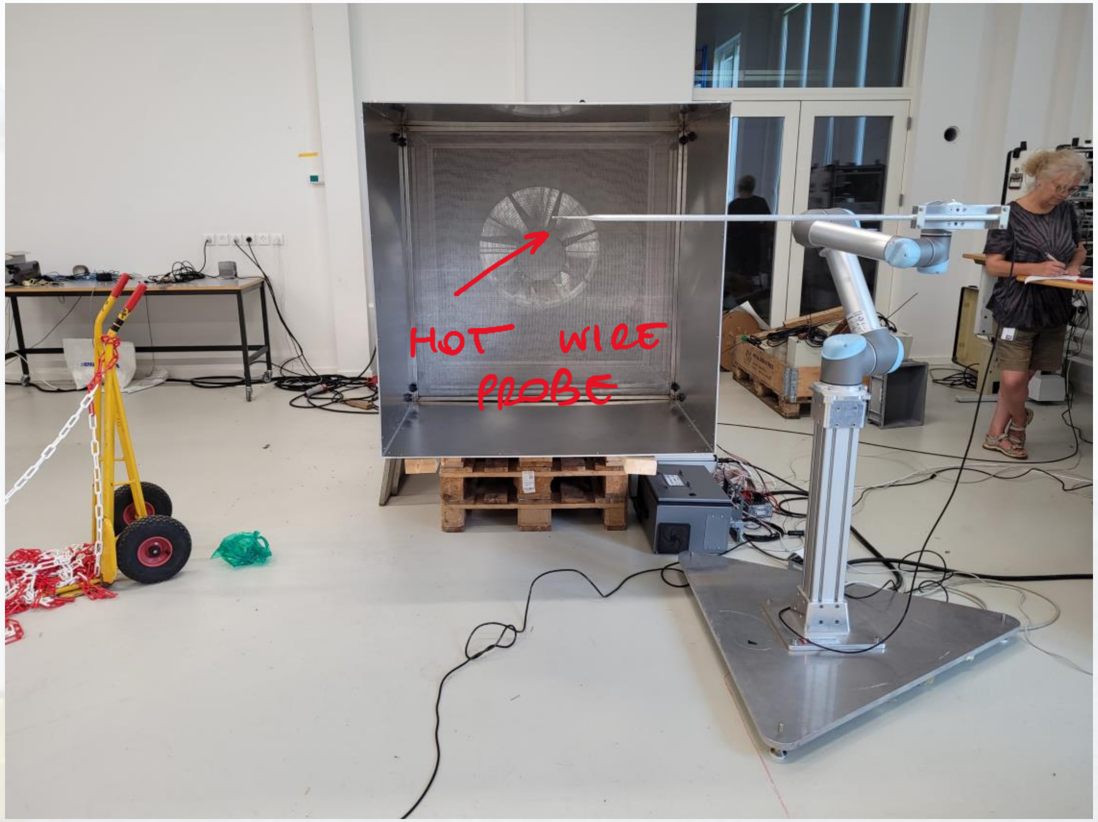
Description of the blower unit



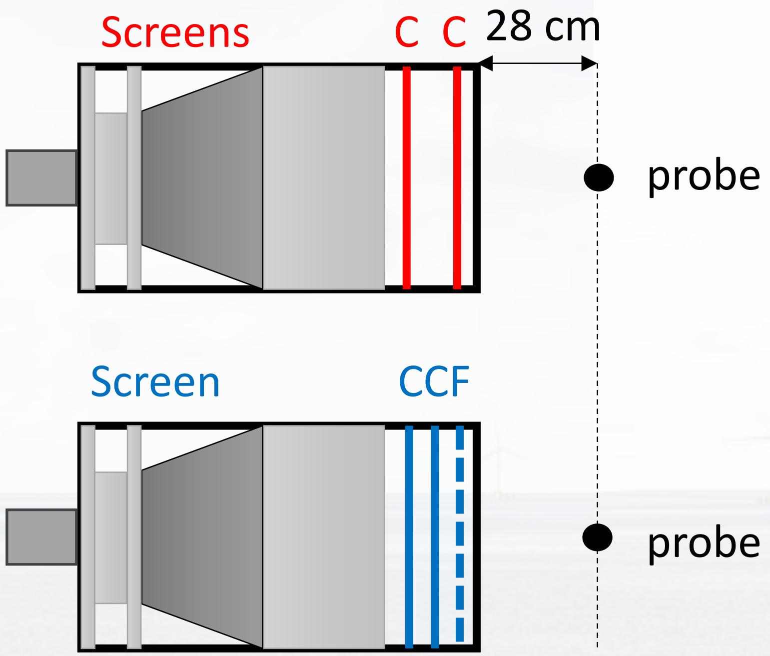


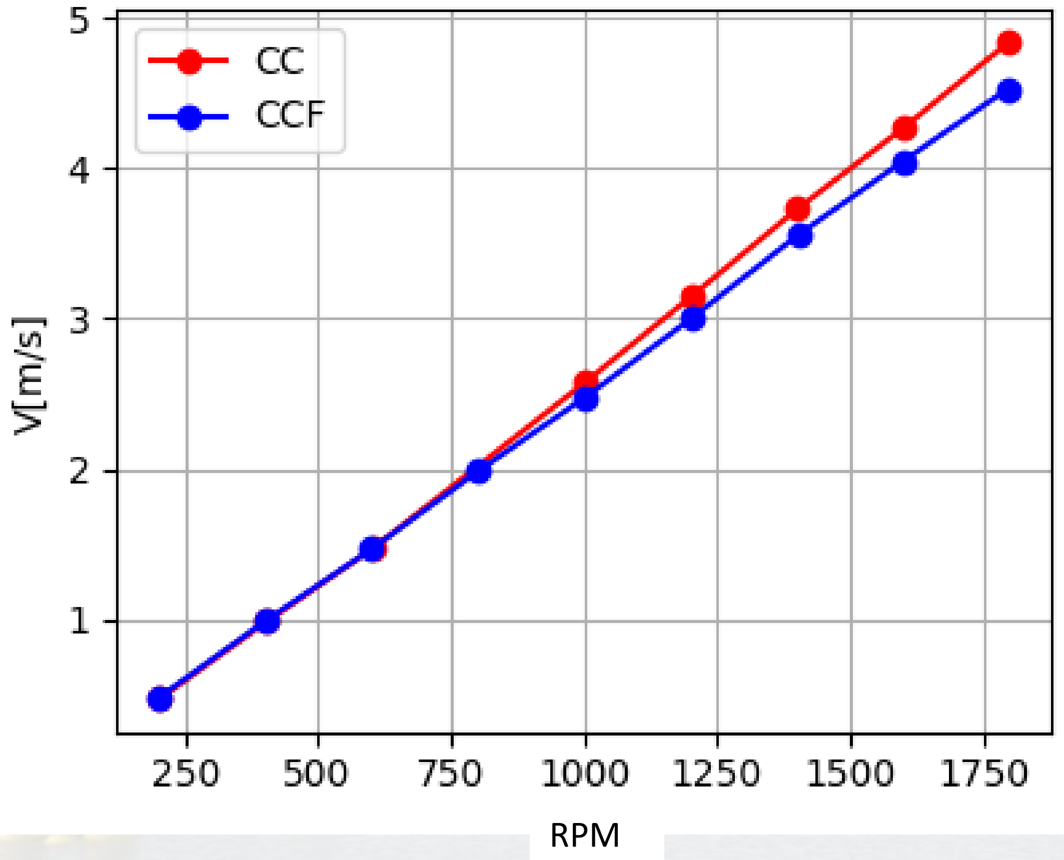
Calibration of the first unit



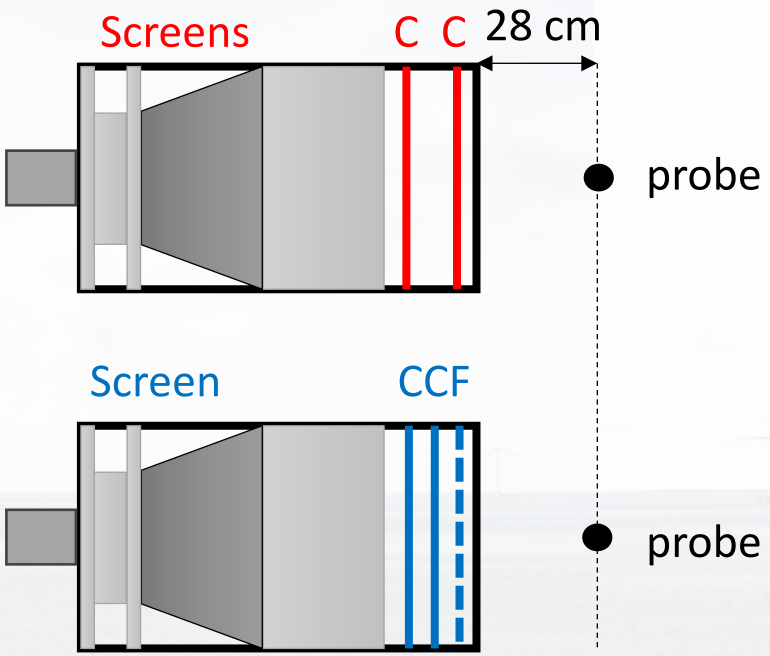


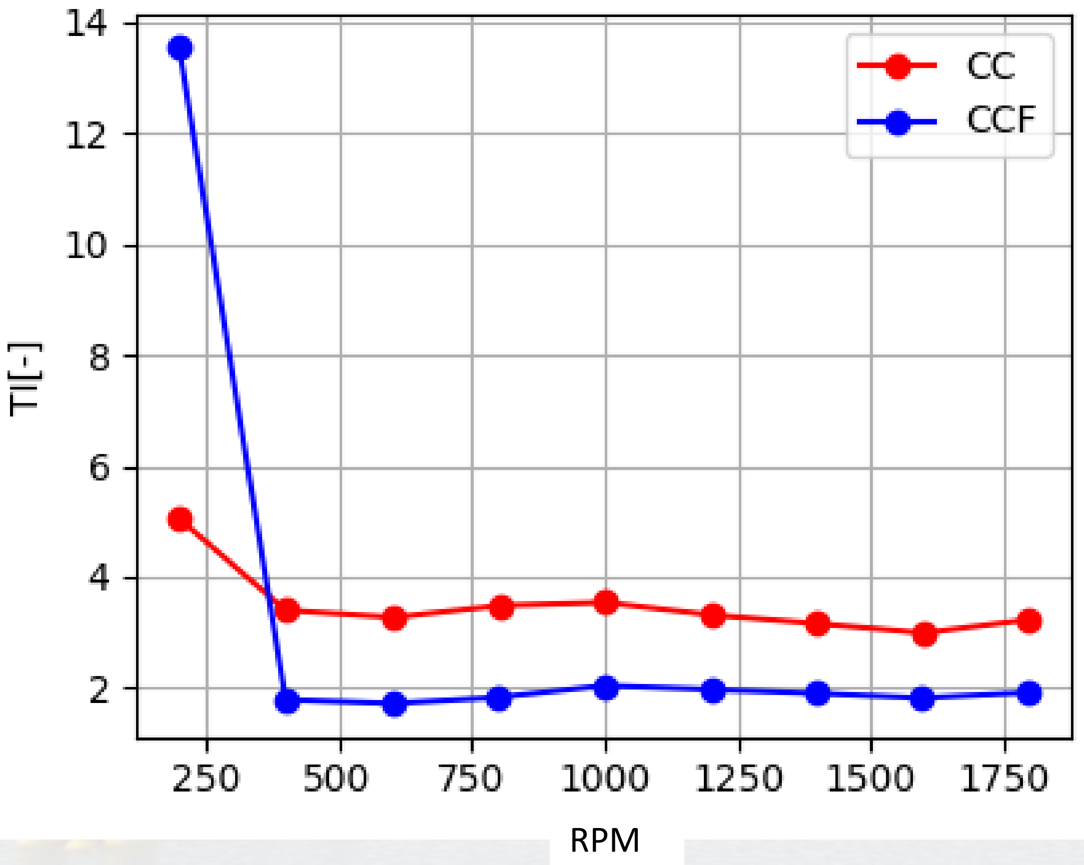
Calibration of the first unit: selection of number of screens



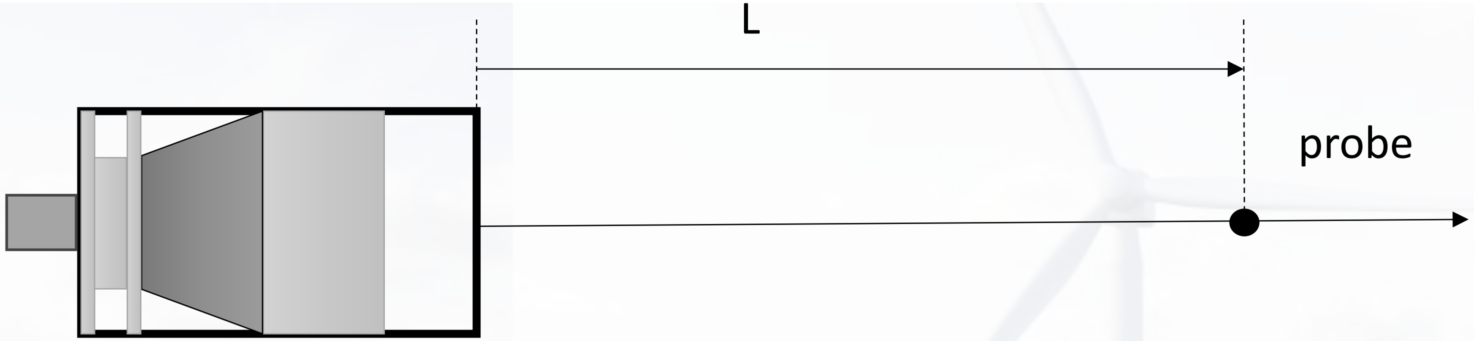


Calibration of the first unit: selection of number of screens



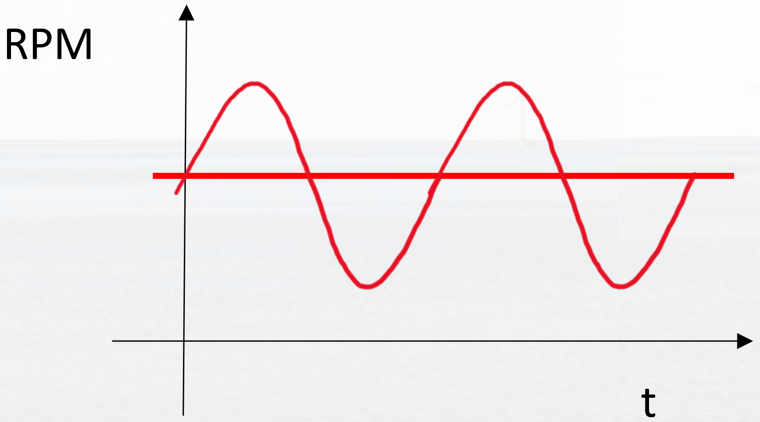


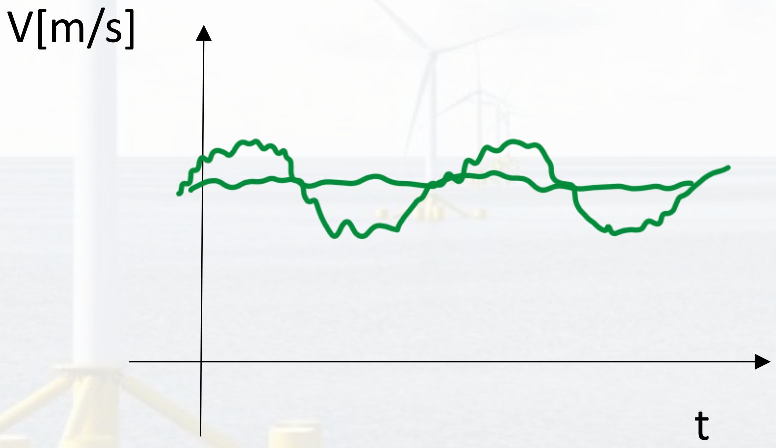
Next task: dynamic calibration



$$\hat{V}(\omega) = \boxed{\hat{H}(\omega)} \cdot \hat{RPM}(\omega)$$

TRANSFER FUNCTION





$$RPM = RPM_0 + RPM_A \sin(\omega t)$$

$$V_1 = K_1 RPM_0 + K_2(\omega) RPM_A \sin((\omega t) + \phi(\omega))$$

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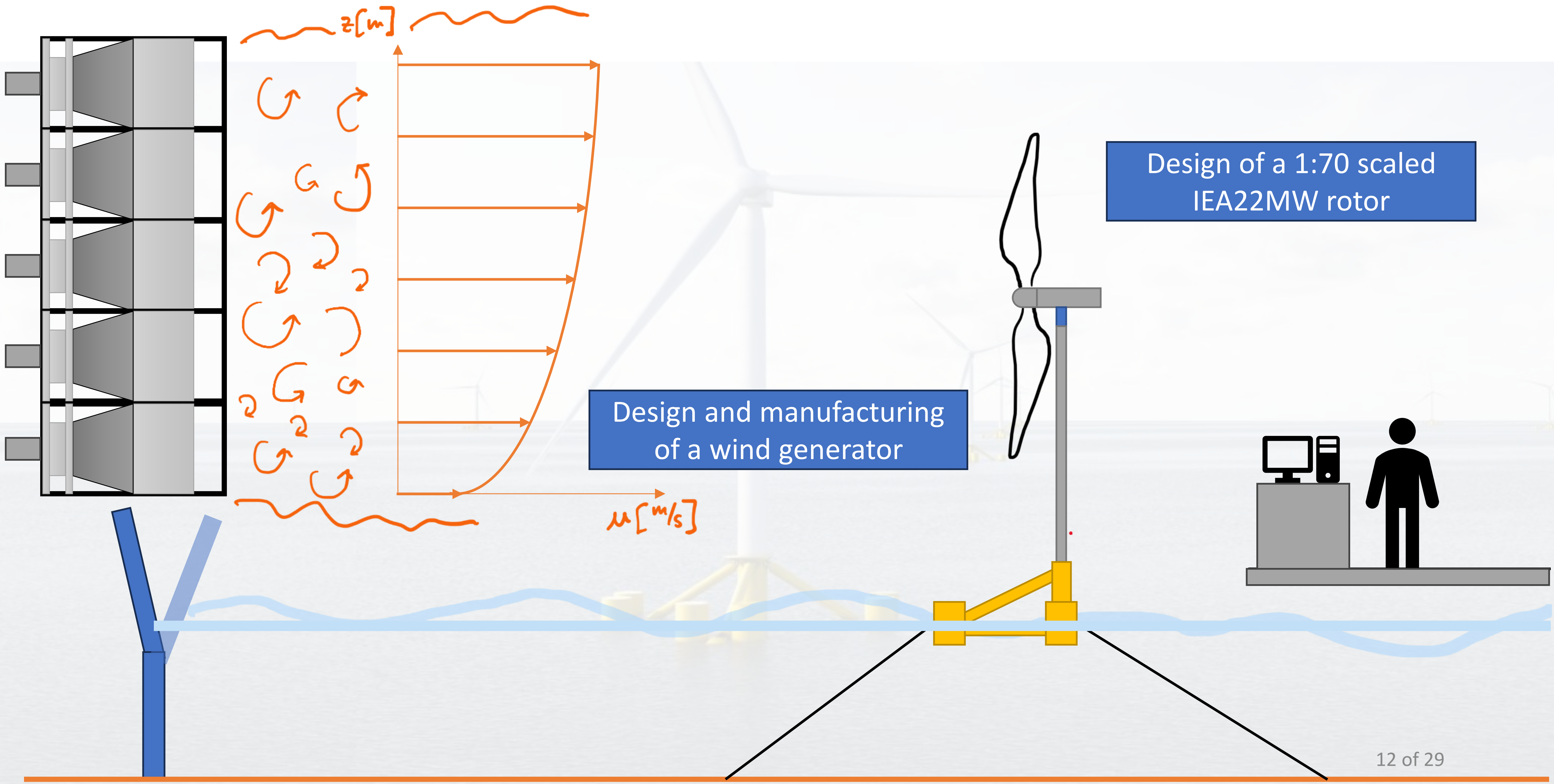
Part 2: the rotor design

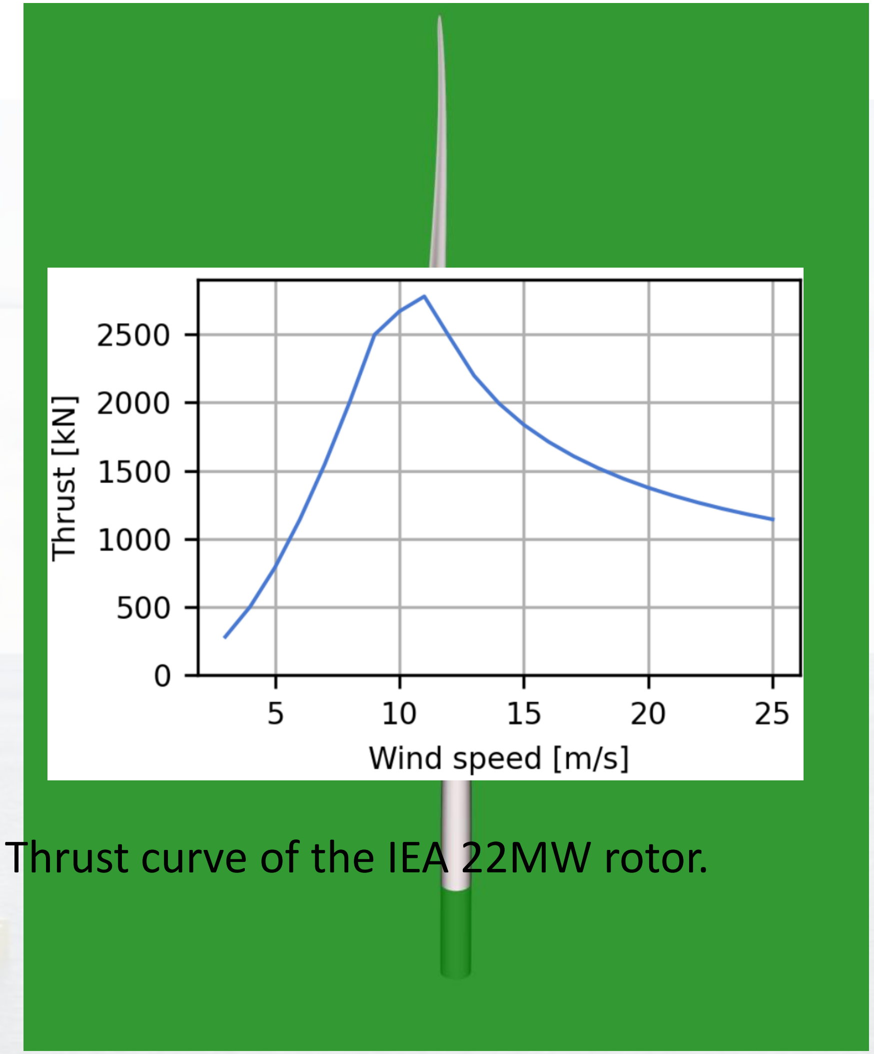


The IEA 22MW reference wind turbine

- D = 284 m
- Design tip speed ratio 9.153
- RNA mass ca. 1215 t

- Rated wind speed 11 m/s
- Rated thrust ca. 2.793 MN

- Airfoil FFA-W3 series
- Rotor Re number ca. 10M



Thrust curve of the IEA 22MW rotor.

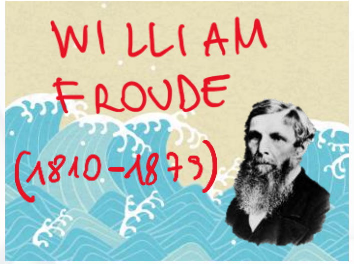
HAWC2 visualization of the IEA 22MW rotor.

Froude vs. Reynolds scaling

- D = 284 m, three bladed
- Design tip speed ratio 9.153
- RNA mass ca. 1215 t

- Rated wind speed 11 m/s
- Rated thrust ca. 2.793 MN

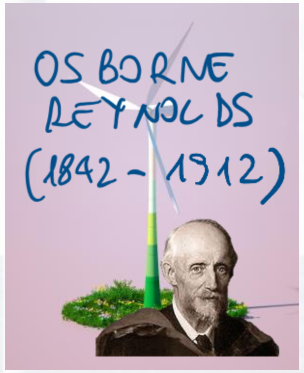
- Airfoil FFA-W3 series
- Rotor Re number ca. 10M



$$Fr = \frac{u}{\sqrt{gL}}$$

INERTIA (u)

WEIGHT ($\sqrt{gL}$)



$$Re = \frac{uL}{\nu}$$

INERTIA (uL)

VISCOUS (ν)

$$\lambda = \frac{L_{FS}}{L_{MS}} = 70$$

$$Fr_{MS} = Fr_{FS}$$

$$Re_{MS} = Re_{FS} \cdot \frac{1}{\lambda^{3/2}} \approx \frac{1}{600}$$

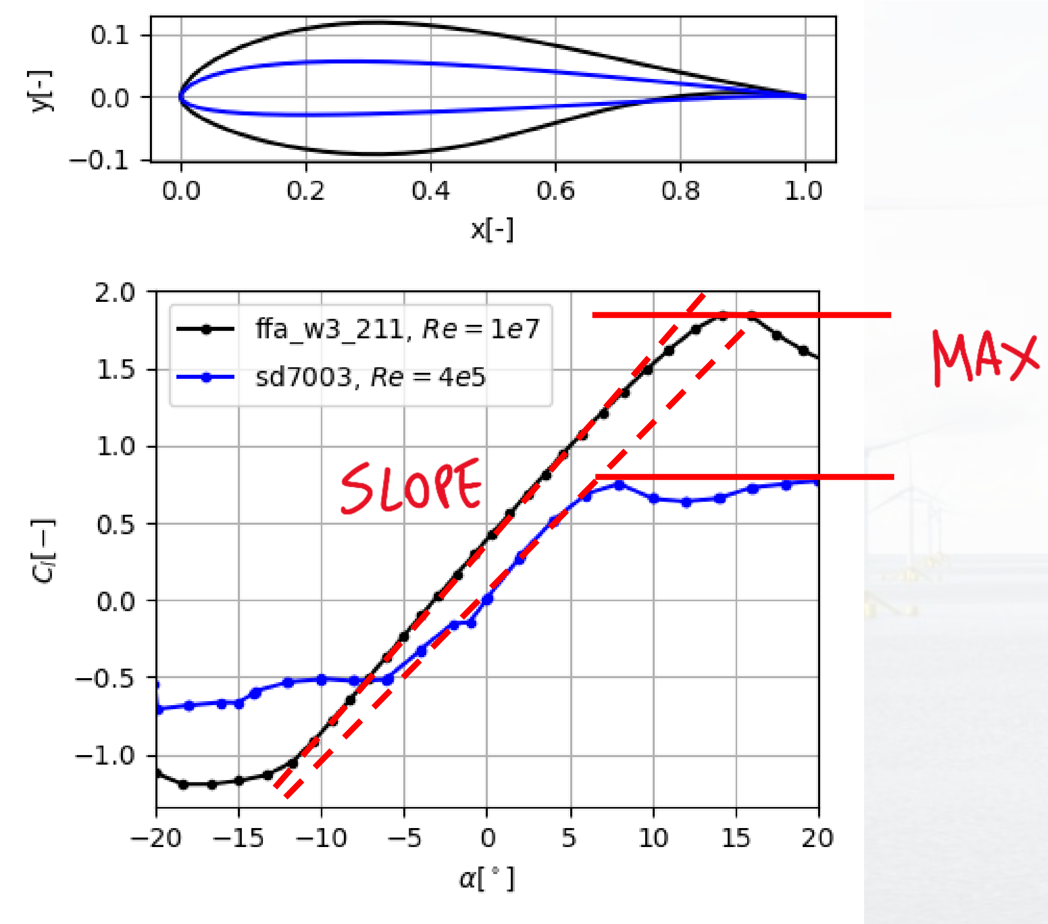
Choosing Froude scaling over Reynolds…

- D = 284 m, three bladed
- Design tip speed ratio 9.153
- RNA mass ca. 1215 t
- Rated wind speed 11 m/s
- Rated thrust ca. 2.793 MN
- Airfoil FFA-W3 series
- Rotor Re number ca. 10M

- D = 4.06 m, three bladed
- Design tip speed ratio 9.153
- RNA mass ca. 3.46 kg
- Rated wind speed 1.3 m/s
- Rated thrust ca. 7.5 N
- Airfoil low-speed SD7003 (8.5% rt)
- Rotor Re number ca. 20k

HUGE IMPACT ON AIRFOIL PERFORMANCE

Lift coefficient for FFA-W2-221 vs. SD7003



Matching the mean aerodynamic thrust

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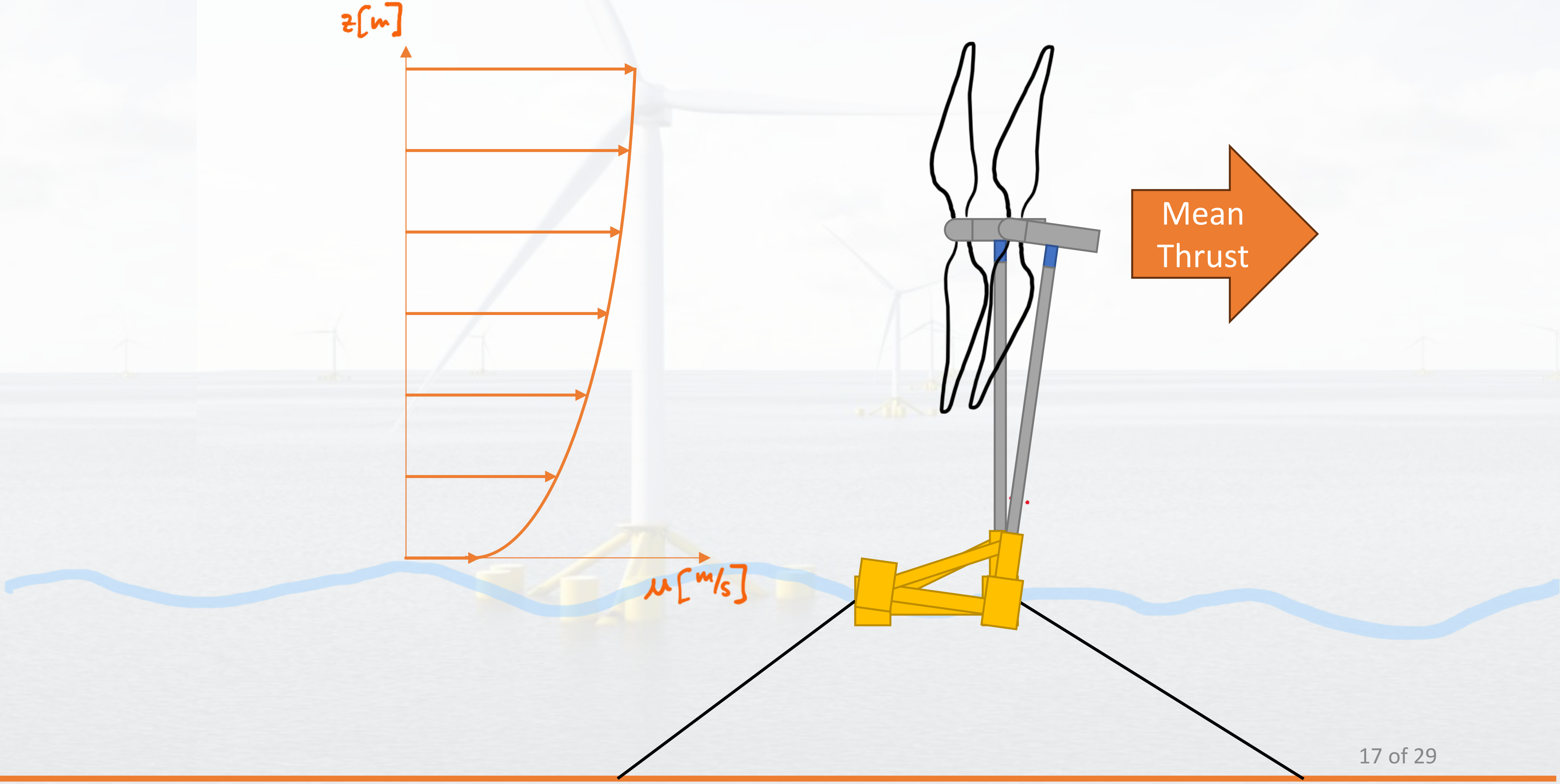
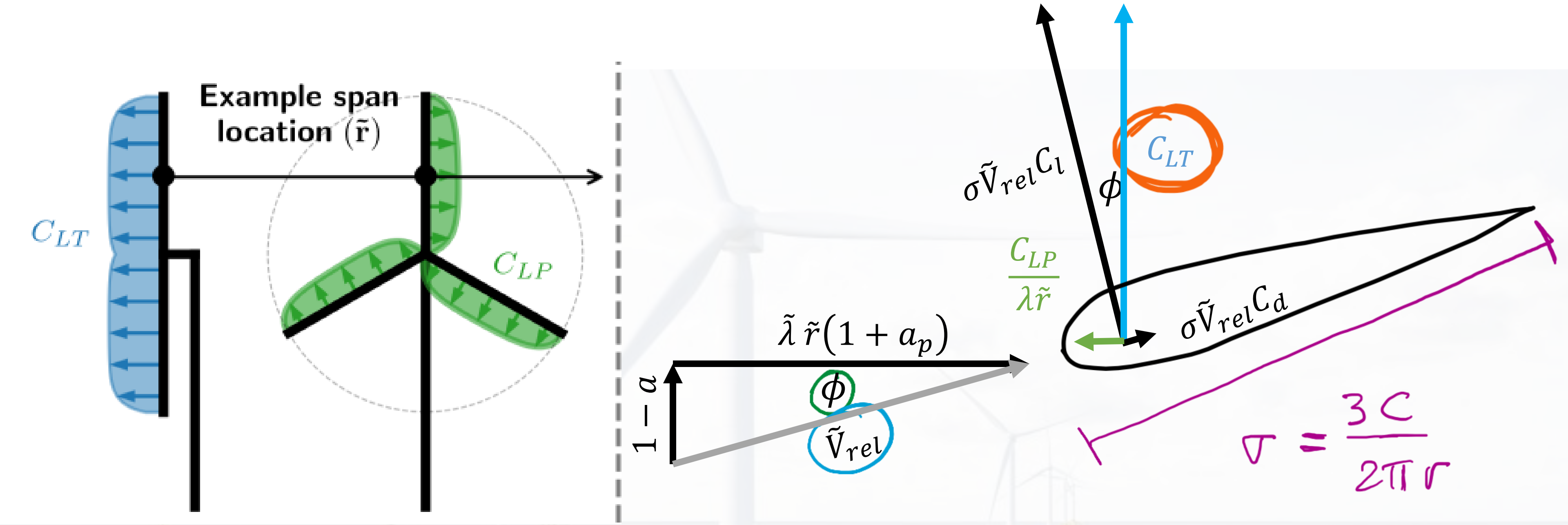


Matching the mean thrust

Innovation Fund Denmark



IEA 22 MW

$$C_{LT} = \sigma \tilde{V}_{rel}^2 \cos\phi \,(C_l + C_d \tan\phi)$$

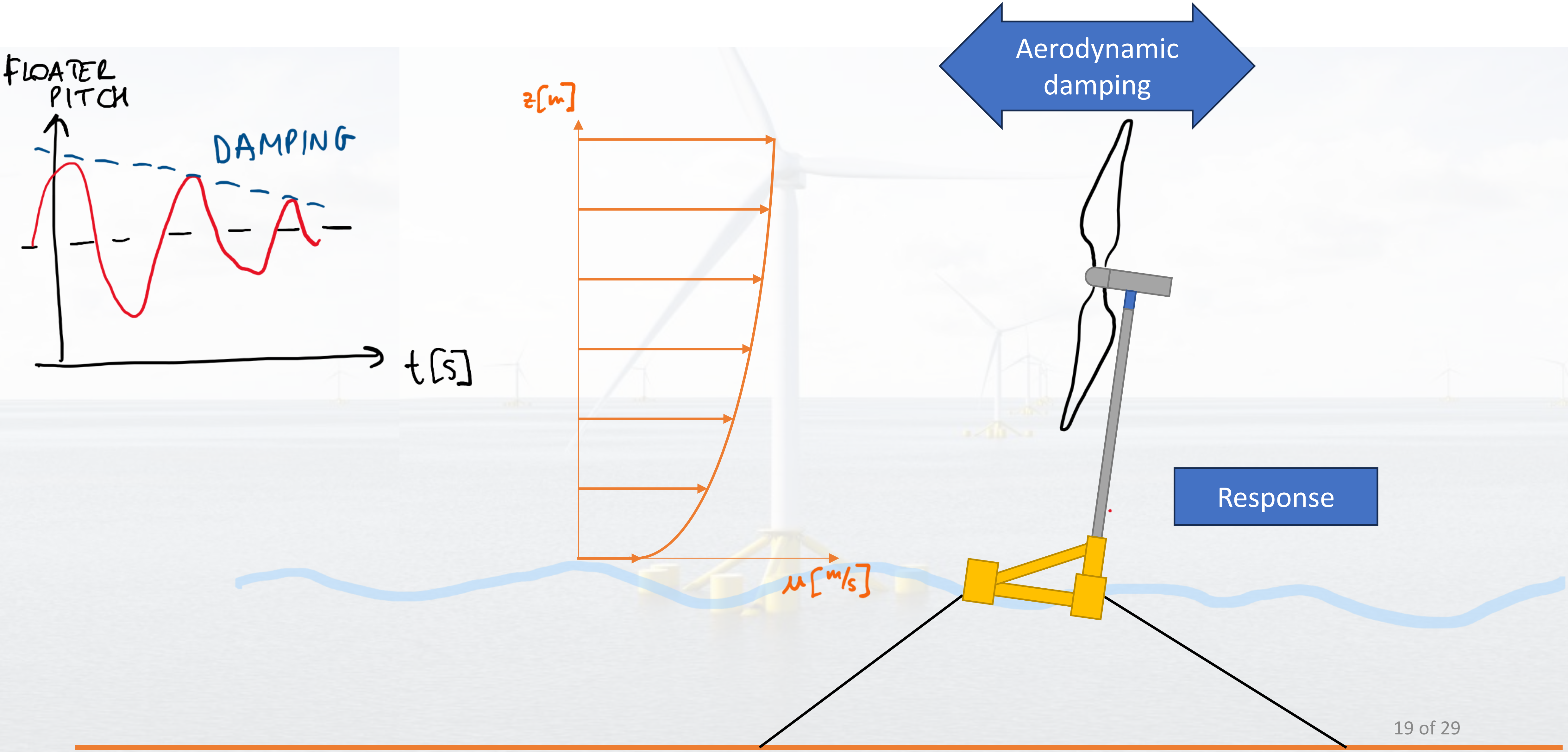
SCALED 1:70

DESIGN CHOICE ↗ | = | LOWER REYNOLDS NR. ↘ | ≈ 0

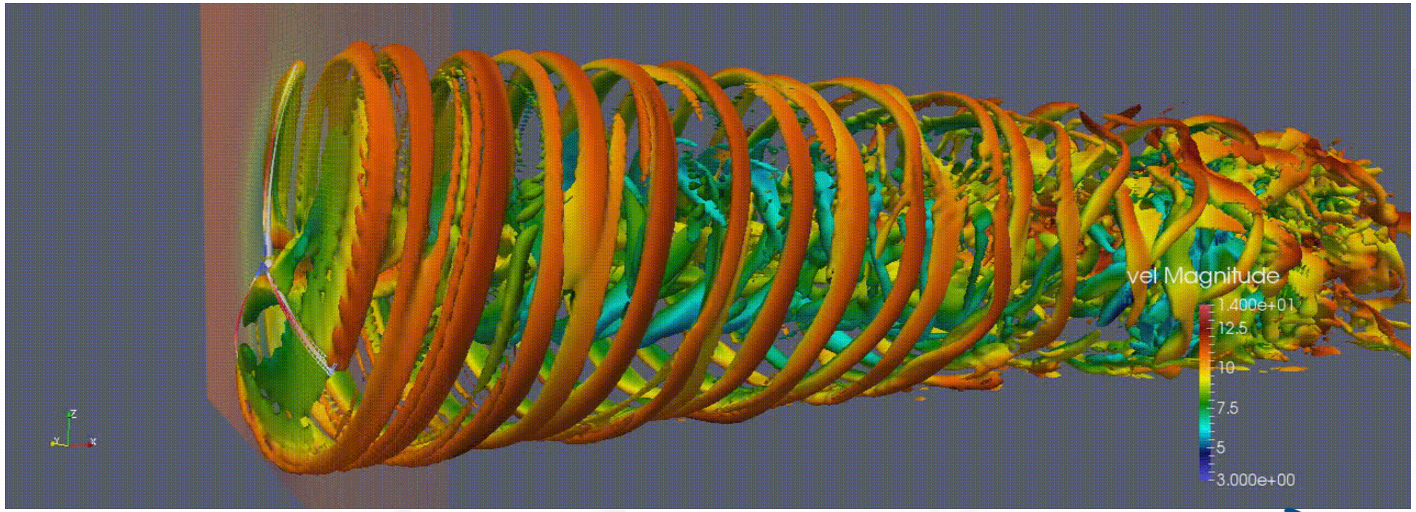
✅ Increase the chord to match the mean thrust

Lønbæk, Kenneth. "Preliminary Wind Turbine Rotor Design: Semi-Analytical aero-elastic wind turbine rotor design optimization." PhD thesis. (2020).

Matching the aerodynamic damping



Key assumption: frozen wake



AERODYNAMIC DAMPING ⇒ $\dfrac{\Delta \text{ THRUST}}{\Delta \text{ VELOCITY DUE TO MOTION}}$

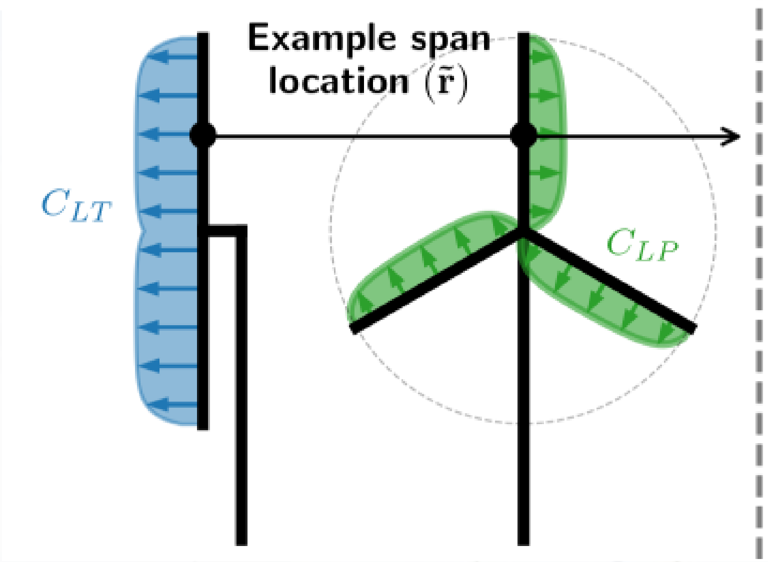
IF $\tau_{\text{MOTION}} \ll \tau_{\text{WAKE FLOW}}$

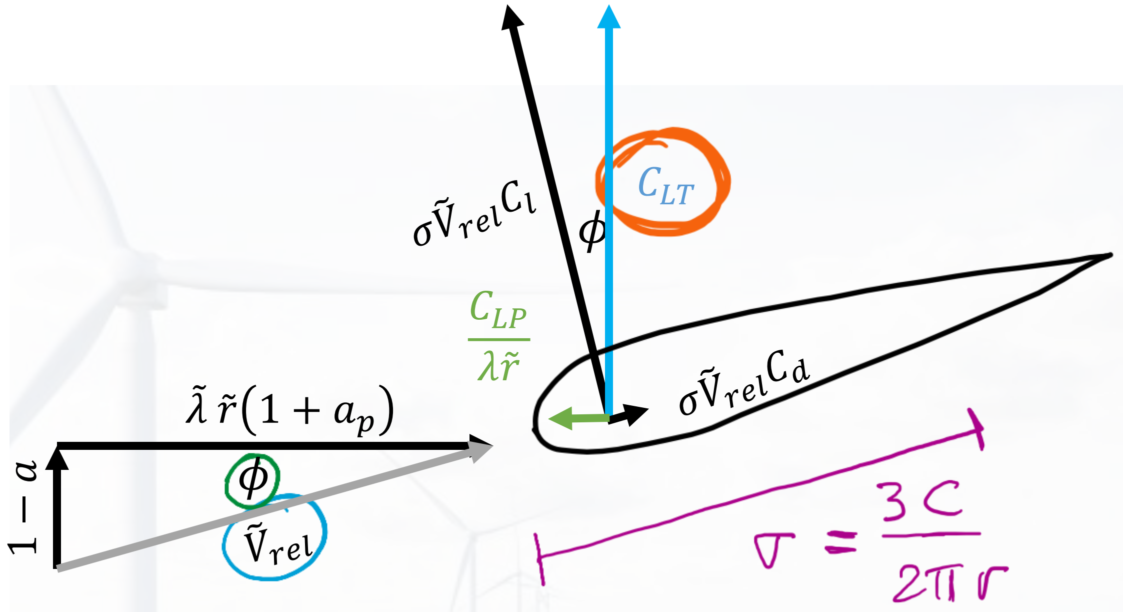
THEN ROTOR INDUCTION (a, a') IS CONSTANT (FROZEN WAKE)

HENCE AERODYNAMIC DAMPING $\propto$ $\dfrac{\Delta \text{THRUST}}{\Delta \text{ BLADE PITCH.}}$ OUR DESIGN OBJECTIVE

Ramos-García, N., Kontos, S., Pegalajar-Jurado, A., González Horcas, S., & Bredmose, H. (2022). *Wind Energy*, *25*(3), 468-504. https://doi.org/10.1002/we.2682

Matching the aerodynamic damping



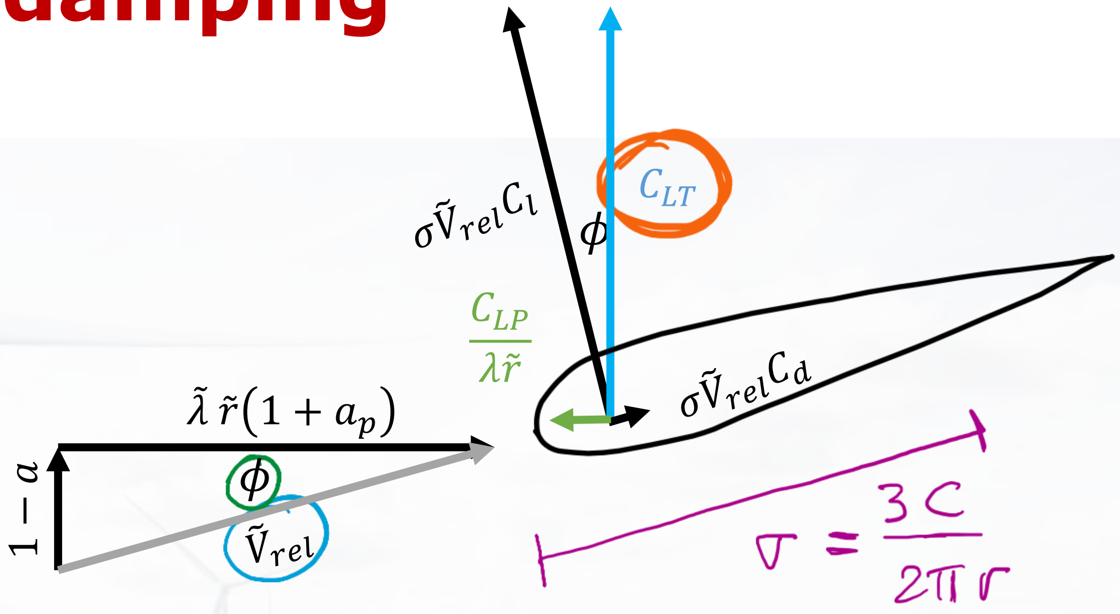


$$C_{LT} = \sigma \tilde{V}_{rel}^2 \cos\phi (C_l + C_d \tan\phi)$$

Matching the aerodynamic damping

Innovation Fund Denmark

$$C_{LT} = \sigma \tilde{V}_{rel}^2 \cos\phi (C_l + C_d \tan\phi)$$



ALREADY MATCHED

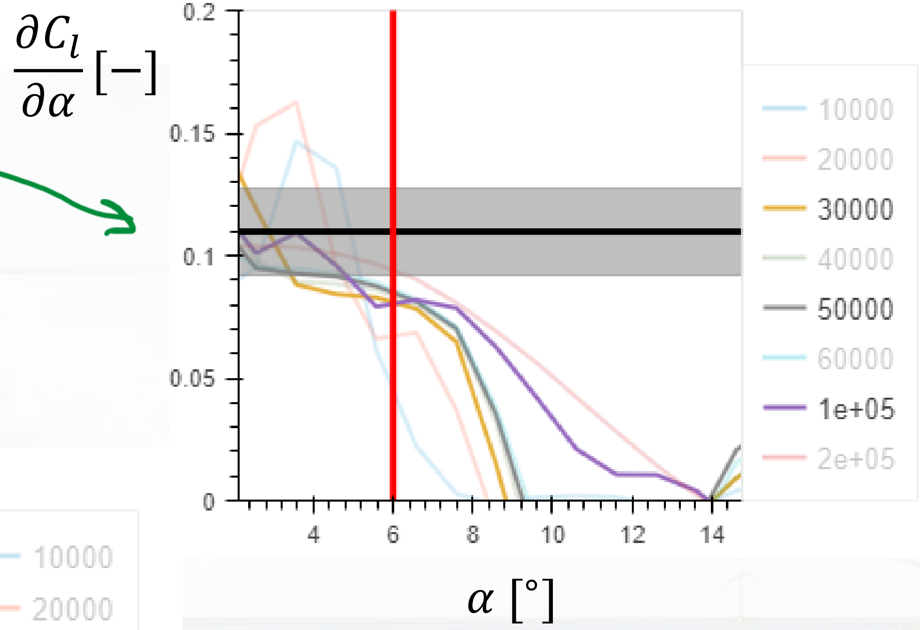
SMALL IF ATTACHED FLOW

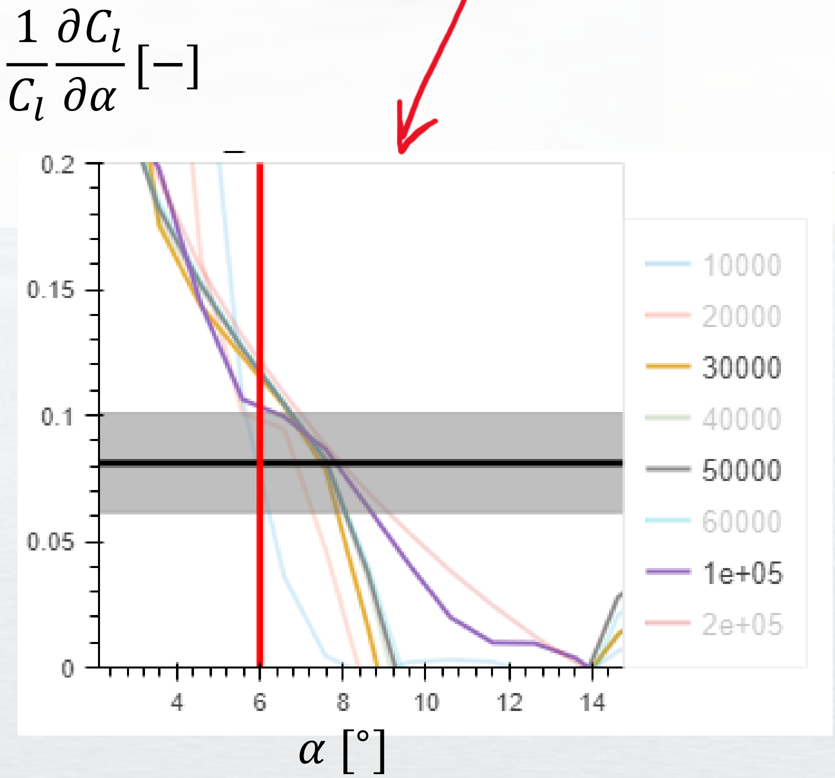
$$\left.\frac{\partial C_{LT}}{\partial \theta_{pitch}}\right|_{\text{frozen-wake}} = -\frac{C_{LT}}{C_l}\left(\frac{\partial C_l}{\partial \alpha} + \frac{\partial C_d}{\partial \alpha}\tan\phi\right)$$

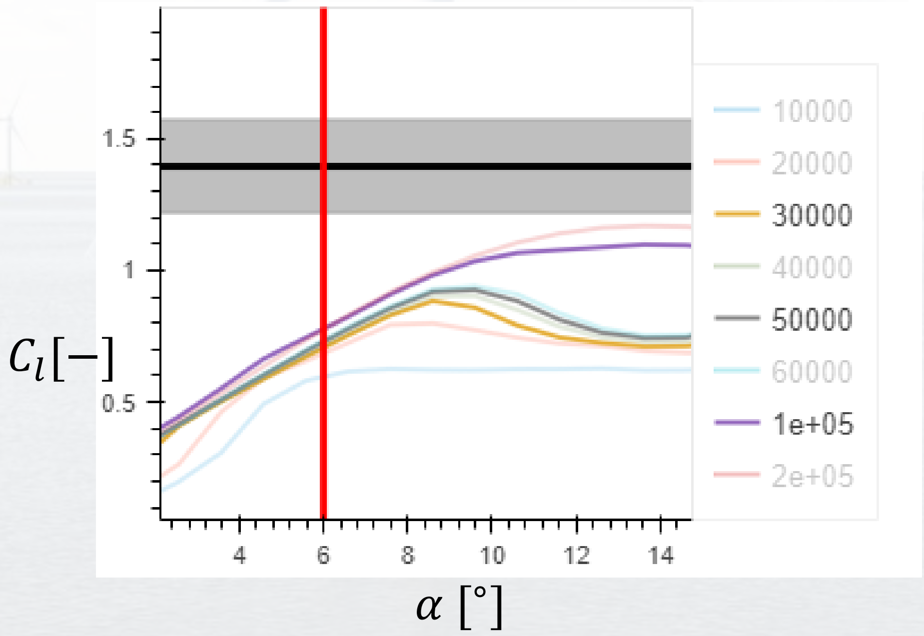
DEPENDS ONLY ON AIRFOIL POLARS!

Let's analyze the airfoil polars for SD7003 8.5%

$$\frac{\partial C_{LT}}{\partial \theta_{pitch}} \propto \frac{1}{Cl} \frac{\partial Cl}{\partial \alpha}$$







ANGLE OF ATTACK $\alpha = 6^\circ$ COMES QUITE CLOSE TO FULL SCALE!

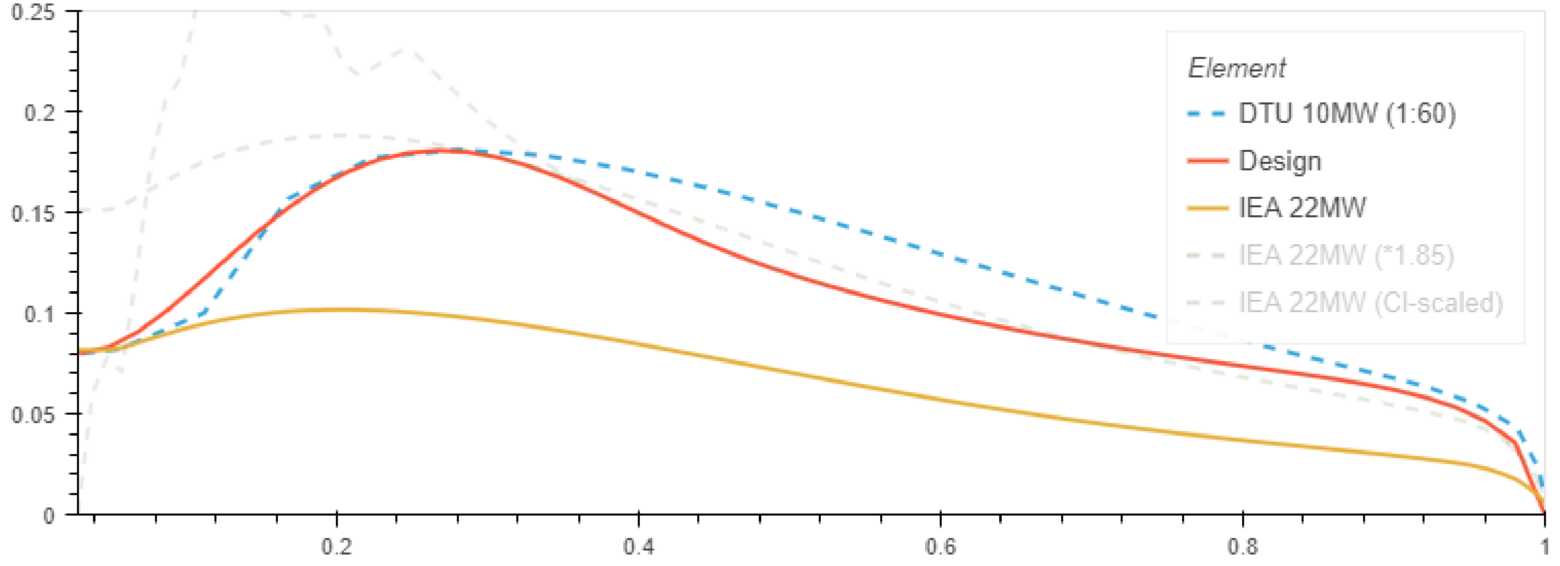
... BUT CLOSE TO STALL.

Based on this… here is the current design

Design angle of attack
$\alpha = 6°$

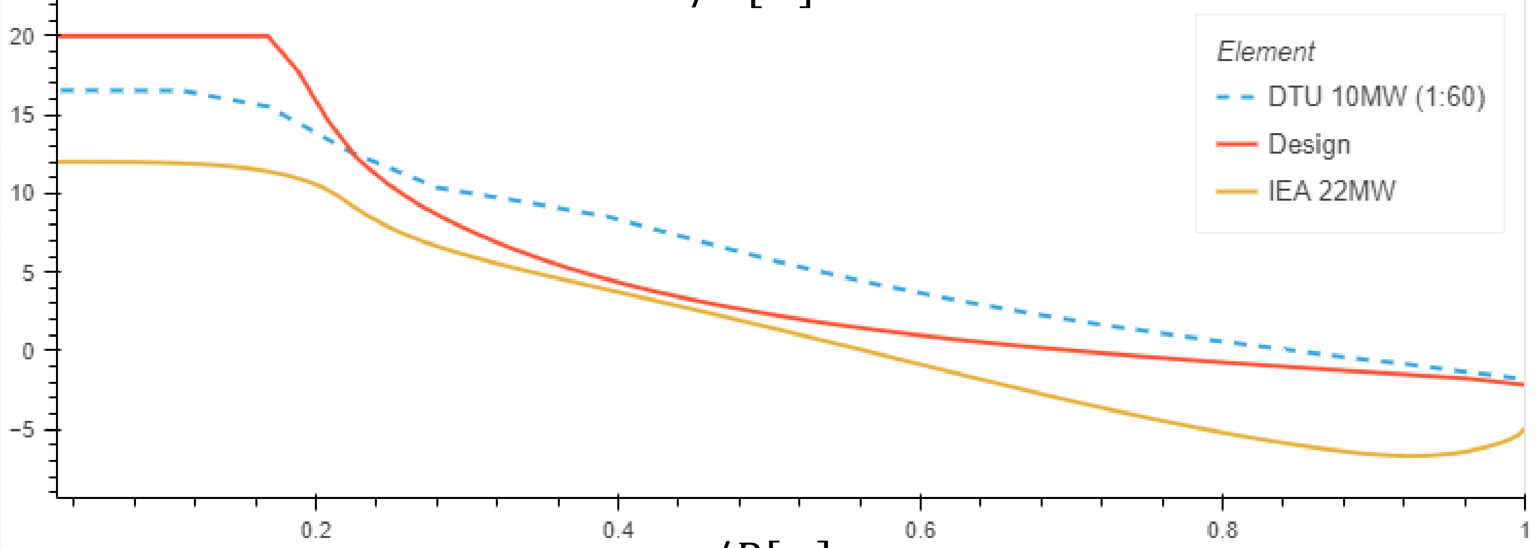
Design lift coefficient
$C_l \approx 0.6$

c$[m]$



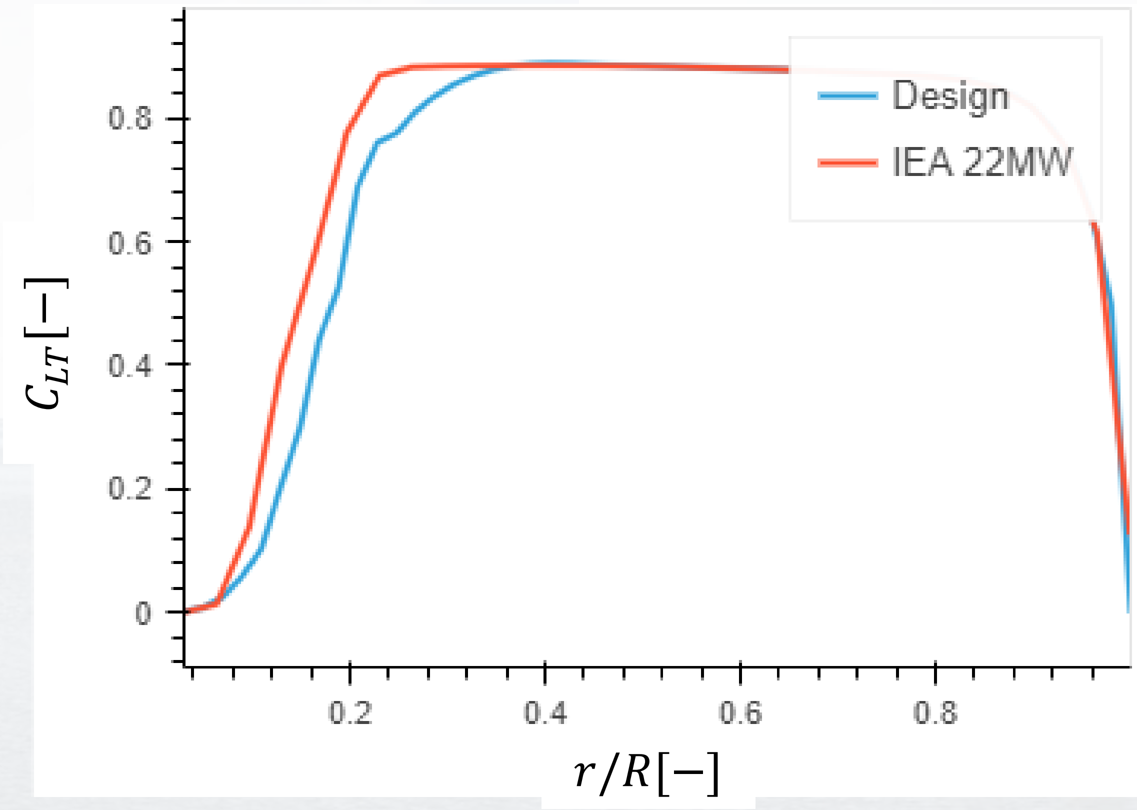
$r/R[-]$

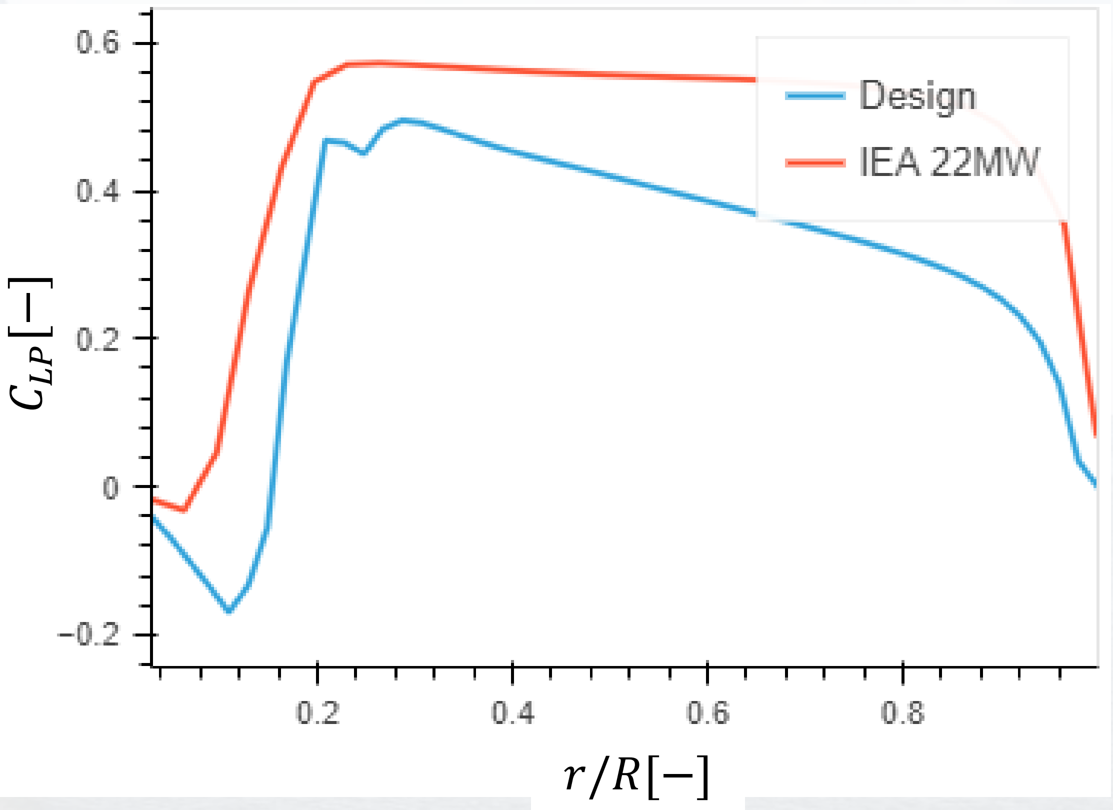
Blade twist [deg]



$r/R[-]$

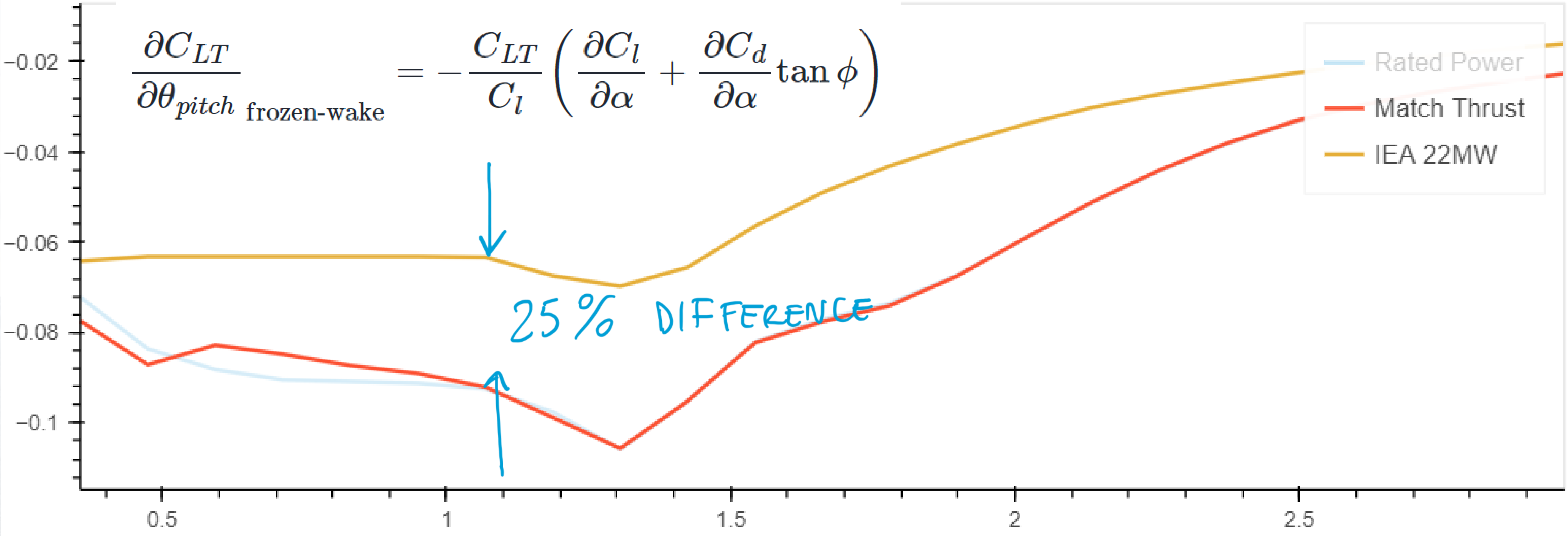
Normal load C_{LT} is nicely matched, penalty on tangential load C_{LP}





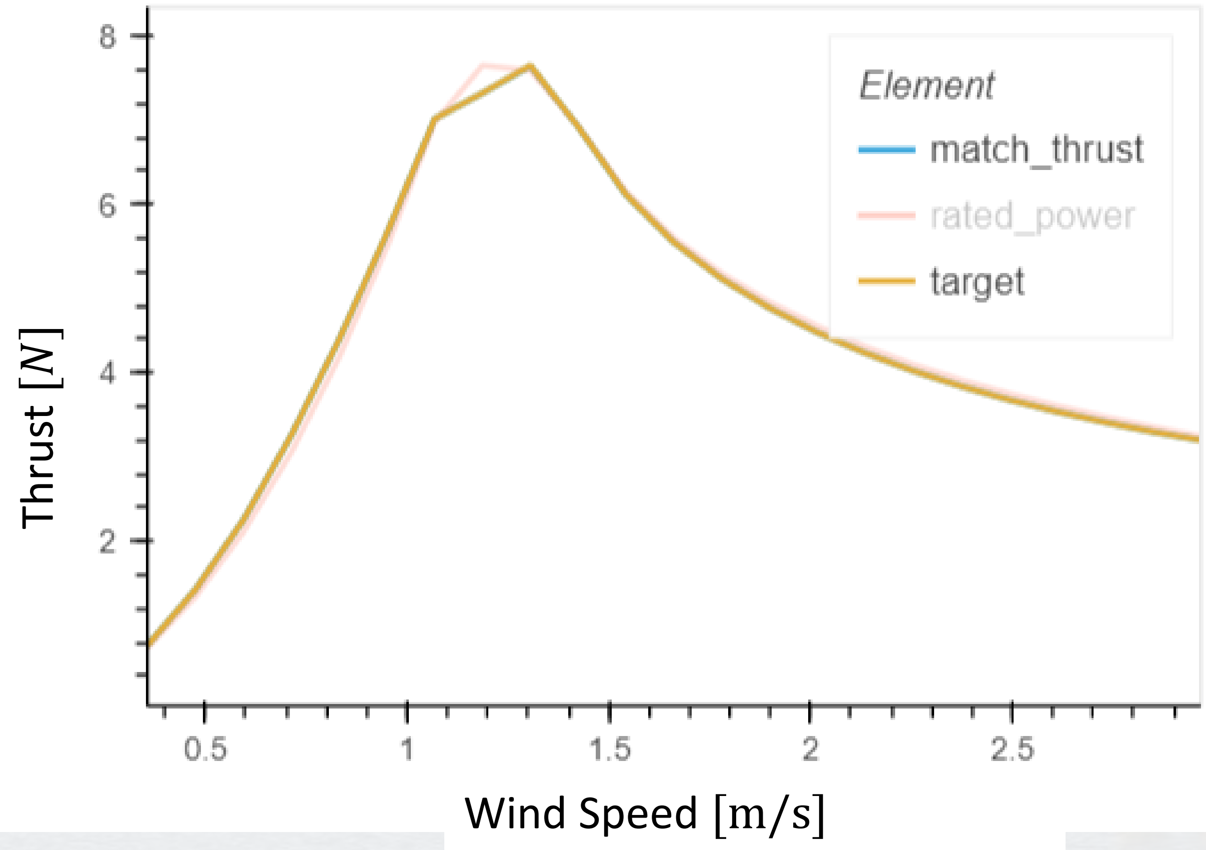
Based on this… here is the current design

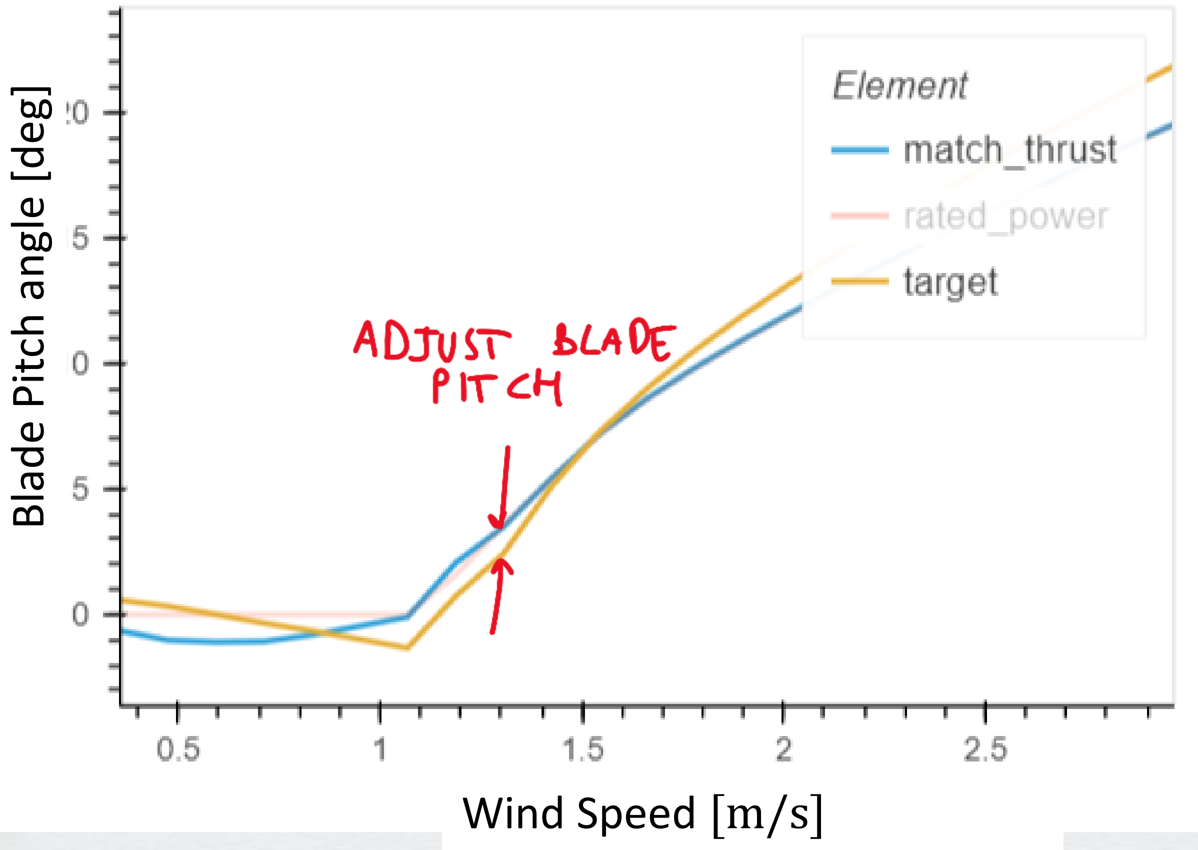
$$\left.\frac{\partial C_{LT}}{\partial \theta_{pitch}}\right._{\text{frozen-wake}} = -\frac{C_{LT}}{C_l}\left(\frac{\partial C_l}{\partial \alpha} + \frac{\partial C_d}{\partial \alpha}\tan\phi\right)$$



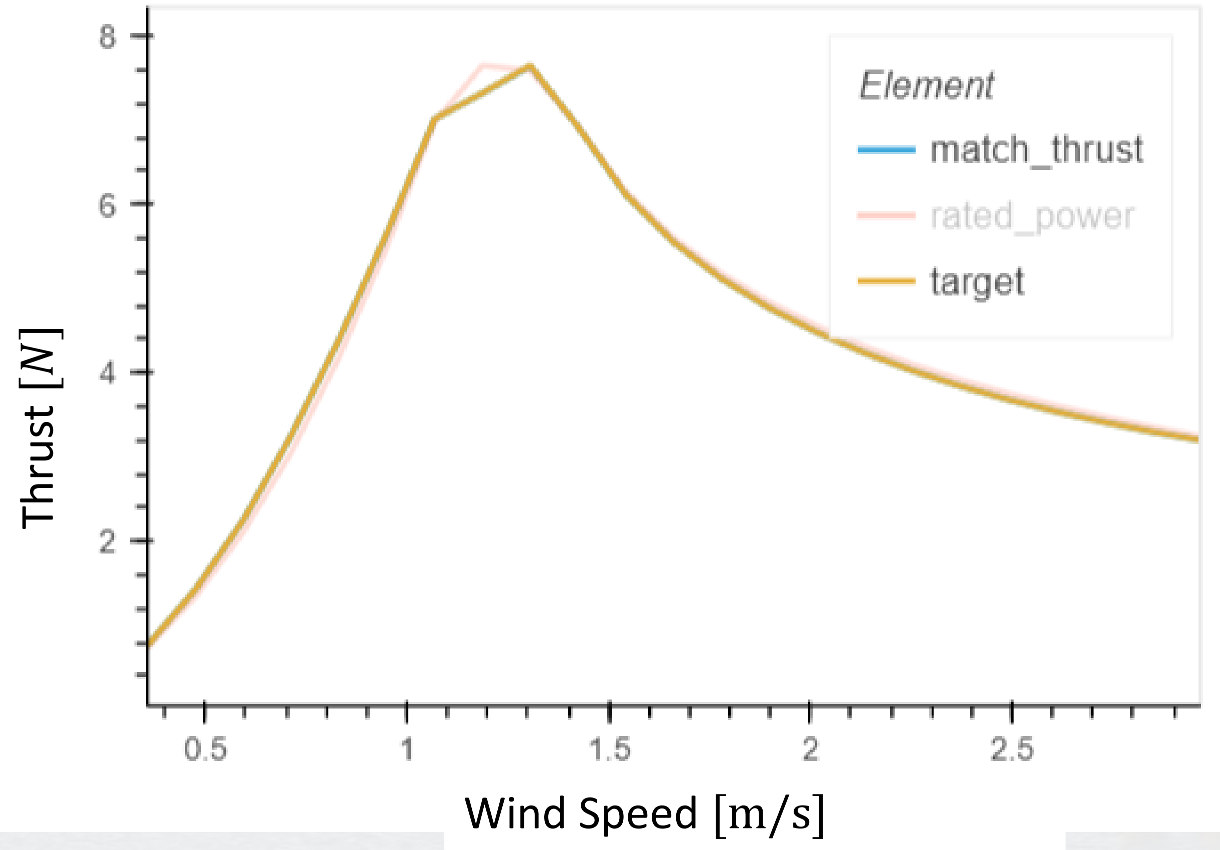
$V_0[m/s]$ Scaled inflow velocity

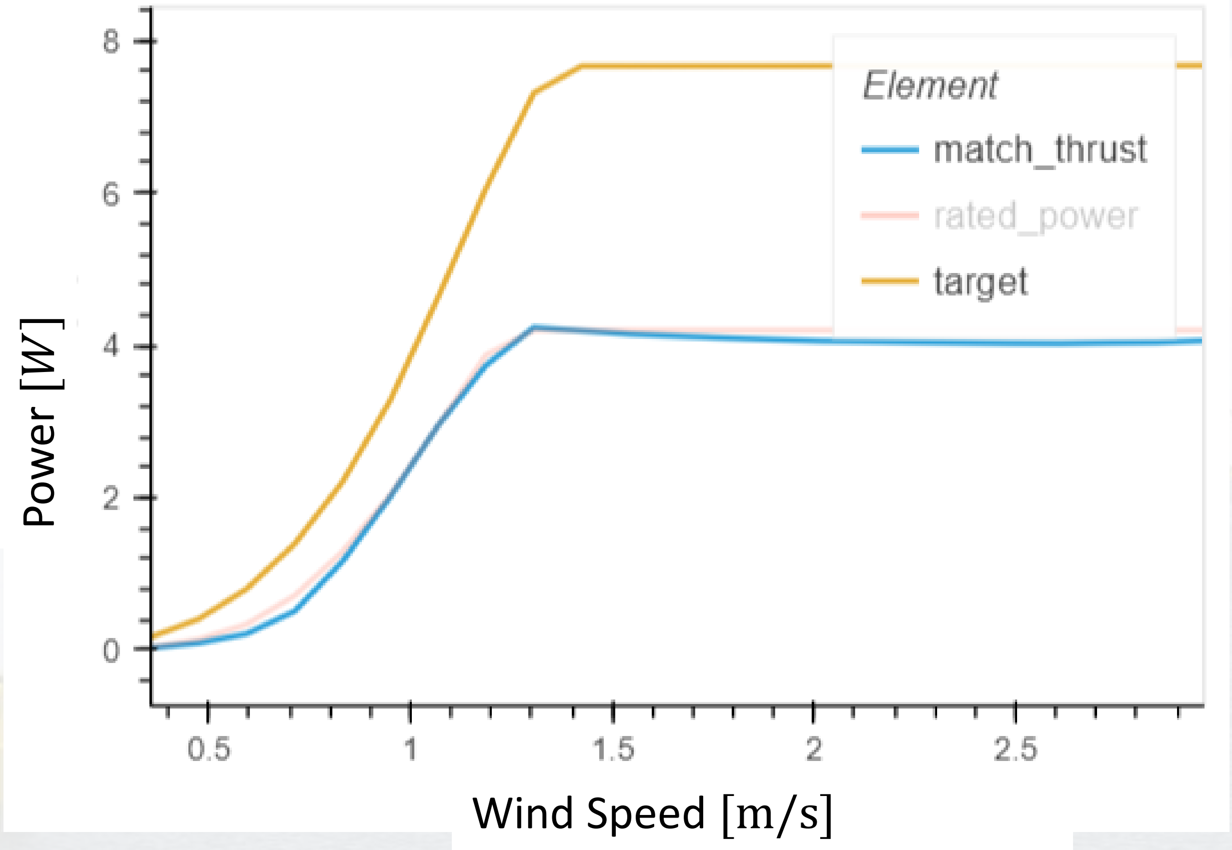
Based on this… here is the current design





Based on this... here is the current design





Conclusions and next steps

- FloatLab is building an experimental facility for testing +20MW scaled wind turbine
  - 5 MSc projects starting soon (manufacture of blades + nacelle, controller design, etc.)
  - Experimental campaign in Apr-May ‘25
- Wind generator under construction
  - One unit tested – promising results
  - 25 units ready in March
- Wind turbine design procedure
  - Accurate match of thrust curve and good match of aerodynamic damping
  - Rotor design ready – blade to be manufactured