POLITECNICO
MILANO 1863

Experimental tests on FOWT models

Structures / Modelling and Design Tools

Control
- Non directly applicable from onshore
- Instability issues
- Cycle limits motion

Aerodynamics
- Turbulence
- Aero-structure
- Unsteady

Overall dynamics
- Integrated tools
- Simplified models for control and design

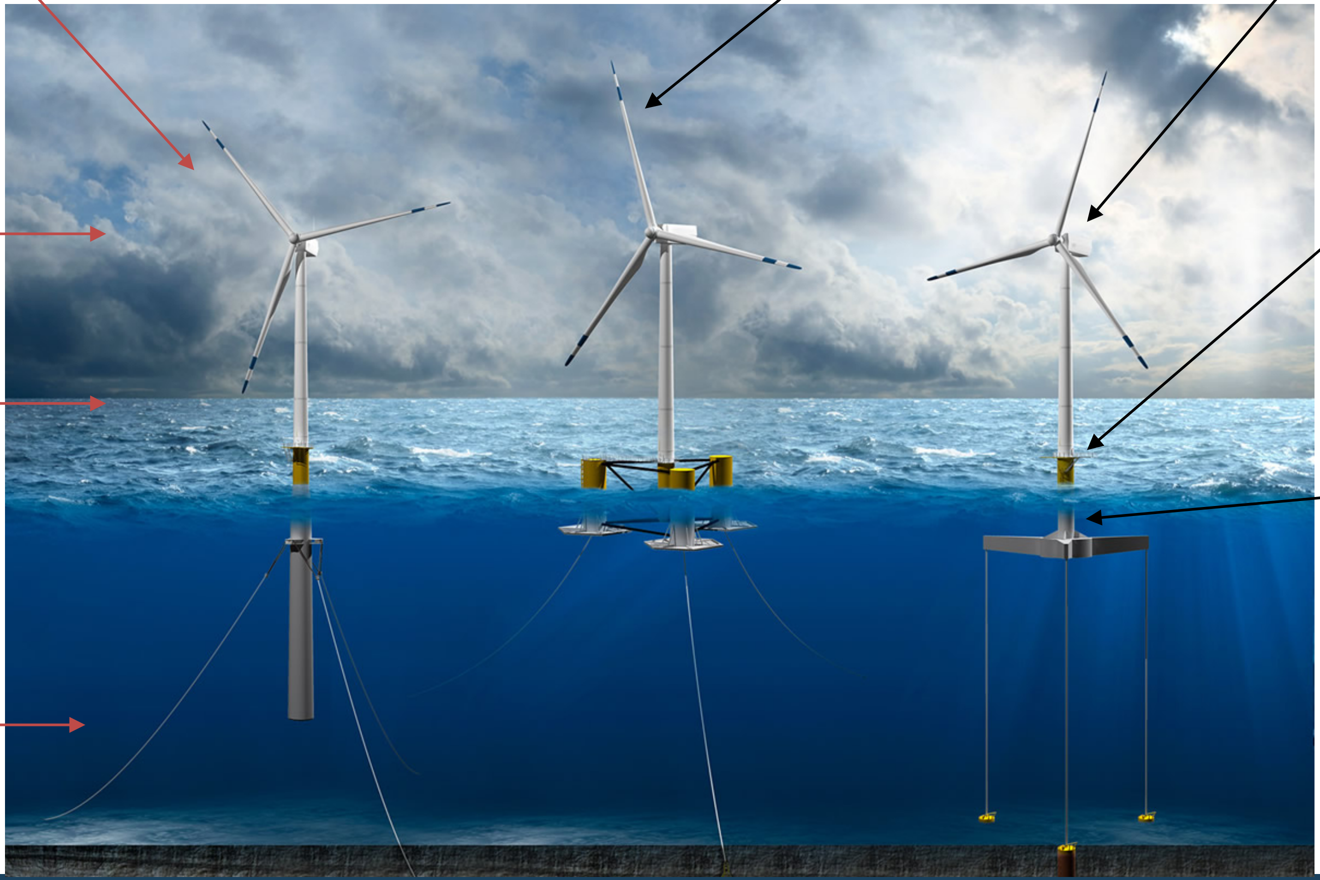
Hydrodynamics
- 2nd order important for lighter structures: sum and diff QTFs
- Multi-directional

Blades: large deformations
- Materials
- Fatigue design

Drivetrains
- Hub's accelerations
- Weight
- Fatigue durability

Tower-Platform connection

Platform design: optimization for lighter structures w.r.t O&G



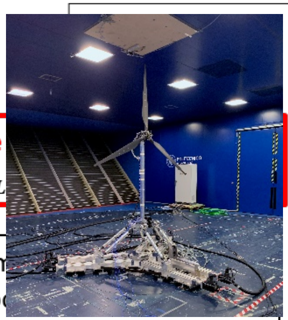
Workflow for the design of scaled wind turbine

Reference Wind Turbine

Definition of the geometrical scale and of the test strategy

Wind tunnel tests
$\lambda_L = 75 - 100$

Natural Laboratory tests
$\lambda_L = 10 - 15$



Level of accuracy

Wave
λ_L

Turbine sim
disc (repro
corresponding thrust)

Turbine simulated by a fan rotating in stationary air

Wind turbine rotor directly modelled and wind field generated by an array of fans

Definition of the velocity scale λ_V

Statistical analysis of the met-ocean conditions of the lab

Definition of all the scaling parameters

Design of the scaled tower

Natural Laboratory tests

Structural assessment

Aeroelastic design of the blade

Aerodynamic design design of the blade

Design of the scaled Blade

Natural Laboratory tests

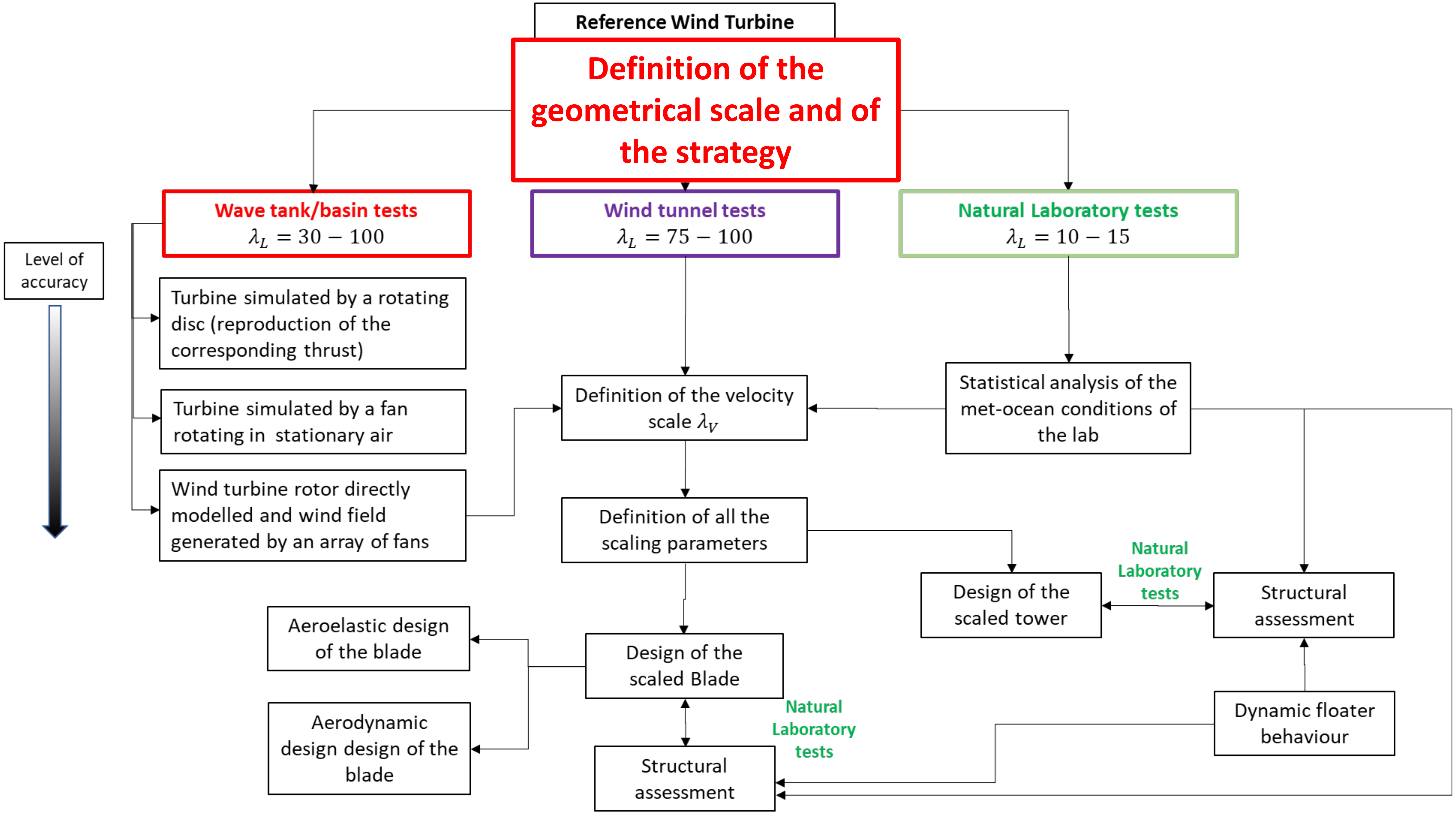
Structural assessment

Dynamic floater behaviour

Reference Wind Turbine: DTU 10 MW

Parameter	Value	Units
Cut in wind speed	4	m/s
Cut out wind speed	25	m/s
Rated wind speed	11.4	m/s
Rotor Diameter	178.3	m
Hub Diameter	5.6	m
Hub Height	119	m
Minimum Rotor Speed	6	rpm
Maximum Rotor Speed	9.6	rpm
Rotor Mass	228	t
Nacelle Mass	446	t
Tower Mass	628.4	t
Thrust	1400	kN
Tower first side-side mode	0.25	Hz
Blade first flap-wise mode	0.61	Hz
Blade first edge-wise mode	0.93	Hz

Workflow for the design of scaled wind turbine



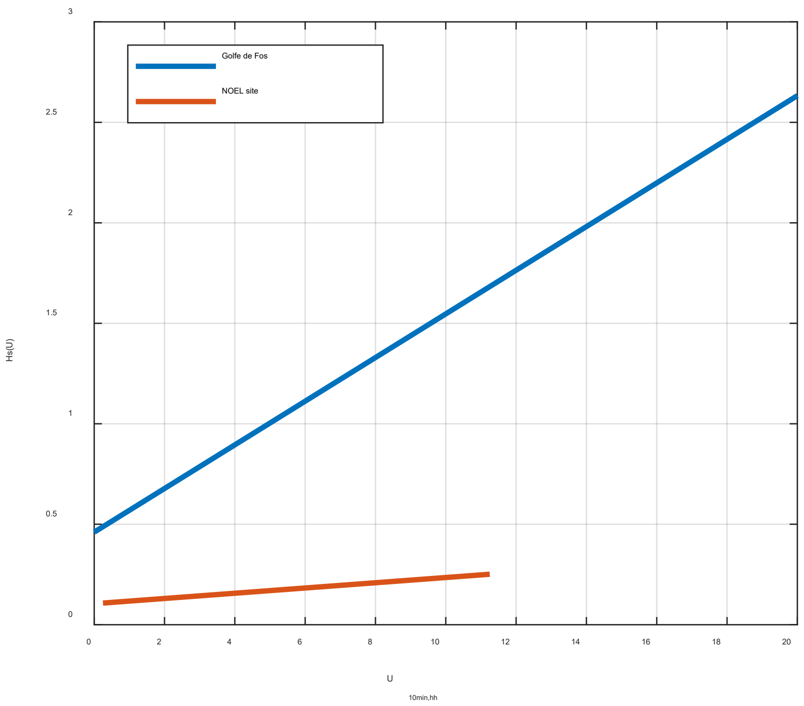
Wind tunnel tests

Maximum model dimensions are limited by WT section height

4 m → Maximum turbine model diameter: 2.0-2.6 m

Natural Laboratory tests

Evaluation of the significant wave height



NOEL: typical scale factor: 1:10- 1:20

Scaling strategies

Froude scaling

$$Fr = \frac{U}{\sqrt{gL}} \Rightarrow \lambda_V = \sqrt{\lambda_L}$$

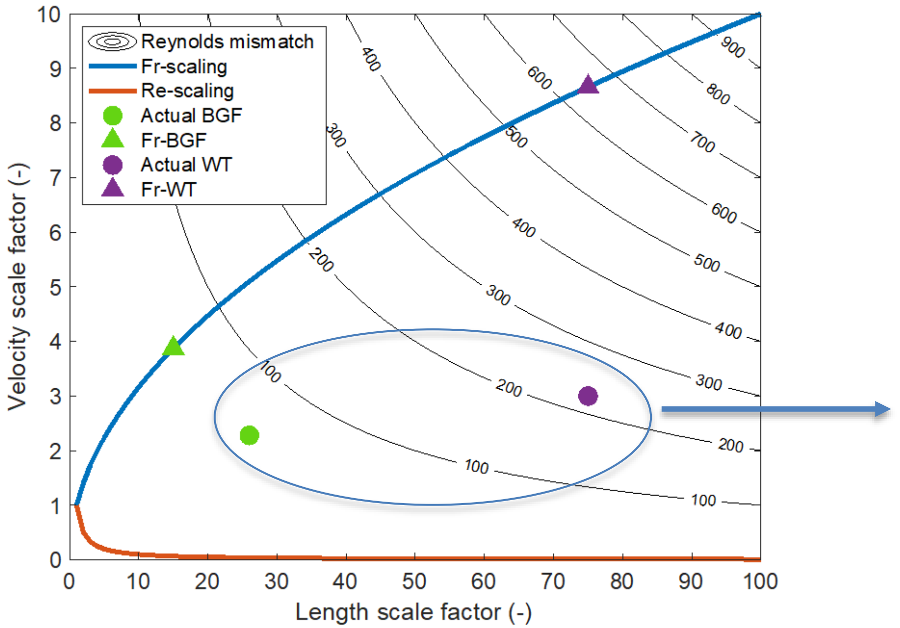
for reproducing the wave and gravity forces

Reynolds scaling

$$Re = \frac{UD}{\upsilon} \Rightarrow \lambda_V = \frac{1}{\lambda_L}$$

for reproducing blade aerodynamics

It is impossible to simultaneously match Reynolds and Froude numbers



a compromise has to be reached considering other factors

Wind tunnel tests

Velocity ratio is limited by the wind tunnel velocity range:

Polimi Wind Tunnel (WT) boundary layer test section:

- Available test wind speed=3-15 m/s
- DTU 10 MW operational range=4-25 m/s

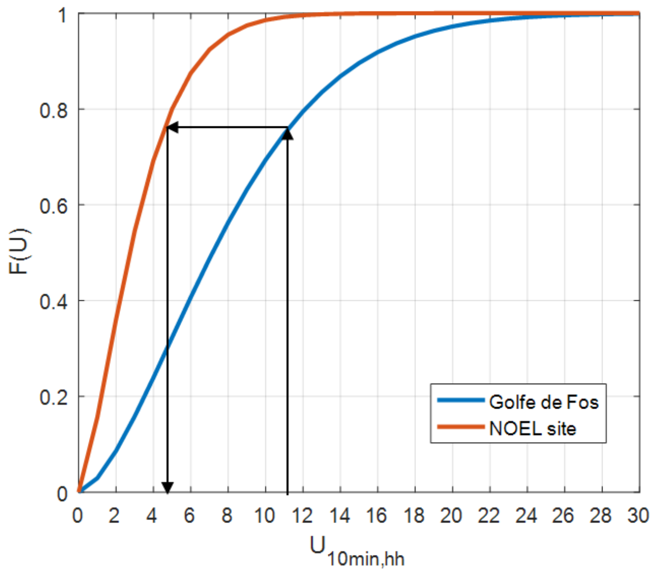
- Preferable rated velocity for the model:
- V_{model} rated=4.6-8 m/s

$$\lambda_V = \frac{U_{Real}}{U_{model}} = 1.25 - 2.5$$

The length and velocity scale factors can set one independently from the other: in hybrid/HIL experiments, it is possible to simulate FOWT dynamics without having to rely on Froude similitude

Natural Laboratory tests

A statistical approach must be used



Wind speed cumulative probability

The turbine structure (except the rotor) can be scaled according to Froude law and the performances (rotor dimension included) can be scaled according to a generic scale

Scale Factor	Symbol	Expression
Length	λ_L	-
Velocity	λ_v	-
Acceleration	λ_a	${\lambda_v}^2/\lambda_L$
Frequency	λ_f	λ_v/λ_L
Mass	λ_M	${\lambda_L}^3$
Inertia	λ_J	${\lambda_L}^5$
Force	λ_F	${\lambda_L}^2{\lambda_v}^2$
Power	λ_P	$\lambda_L{\lambda_v}^3$
Re num. ratio	λ_{Re}	$\lambda_L\lambda_v$
Fr num. ratio	λ_{Fr}	$\lambda_v/{\lambda_L}^{0.5}$

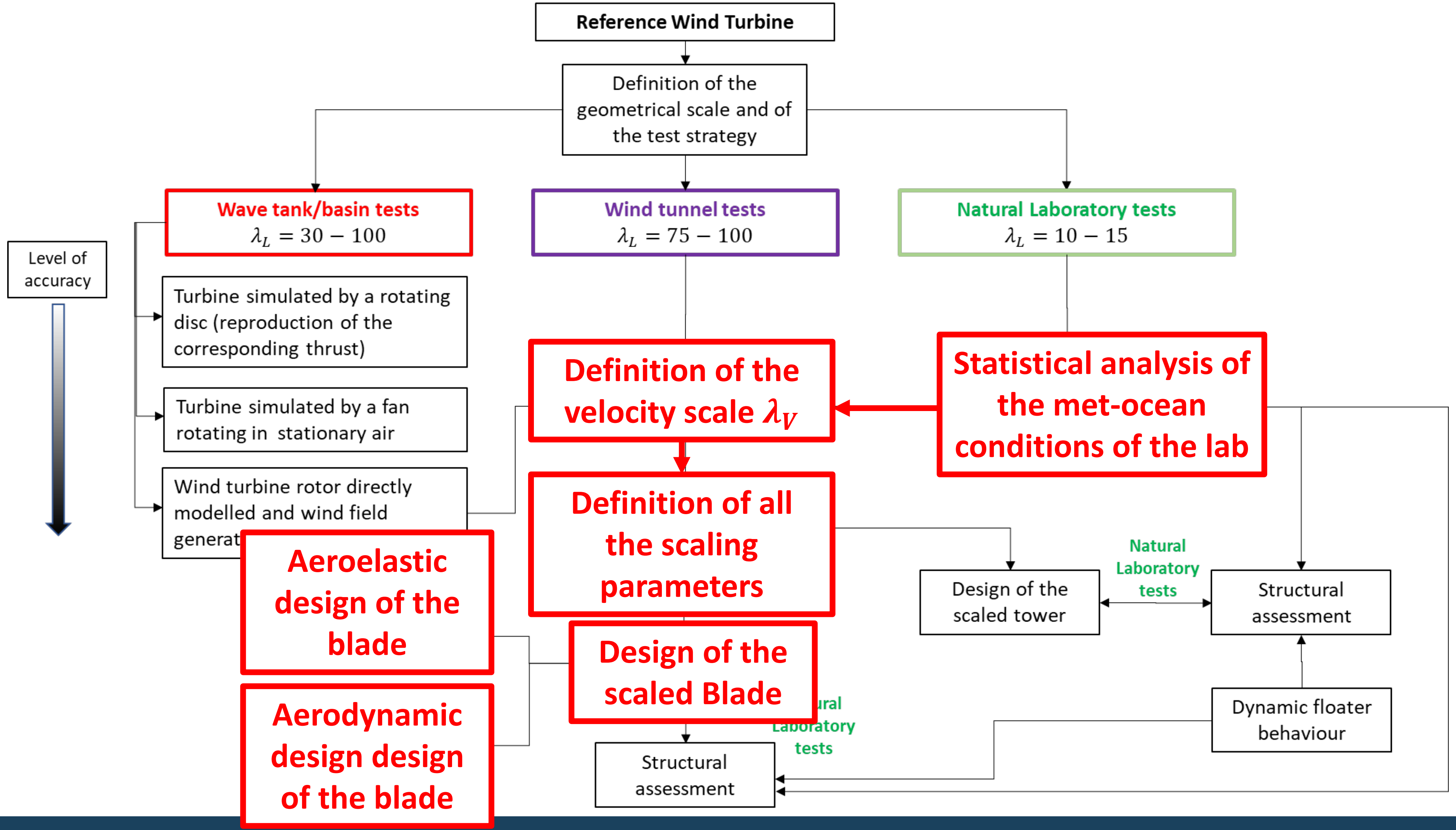
Wind tunnel model

Scale factor	Value
Length	75
Velocity	3
Frequency	1/25
Mass	421,875
Force	50,625
Re num. ratio	225
Fr num. ratio	26

Natural Laboratory model

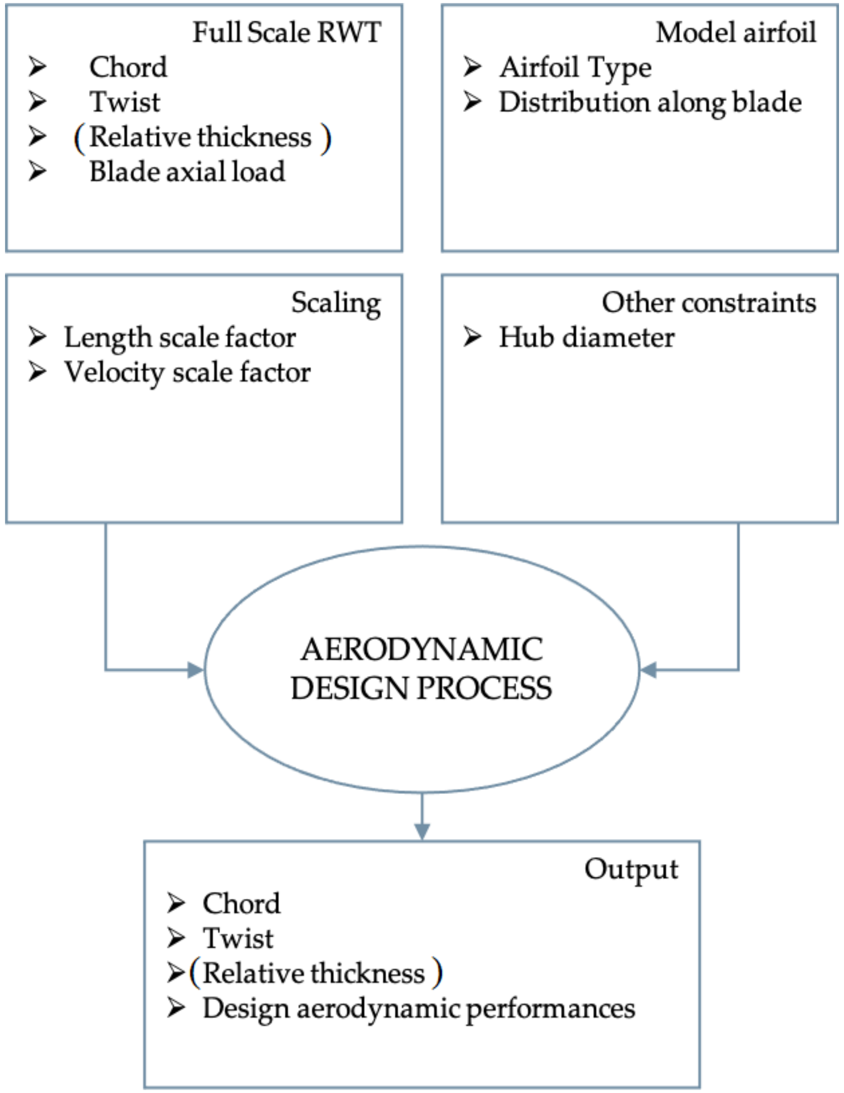
Wind Turbine sub-system	Scale Factor	Value
Structure (Froude)	Length	15
	Frequency	0.258
	Mass	3375
	Inertia	759,375
	Force	3375 [1]
	Re num.	58
Rotor (non-Froude)	Length	26
	Velocity	2.28
	Frequency	0.088
	Inertia	11,881,376
	Force	3514.12 [1]
	Power	8012.19
	Re num. ratio	59
	Fr num. ratio	12

Workflow for the design of scaled wind turbine



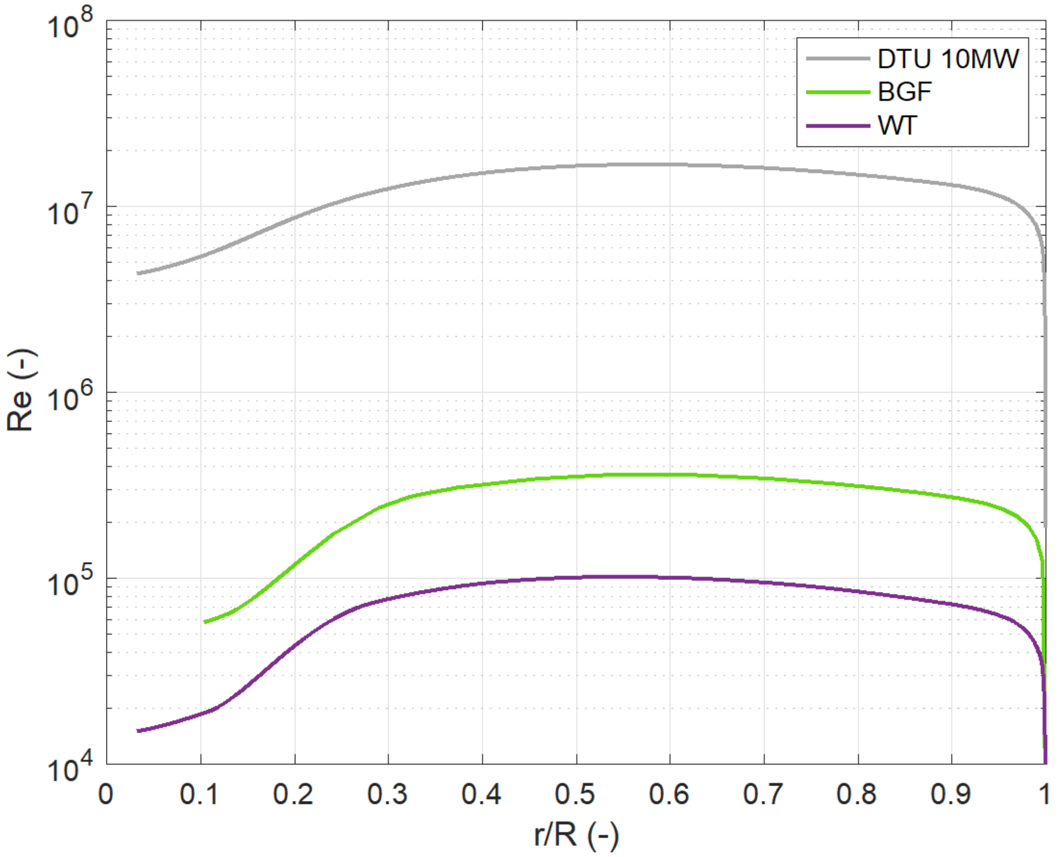
Main requirements:

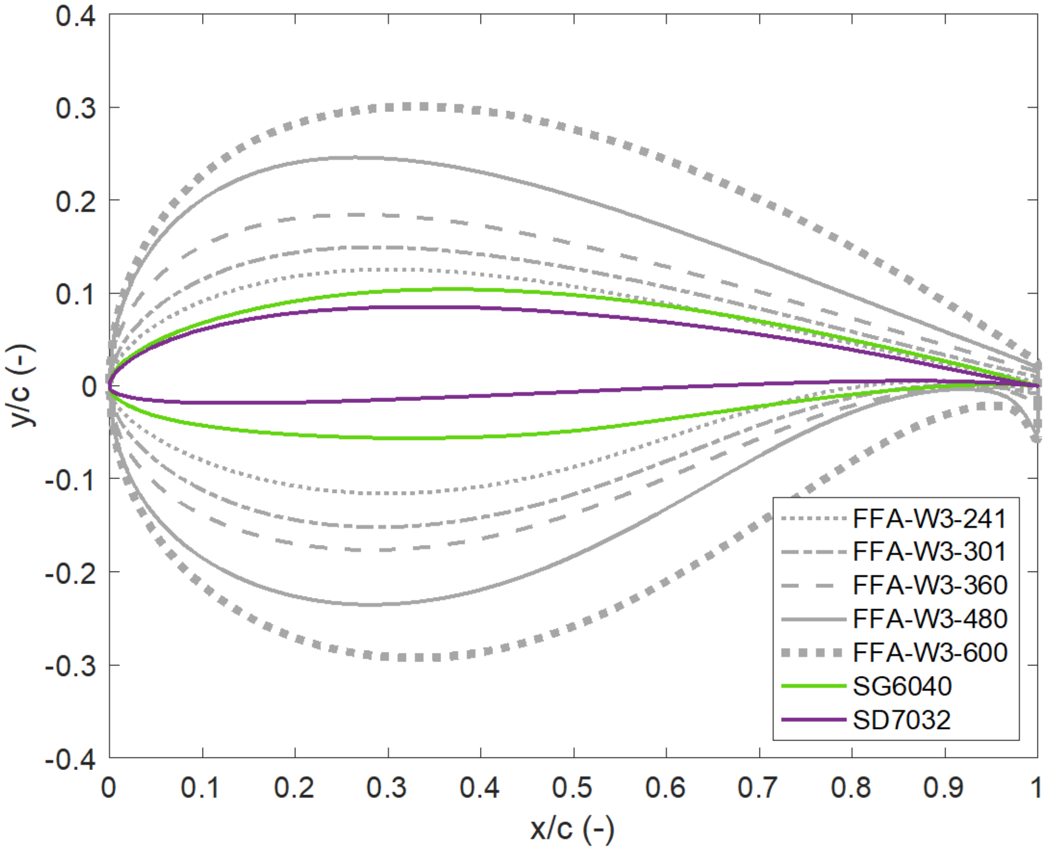
- ❑ match the rotor thrust force ➡ responsible for the coupled rotor–platform dynamics
- ❑ reproduce the power as good as possible and
- ❑ match the first flap-wise bending mode.

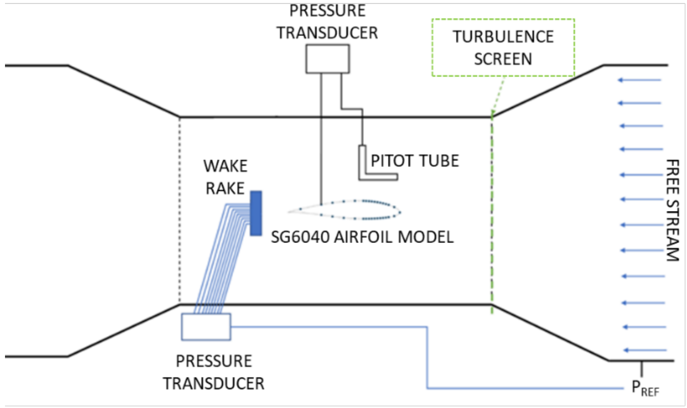


↓ Re ↓ Thickness 👍 Drag-Lift ratio

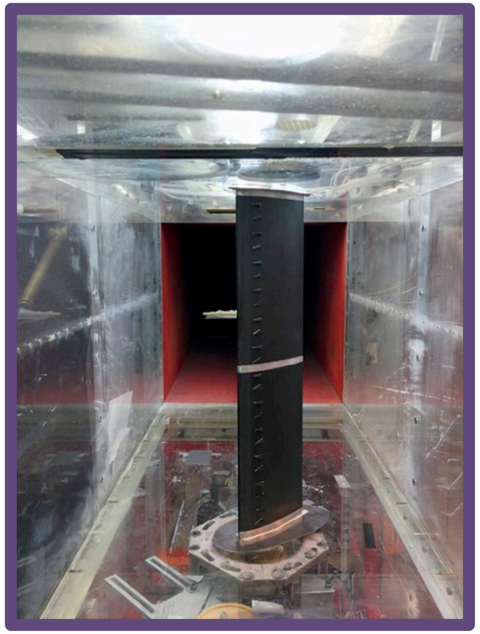
Reynolds number along the chord: models compared with the RWT

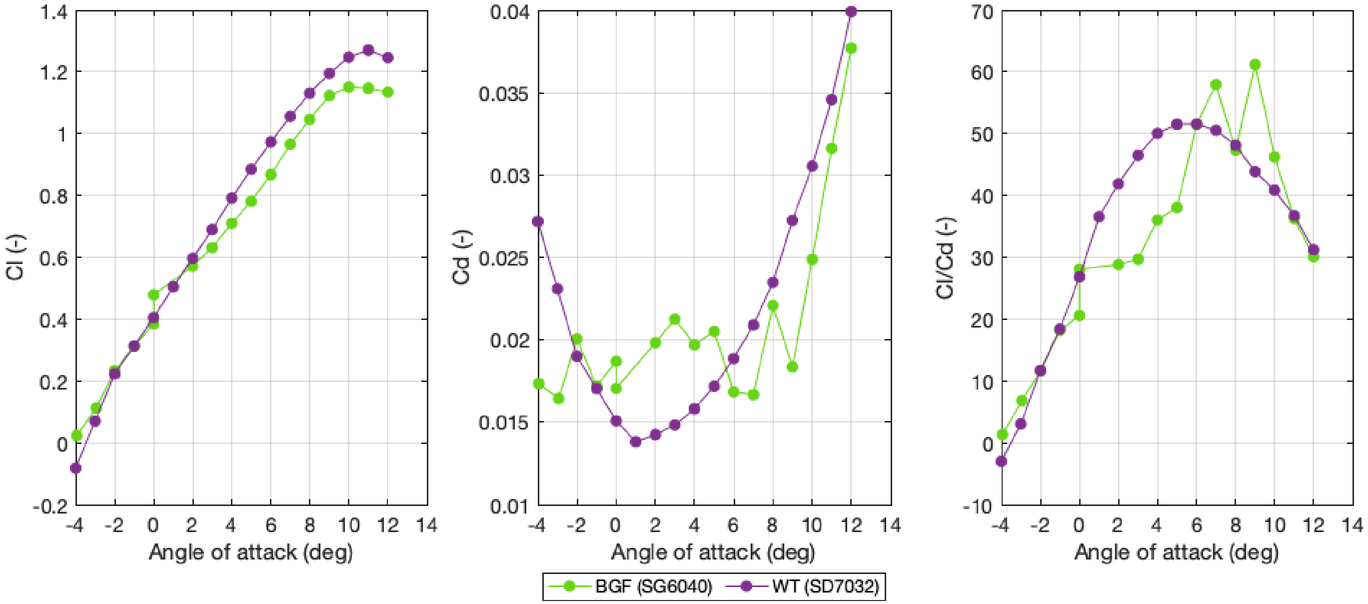






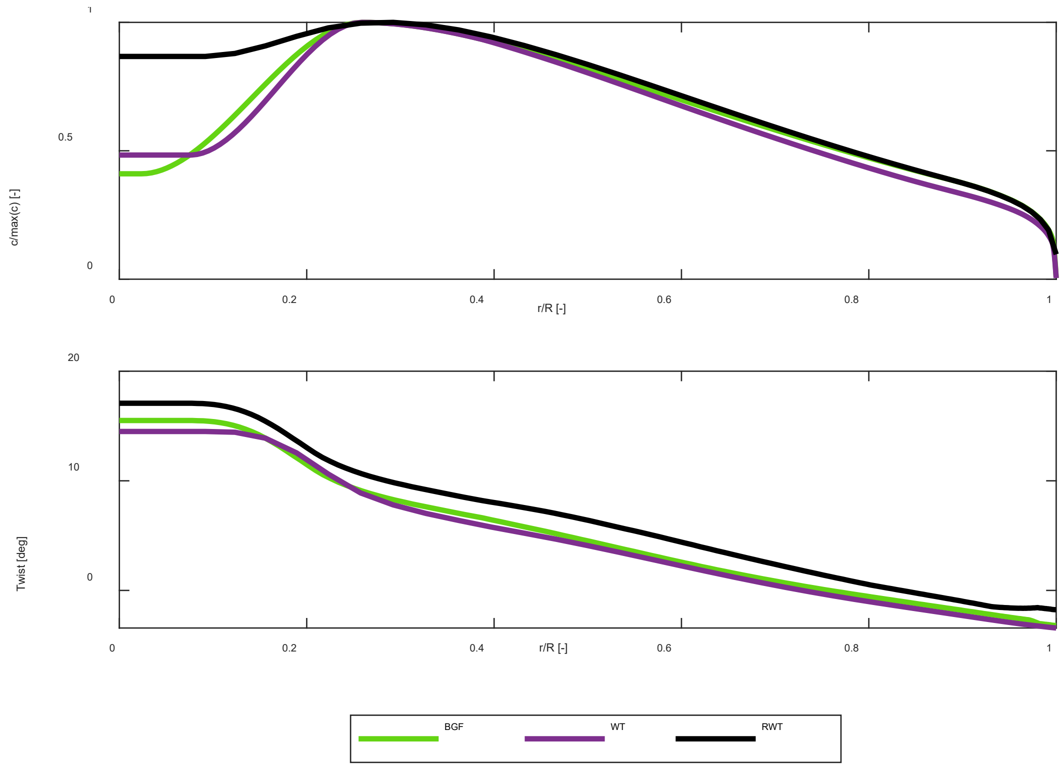
Tests performed on 2D profile permit to verify the aerodynamic coefficients provided by literature





GOAL OF THE 3D DESIGN: preserve the thrust imposing **kinematic similarity**

At every iteration the optimal chord and twist distributions are computed to match the thrust force on the rotor.



$$TSR_R = \frac{\Omega_R R_R}{V_R} = \frac{\Omega_m R_m}{V_m} = TSR_m$$

$$\lambda_\Omega = \frac{\Omega_R}{\Omega_M} = \frac{R_M V_R}{R_R V_M} = \frac{\lambda_U}{\lambda_L}$$

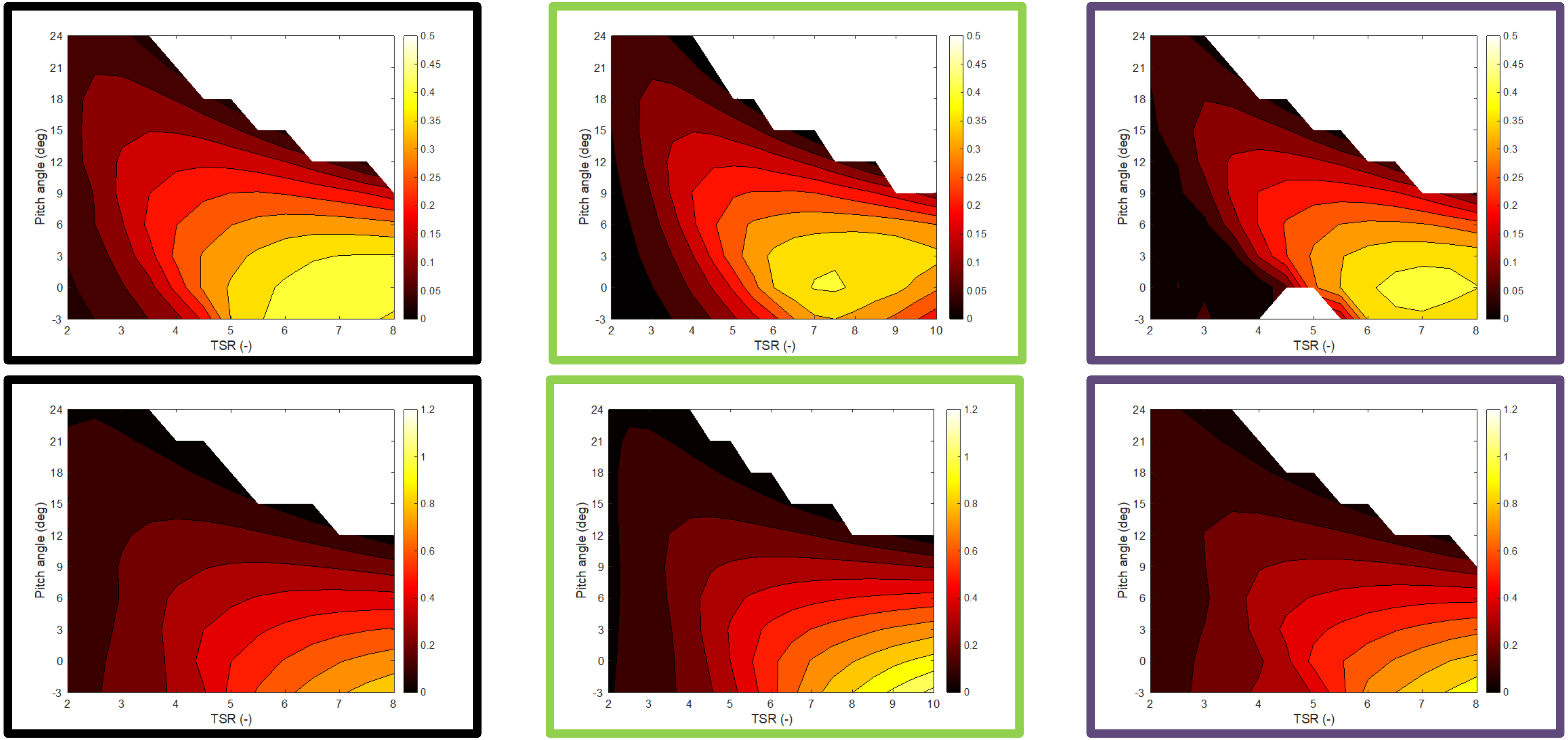
TSR: Tip Speed Ratio

Blade aerodynamic design: 3D optimal shape

RWT | NATURAL LAB | WIND TUNNEL

POWER COEFF.

THRUST COEFF.

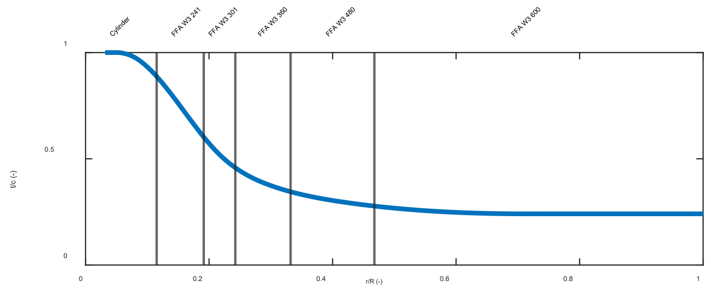


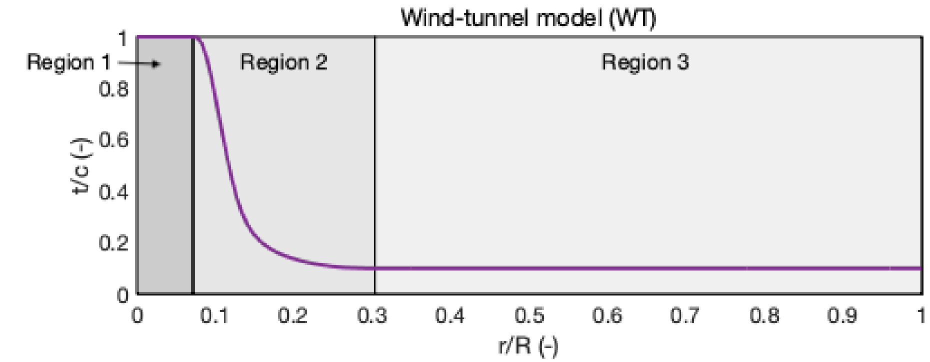
Main parameters:

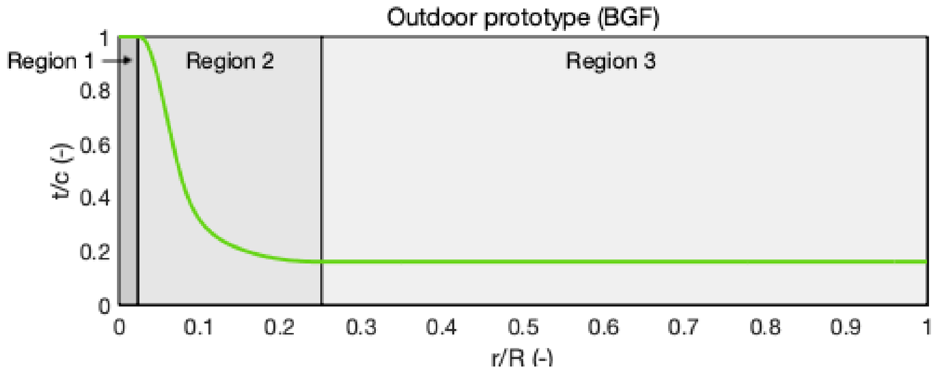
Effects on the Floating structure dynamics

- ❑ Mass: match/minimization
- ❑ Stiffness

Effects on the flexible dynamics of the rotor





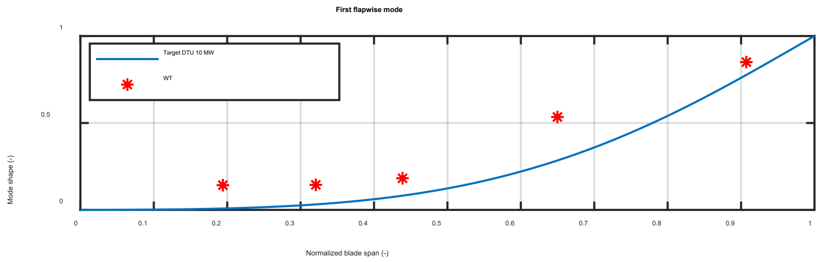


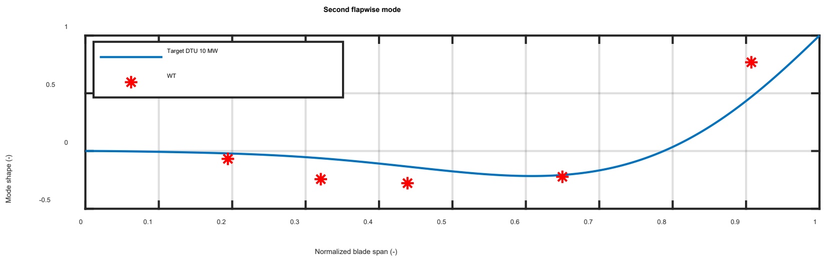
- **Region 1** - blade root. t/c=1 - the radial extension given by manufacturing and assembly constraints.
- **Region 3** - tip region - nominal t/c for the selected airfoil.
- **Region 2** - transition region - longer transition ↑ flapwise stiffness ↓ aerodynamic performances.

Wind tunnel model

Flapwise Mode	Target Frequency (Hz)	WT Model Frequency (Hz)
First	22.87	17.10
Second	65.25	56.40

Region 2 was defined in order to optimize the aeroelastic design

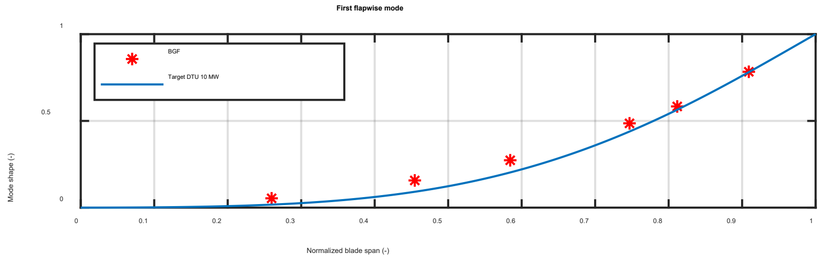


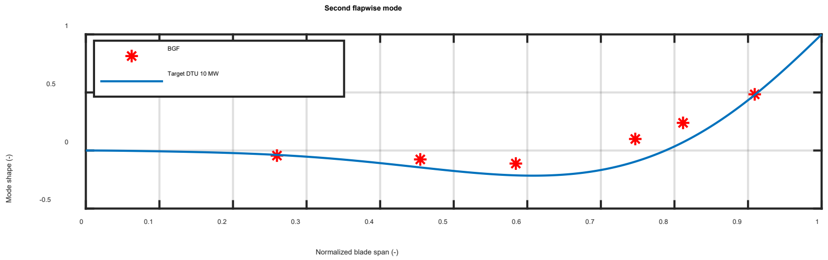


Natural Laboratory model

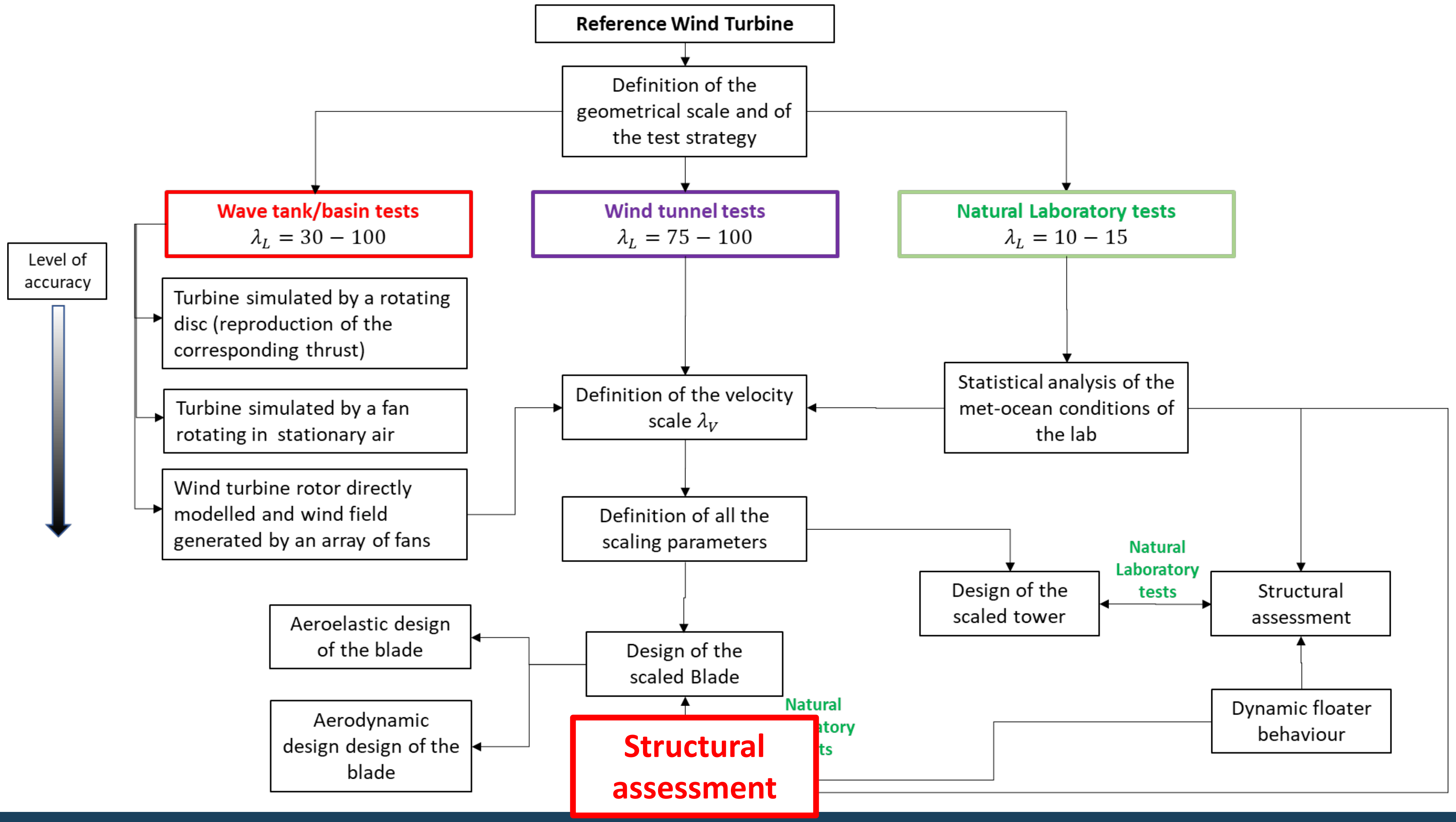
Flapwise Mode	Target Frequency (Hz)	WT Model Frequency (Hz)
First	2.36	7.82
Second	6.74	19.38

Region 2 was defined in order to have the minimum stiffness permitted by the structural design





Workflow for the design of scaled wind turbine



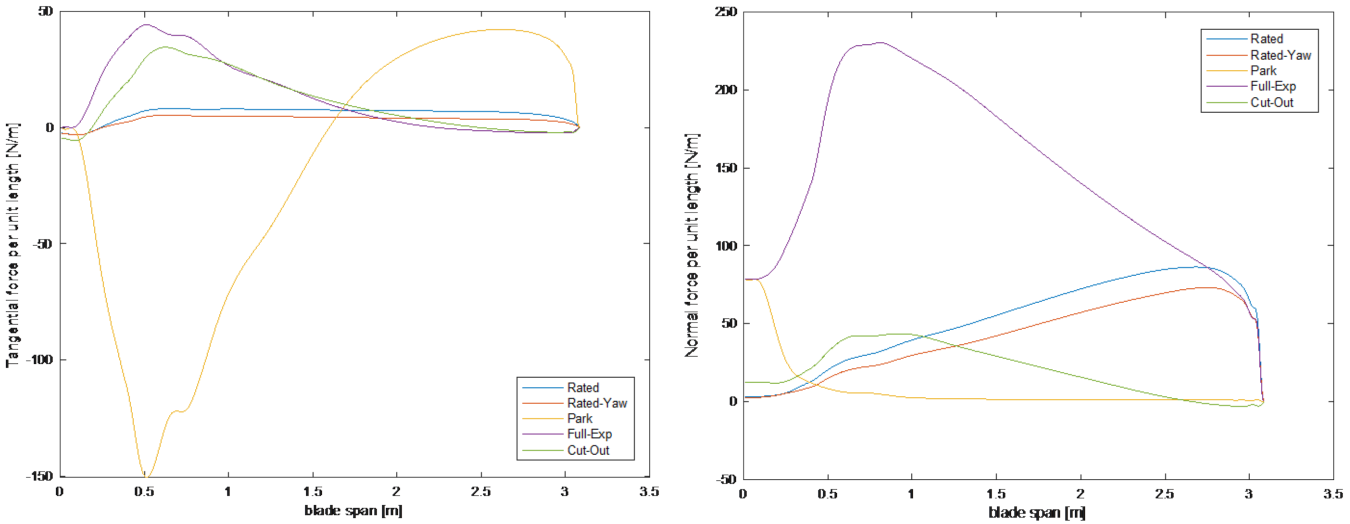
Blade structural design/assessment for Natural Laboratory model

DLCs [IEC61400]

Case Name	U [m/s]	W [rpm]	Blade Pitch [°]	Yaw Angle [°]
Rated	5	101.9	0	0
Rated Yaw	5	101.9	0	30
Park	33	0	90	0
Full Exposure	33	0	0	0
Cut-Out	10.96	109.47	22.67	0

- Rated (5m/s, pitch 0°)
- Rated-Yaw
- Cut-Out

- Full-Exposure (33m/s, pitch 0°)
- Park



Force per unit length tangential and normal to the rotor plane (eval. FAST)

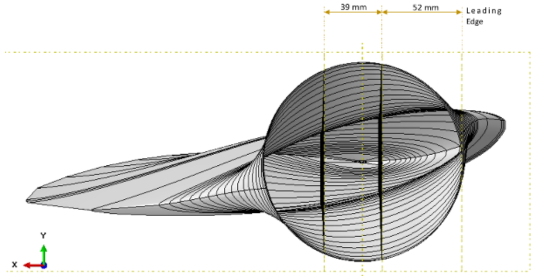
Requirements:

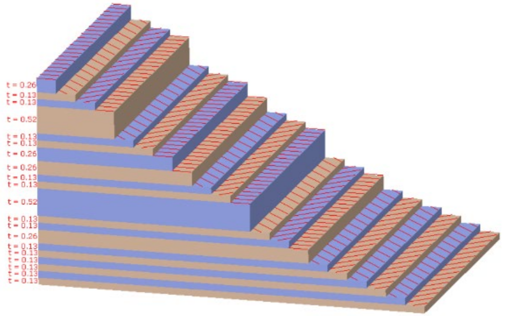
- **Static** assessment
- 1:15 Mass constraint
- 1st frequency > 3p

Blade structural design/assessment for Natural Laboratory model

Materials: GFRP
- S2-glass UD (0°)
- E-glass FABRIC (±45°)

	Bladespan [m]	Stacking Sequence	Thick [mm]
External shell	0-0.774	*3X[±45°]+2X[0°/±45°/0°]$_S$*	3.9
	0.774 - 1.666	2X[±45°]+2X[0°/±45°/0°]$_S$	3.12
	1.666 - 2.576	2X[±45°]+[±45°/0°/±45°]$_S$	1.3
	2.576 - 2.902	2X[±45°]	0.52
	2.902 - 3.086	[±45°]	0.26
Webs	0.089 - 0.774	[±45°/±45°/90°/±45°/±45°/90°]$_S$	3.12
	0.774 - 2.19	[±45°/90°/±45°/±45°/90°/±45°]	1.56



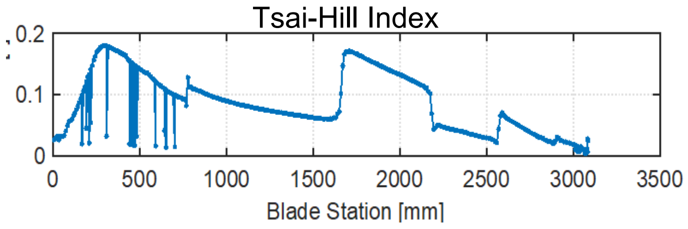


FEA - Abaqus model

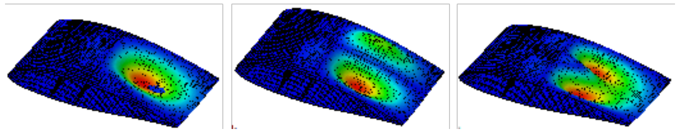
Blade mass: $7.317\ kg$

Natural frequencies:
- Mode 1: $9.71\ Hz$
- Mode 2: $23.54\ Hz$

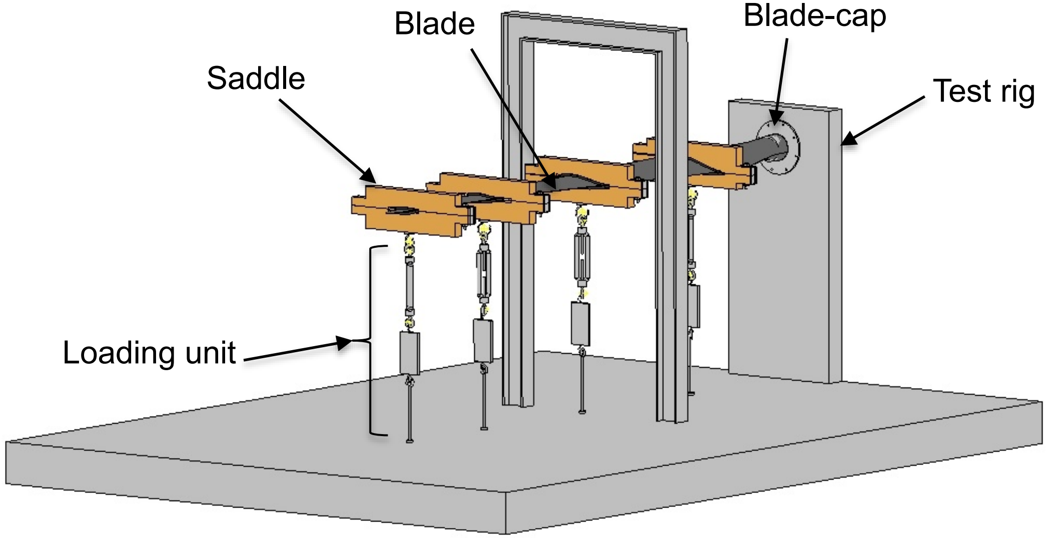
Assessment performed:
- ✓ Static Analysis
- ✓ Buckling Analisis
- ✓ Tip-Tower Clearance

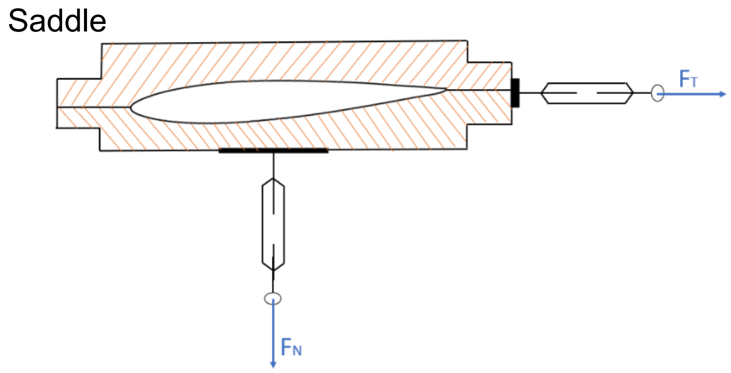


Buckling



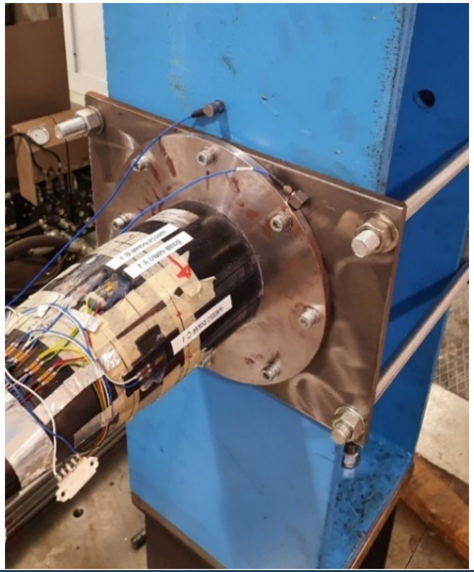
Blade structural design/assessment for Natural Laboratory model



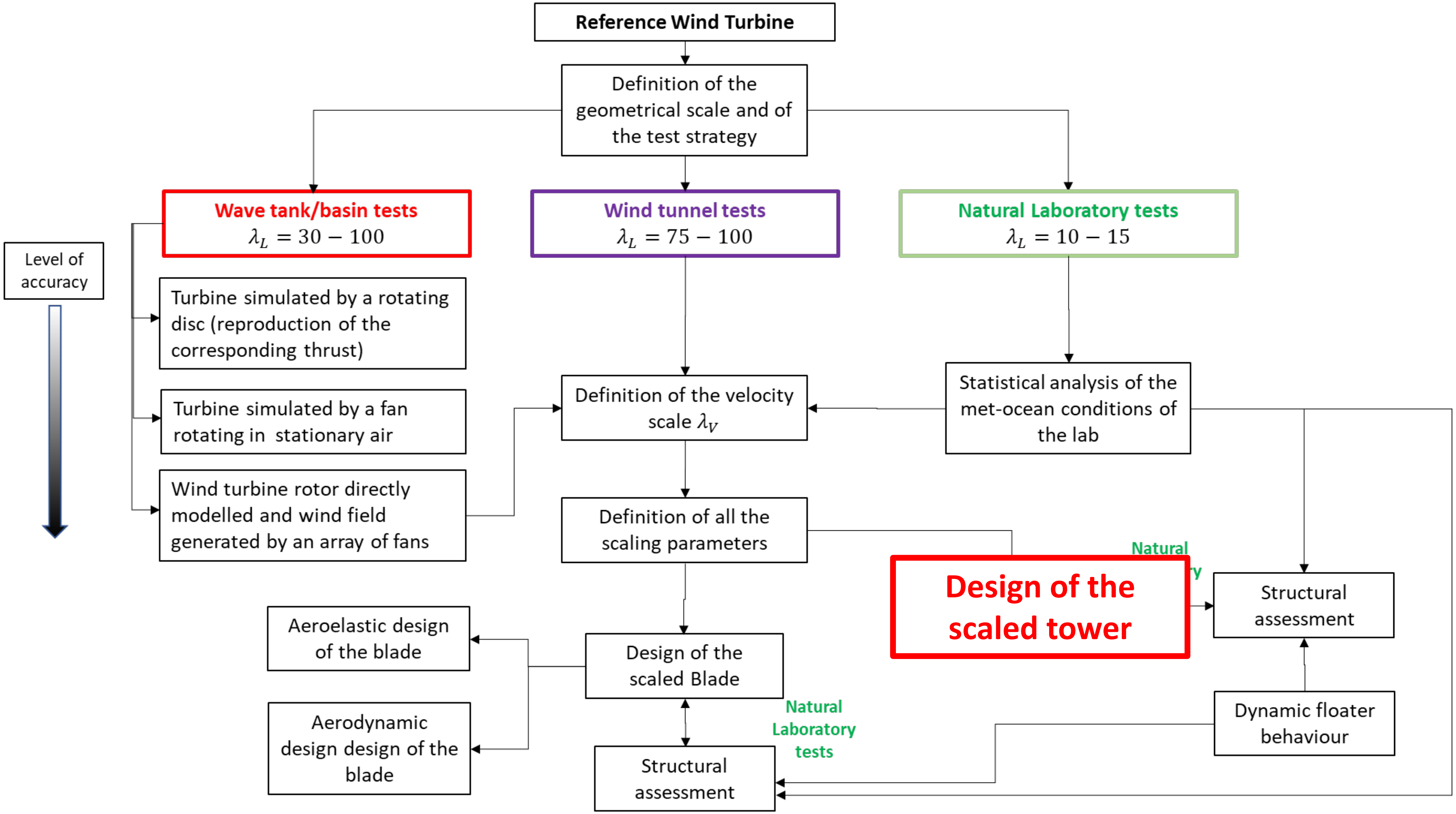


Structural tests:

1. FEM validation:
   Target: verify material properties
   Strategy: reproduction of *bending moment*
2. Blade structural assessment:
   Target: verify blade resistance in design conditions
   Strategy: reproduction of *shear stress*
3. Blade root to flange connection assessment



Workflow for the design of scaled wind turbine



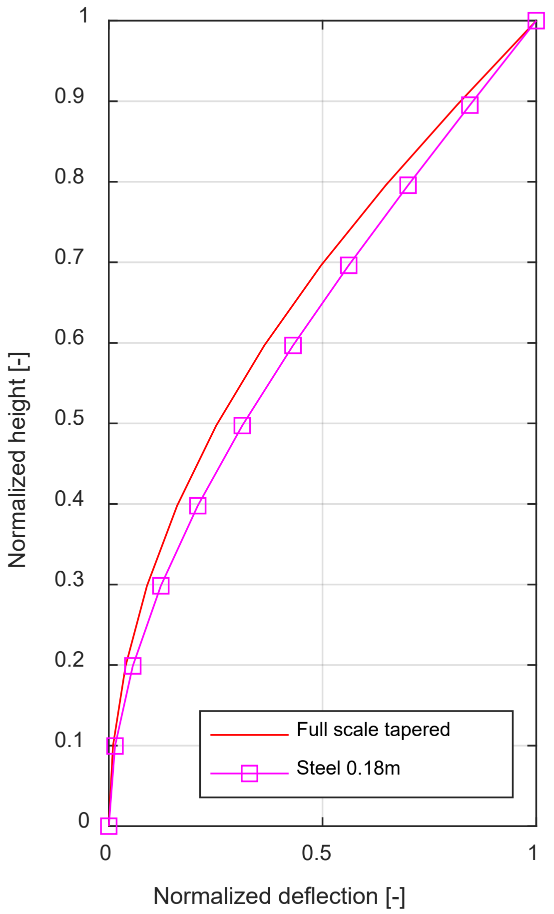
Structural tower design

Froude scaling of the aeroelastic tower parameters in order to match f-a and s-s frequencies and modal shape

↓

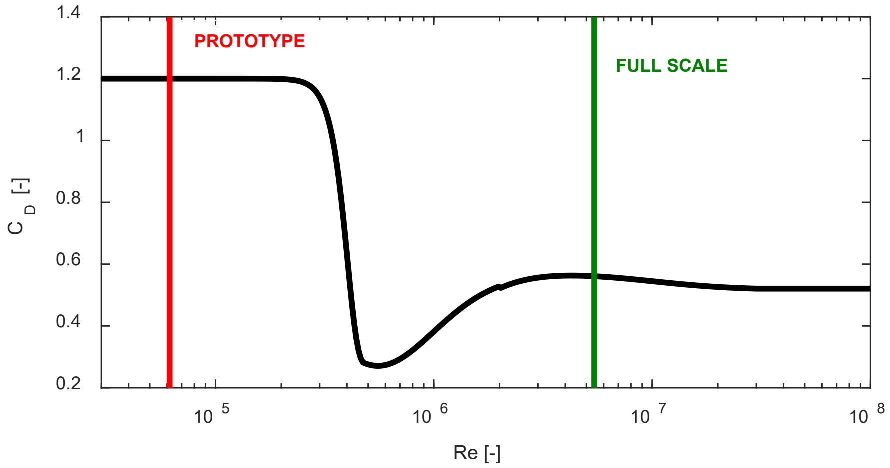
Scaled distributed stiffness and inertial properties

Assessments (for **Natural Lab model**):
- ✓ Tower buckling
- ✓ Top plate connection
- ✓ Stress concentration at tower-stiffener interface



Aerodynamic tower design

Lack in Re Number between model and full-scale is expected

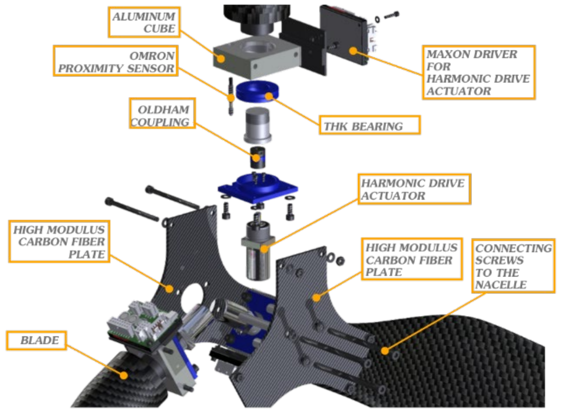


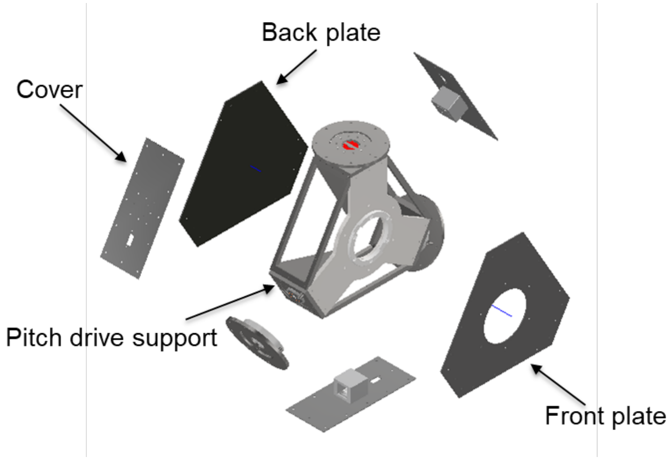
Similar fluid-structure interactions are expected in postcritical and subcritical Re Number range

Main requirements:

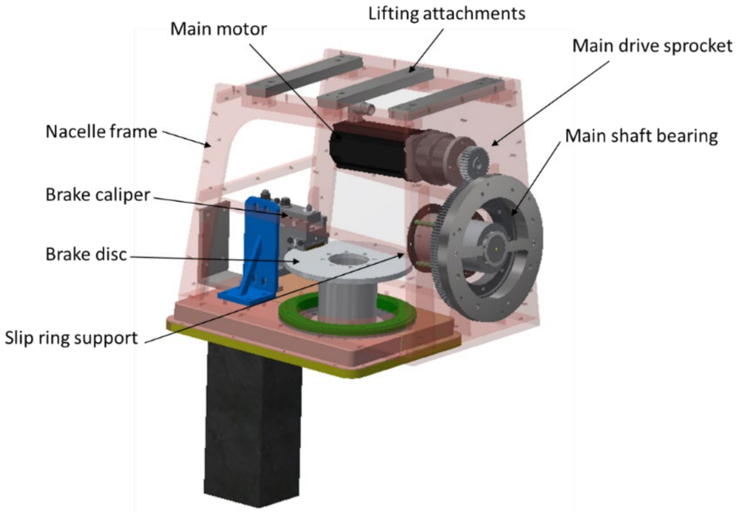
- ❑ Masses properly scaled
- ❑ Hub and Nacelle functionalities properly reproduced

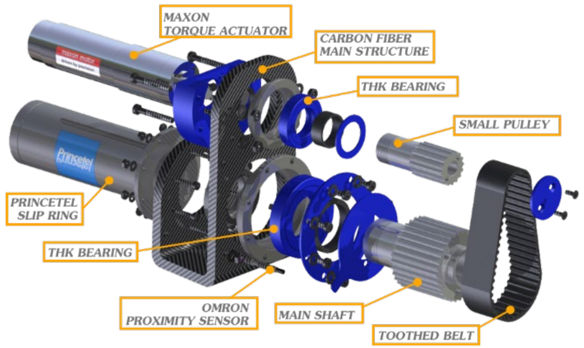
→ Optimized solutions to obtain the functionalities controlling the masses





Component	Target [kg]	Model [kg]
Rotor	68	122
Nacelle	131	174





Component	Target [g]	Model [g]
Rotor	540	1270
Nacelle	1535	1057.3

POWER CONTROLLER

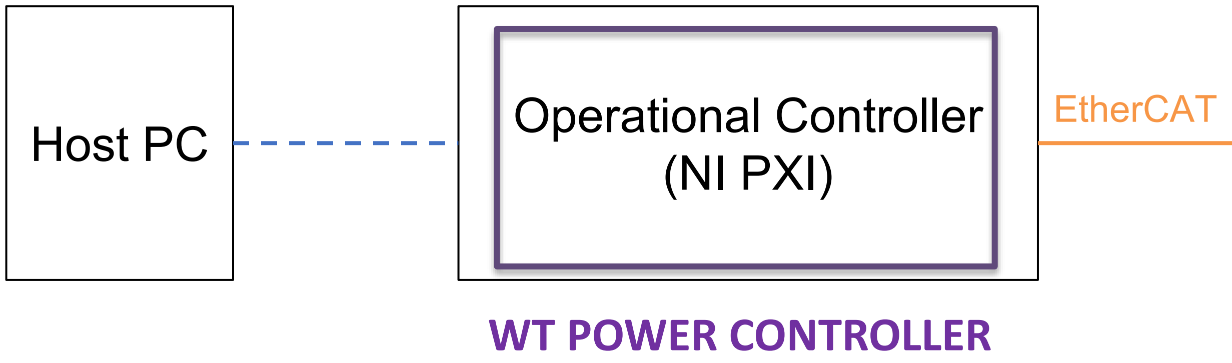
- VSVP region based, derived from DTU Basic WE controller / previous works
  - Torque controller
  - Collective pitch controller

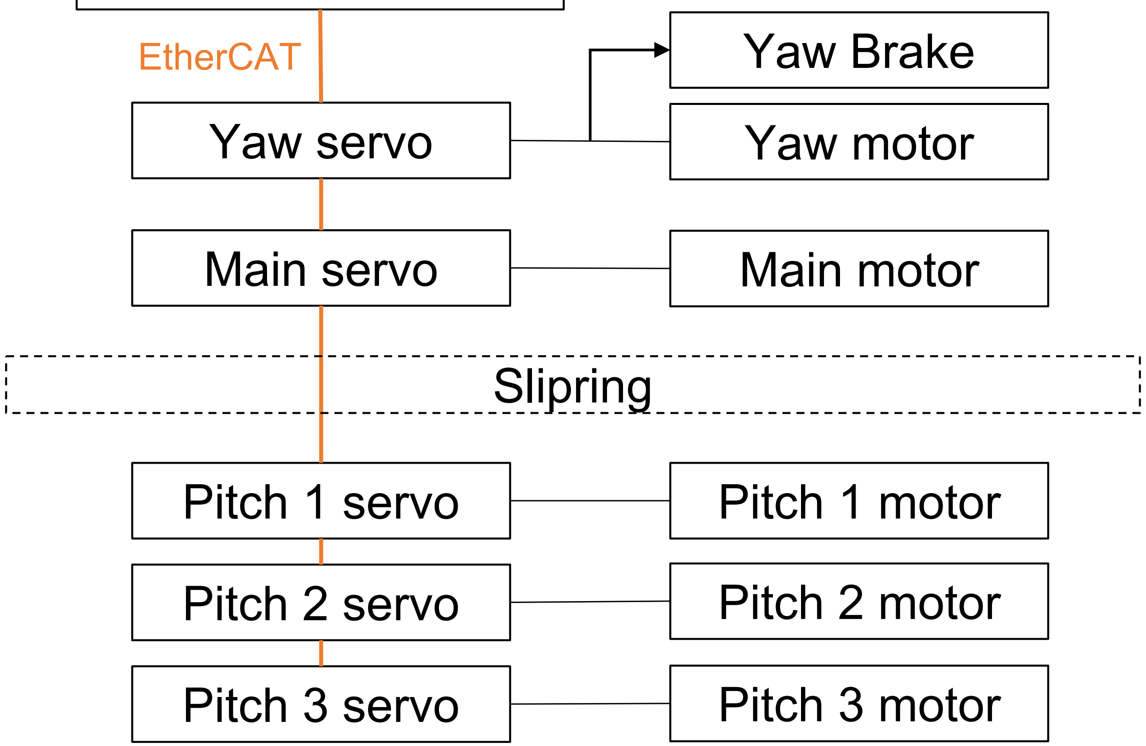
- First attempt parameters:
  - Scaled from DTU10MW
  - Adjusted with 1dof drivetrain model to reproduce FS dynamics
  - New aerodynamic gain scheduling factors from aero sensitivity fititng
  - Simulations in FAST/Simulink (turbine-only model)
  - Check floating issue (in FAST aero/hydro model)

YAW CONTROLLER

- Anemometer wind direction feedback
- Misalignment range

→ For Natural Laboratory tests





Operational controller

- RT controller for turbine power control and yaw control
- Manages all operating modes: **state machine**
- EtherCAT communication with SC: actuators ref, sensors fb, state
- Acquisition
- Monitoring
- Programmable in house (labview)

Safety controller

- Operation supervision: safety boundaries
- Faults management
- Manages system initialization
- Allow manual operations
- Externally programmed and certified