TotalEnergies

# On multi-physics modelling in Wind Energy industry

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1. Intro Wind Energy
2. Motivations and needs for simulations in Wind Energy
3. Multi-physics modelling
4. On-going challenges

# 01.

# Intro Wind Energy

# Wind Energy status

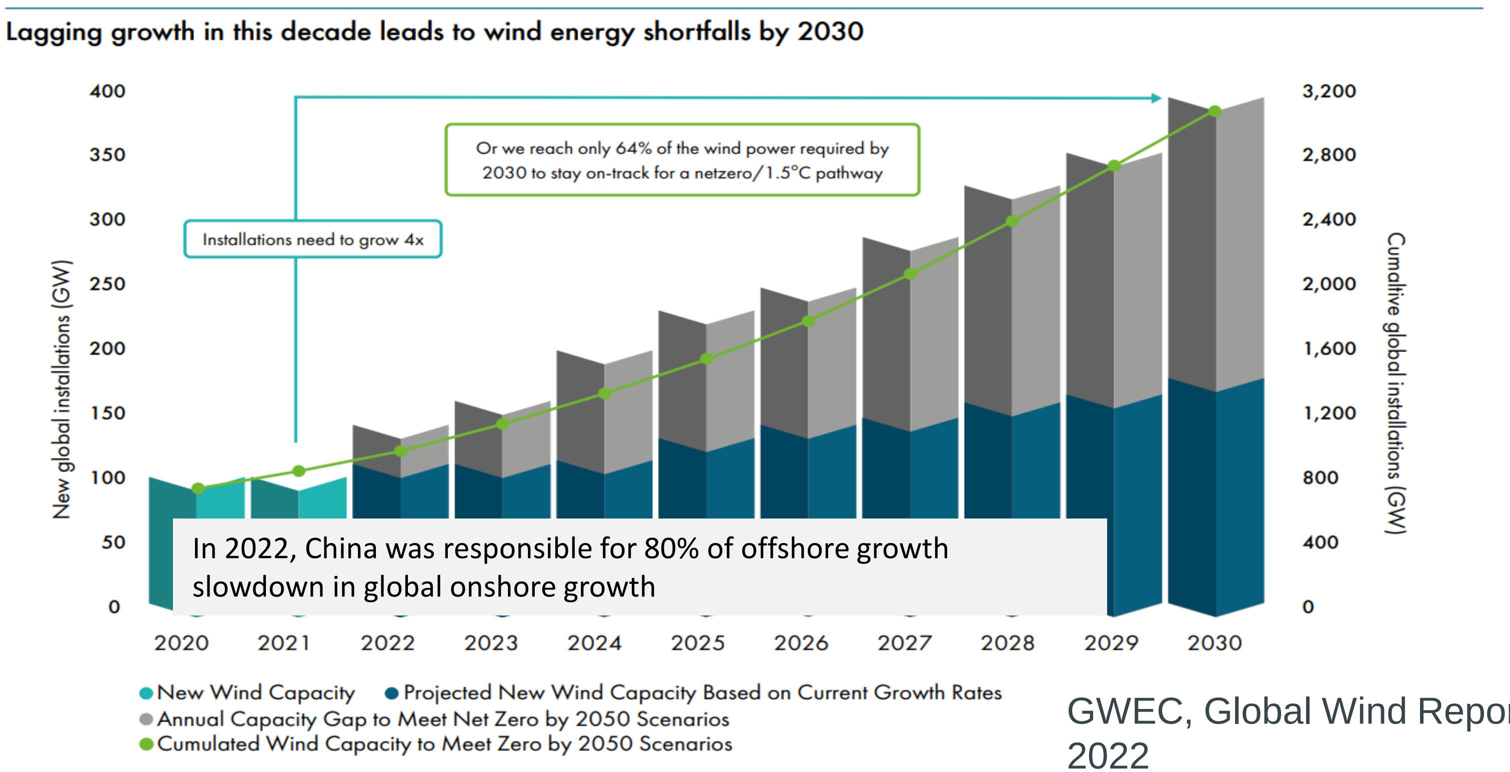
- Status today: **~830 GW worldwide** (for the energy consider 25% of capacity factor)

Wind farms:

**Onshore 93% of the 830 GW**

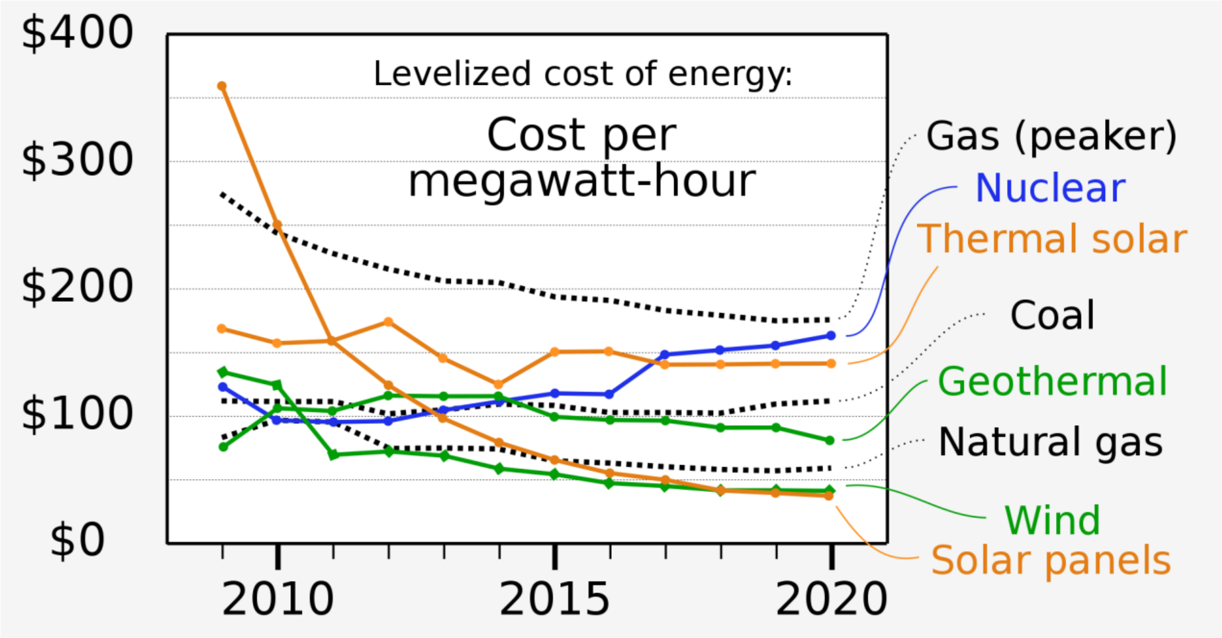
Offshore 7% but with fast growth

- bottom-fixed, Water Depth < 60m
- Floating, Water Depth > 60m

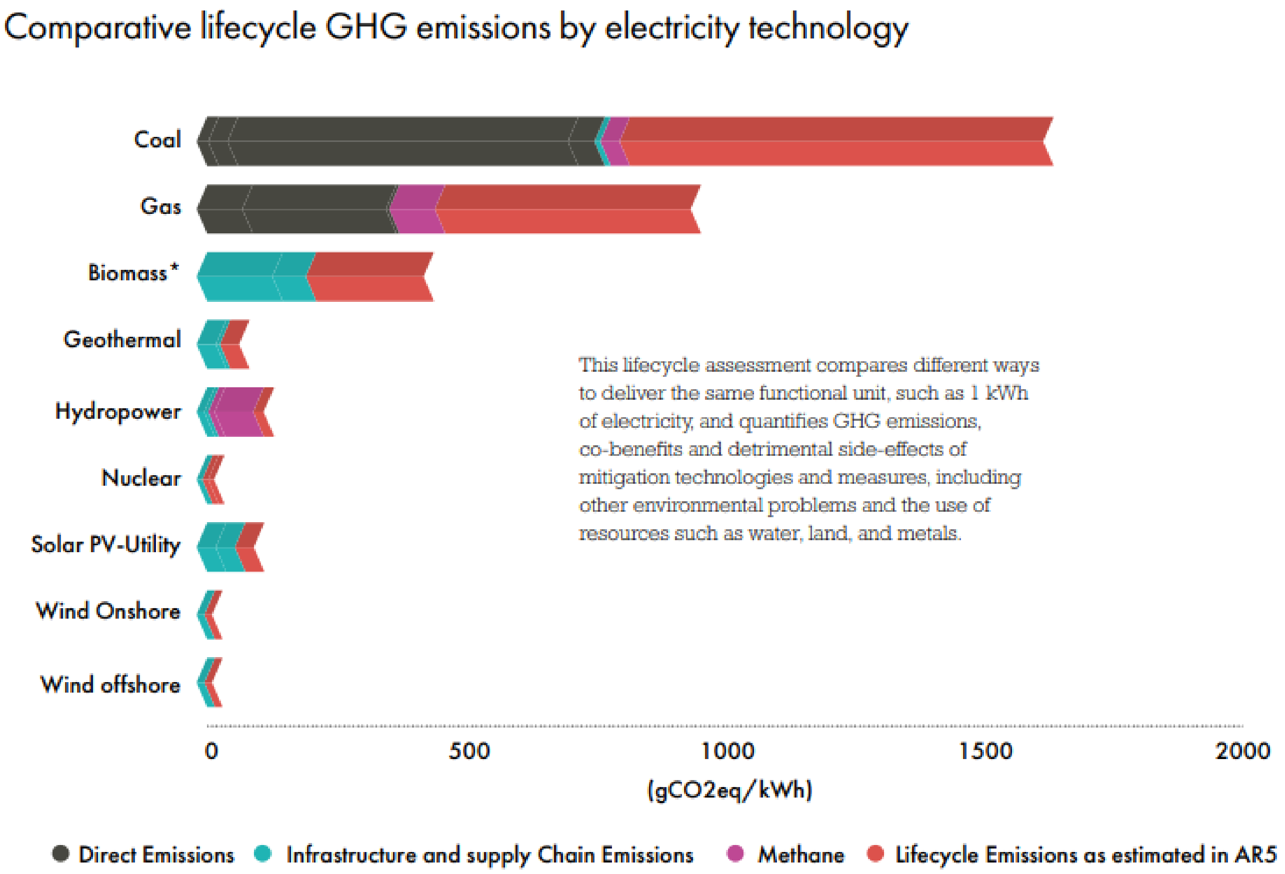



GWEC, Global Wind Report 2022

# Costs and GreenHouse Gas emissions

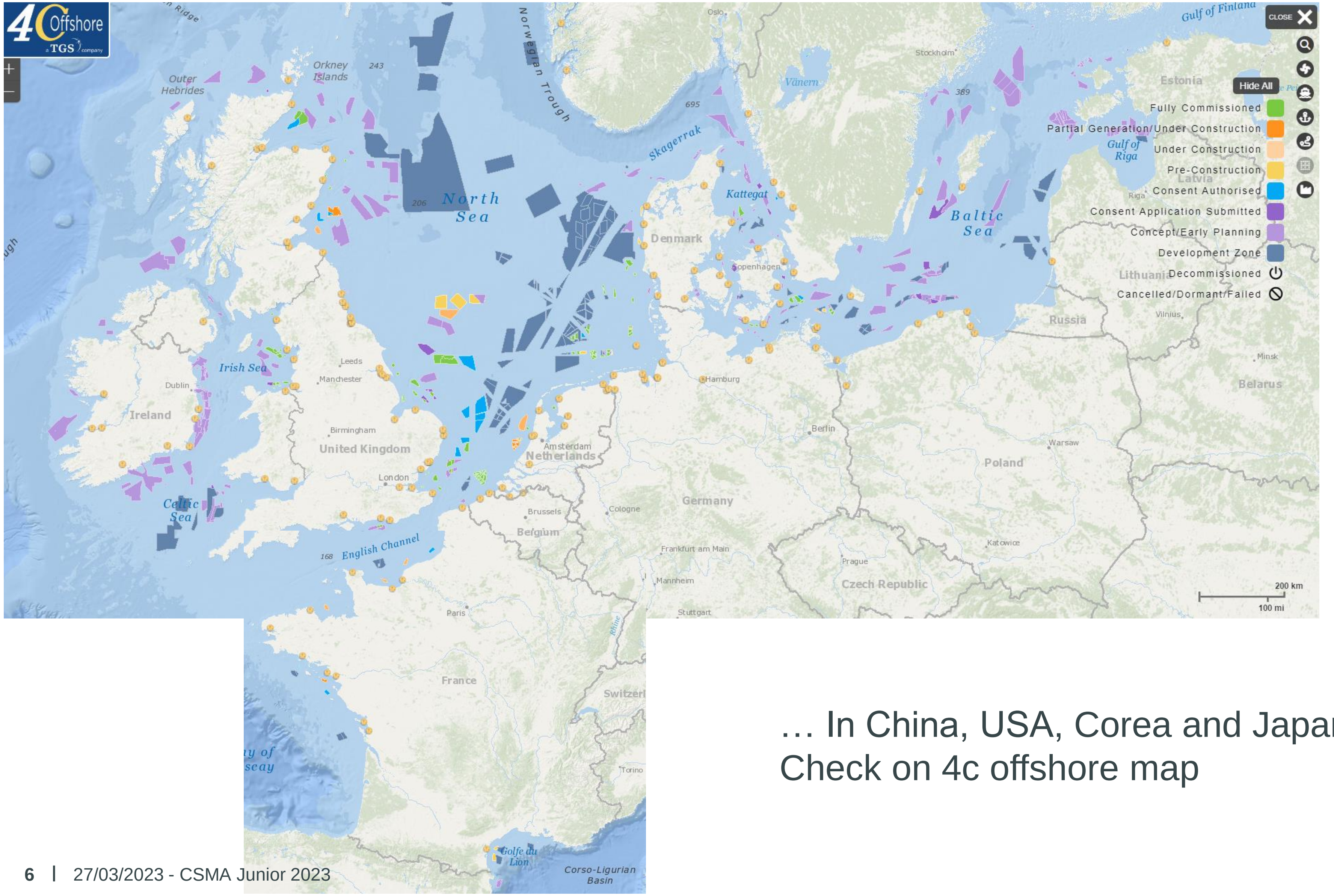



Source: Lazard, levelized cost of electricity

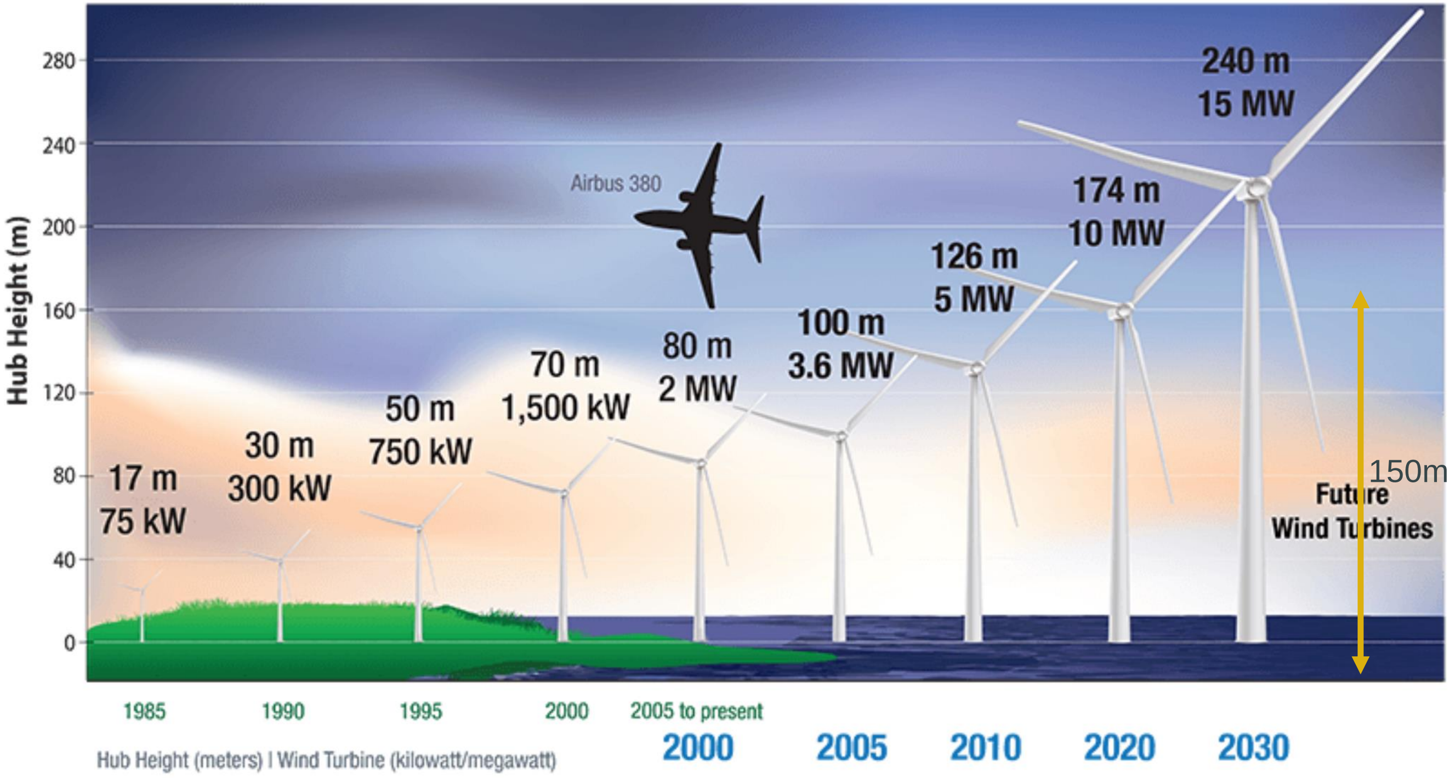



Source: GWEC, global wind report 2022

# Where is the Offshore wind




… In China, USA, Corea and Japan is also growing
Check on 4c offshore map




Offshore wind turbines on the rise. Improved technology has increased the size of offshore turbines, and a single General Electric 12-megawatt Haliade-X turbine can power up to 4,500 average U.S. homes, depending on the wind resources available at a given moment. *Illustration by Josh Bauer, NREL*

Offshore:
biggest prototype installed: 14MW SGRE, 236 m diameter.
biggest operating: GE 12MW. 15MW, 16MW already announced. 20MW and more to come.

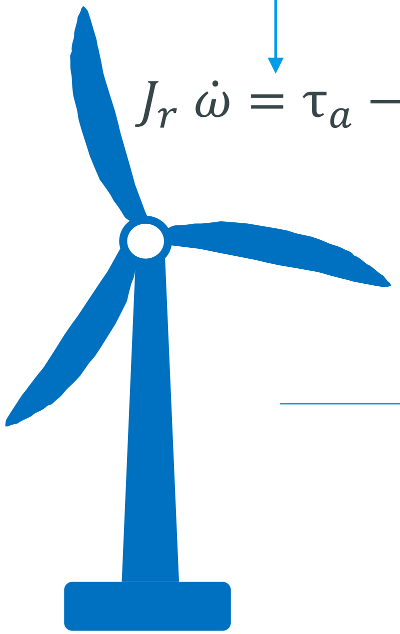
Onshore: 5 – 7 MW.
Limitations: **logistic, civil consent, impact on the ecosystem, price of the land**

# WTG functioning

Input: $\tau_a$ increase because of wind increases

P-I control: $\Delta\beta = K_p\,\Delta\omega + K_I \int_0^T \delta\omega \; dt$

$$J_r\,\dot{\omega} = \tau_a - \tau_g \;\rightarrow\; \Delta\omega$$



$\beta$, $\beta_{min,max}$, $\Delta\omega$

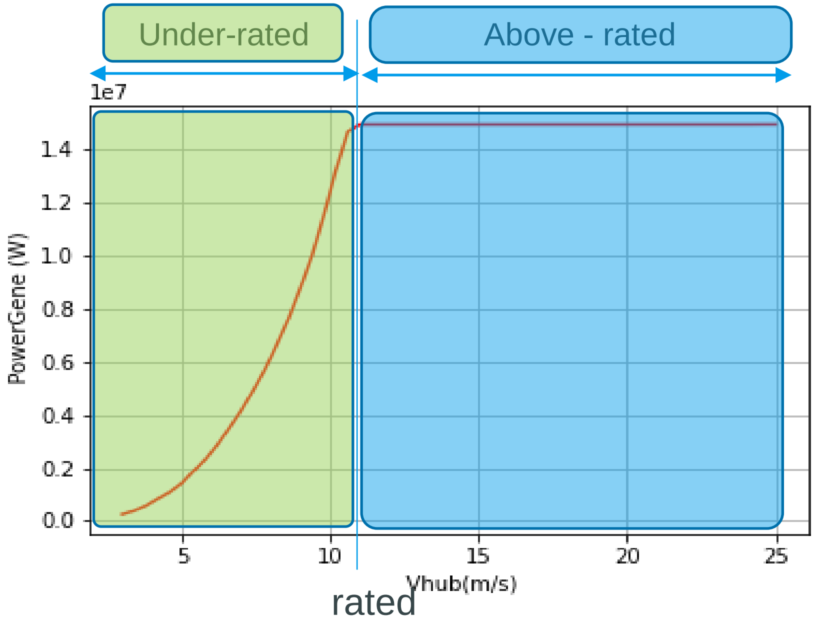
Collective blade pitch control

$\tau_a \propto \Delta\beta$

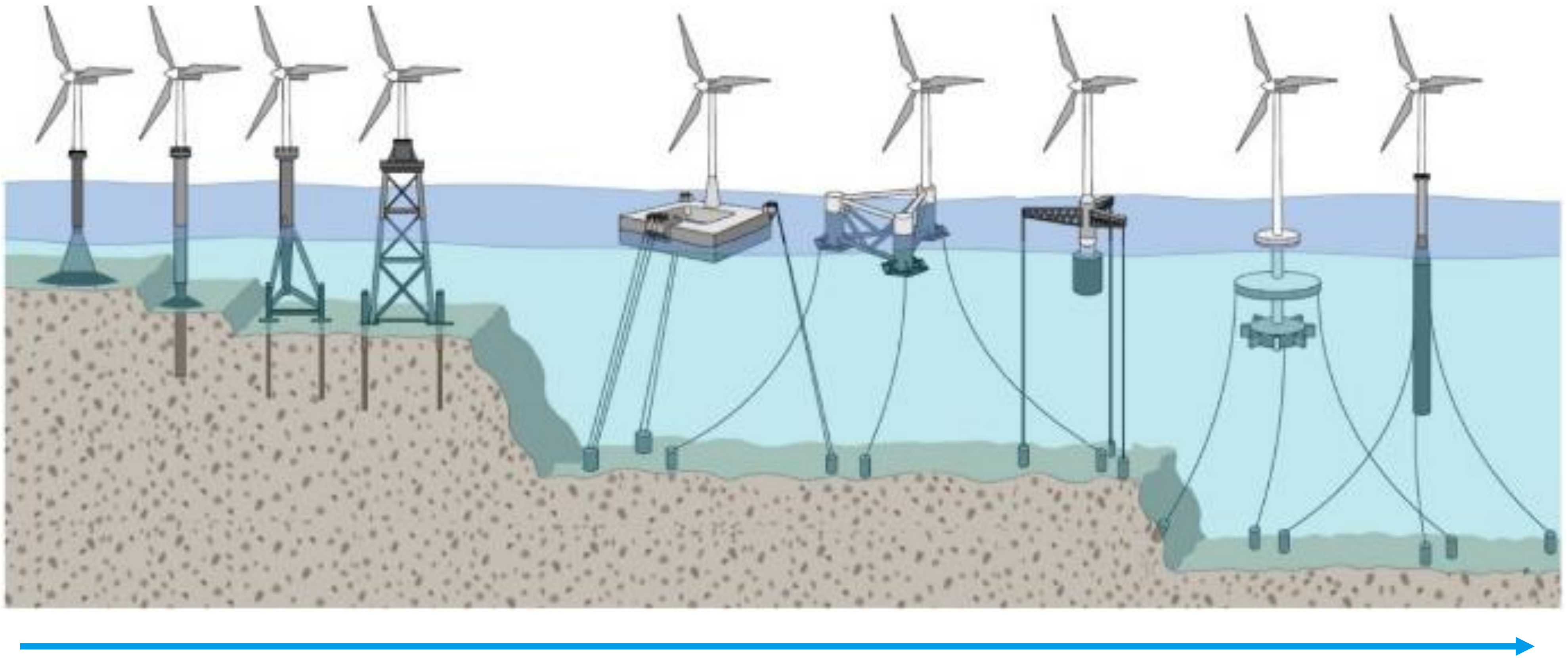
Generator torque control

$\tau_g$

$$T_{gene} = K_\tau\,\left(\omega_{gene}^2 + \Delta\omega^2\right) = K\omega_{new}^2$$




$K_\tau$ , $K_p$ , $K_I$ to be set-up by control tuning

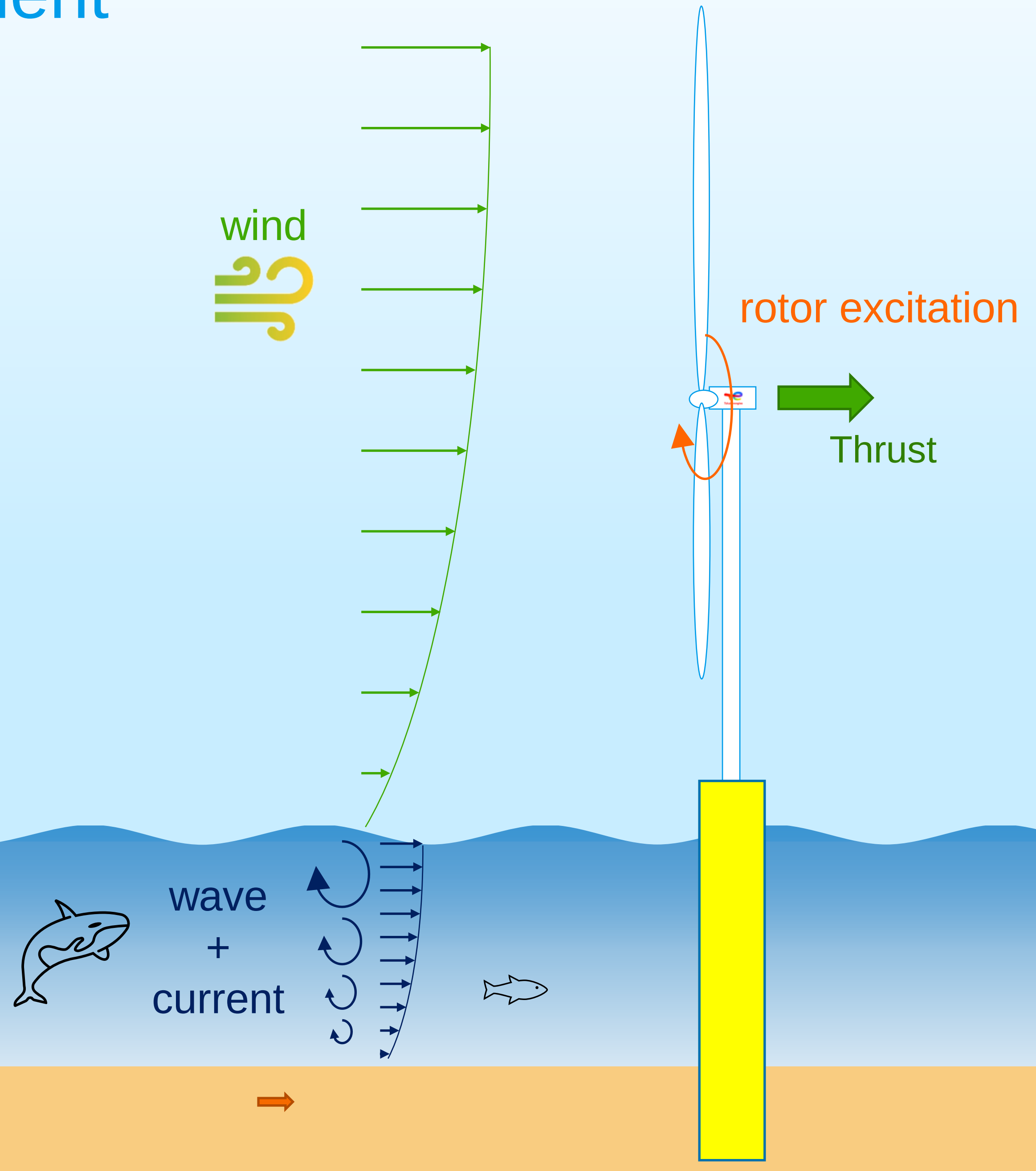


→ 30m 60m 200m 600m – 1000m

# 02.

## Motivations and needs for simulations in Wind Energy

# Environment



# Elements of design of structures

Design consists in:

- To evaluate the external environmental conditions relative to each possible scenario:

  - Collect data for wind and waves during X years
  --> hp: data representative of N*X years of system life-time

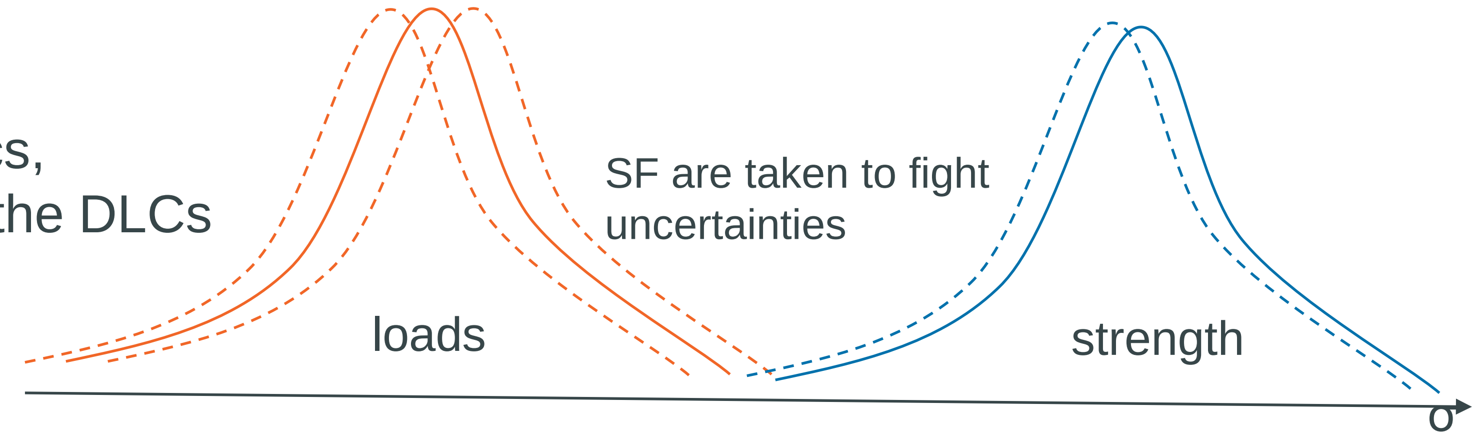
  - Fit models on the data to extrapolate long-term conditions

  - Discretize the distributions to generate case studies (DLCs)
  --> hp: discretization enough accurate to avoid errors in the integration

- To model the environmental loads

- Considering the loads and the kinematics,
  Model the resistance of the structure to the DLCs

- Check the criteria



# Elements of design of structures

Design consists in:

- To evaluate the external environmental conditions relative to each possible scenario:

- Collect data for wind and waves during X years
--> hp: data representative of N*X years of system life-time

- Fit models on the data to extrapolate long-term conditions

→ Stochastic uncertainties

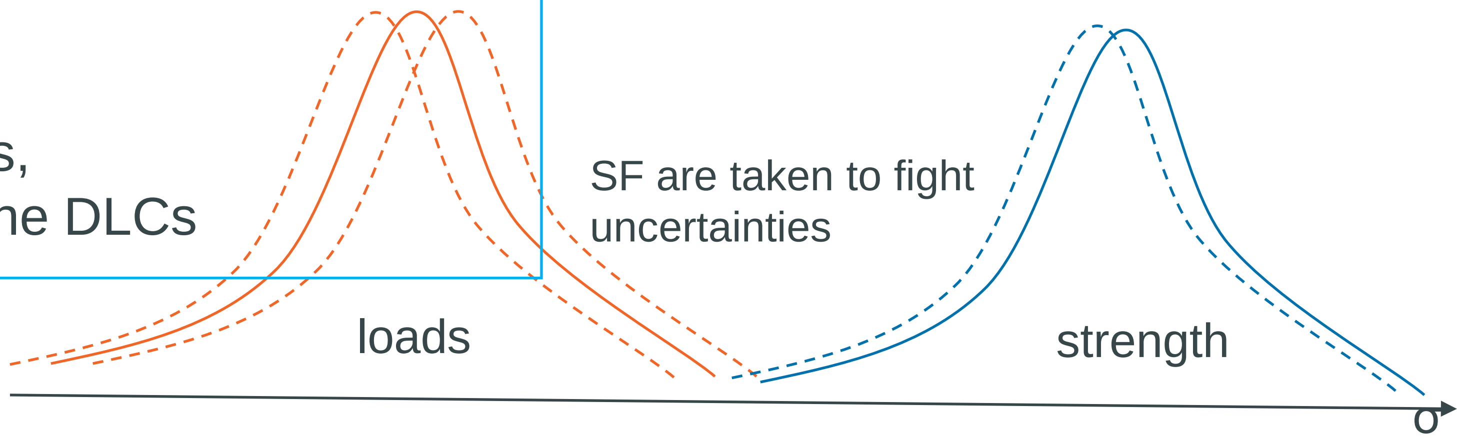
- Discretize the distributions to generate case studies (DLCs)
--> hp: discretization enough accurate to avoid errors in the integration

→ Epistemic uncertainties

- To model the environmental loads

- Considering the loads and the kinematics,
Model the resistance of the structure to the DLCs

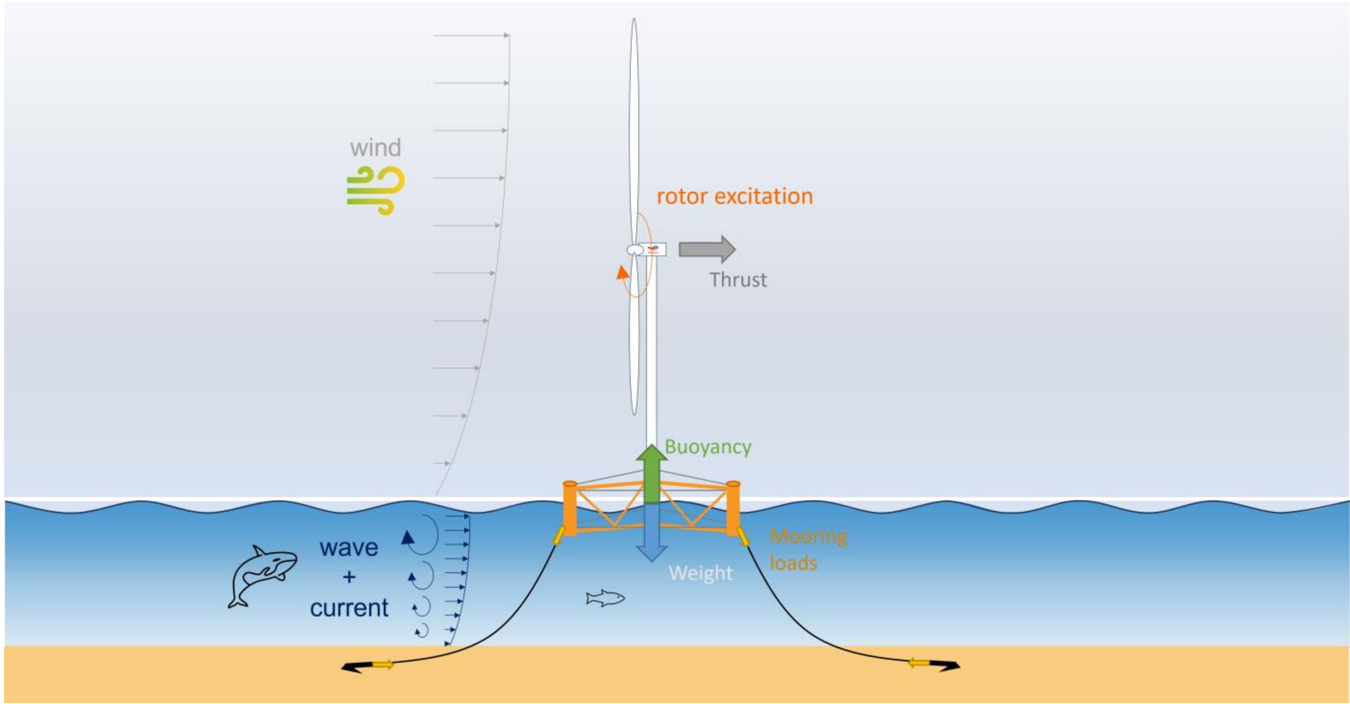
- Check the criteria



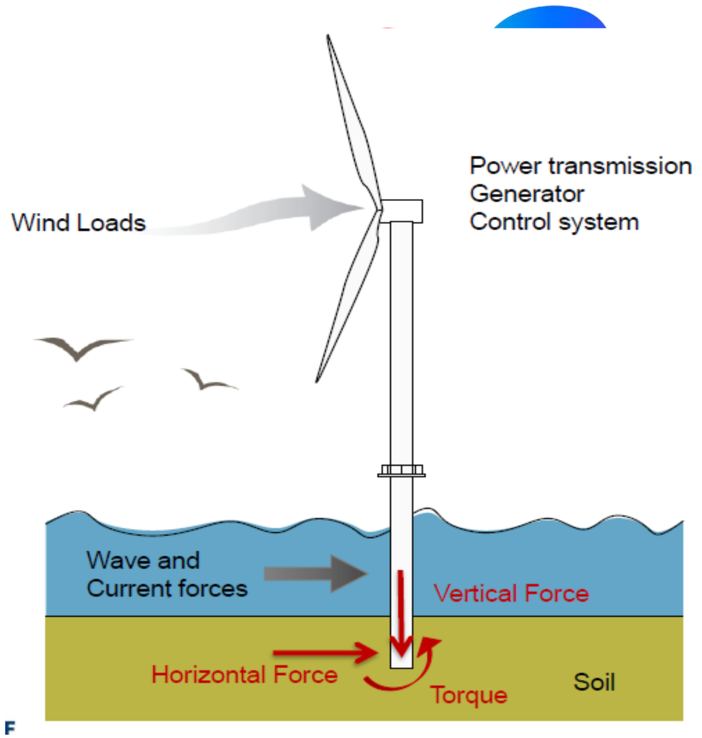
# Elements of design of structures

- Design of each component of the structure must comply with different criteria

- Each component has criteria related to:
  - extreme events (Ultimate Loads S.)
  - service scenarios (Service Loads S.)
  - in-operation scenarios, leading to fatigue (Fatigue Loads S.)



# Fatigue, damage counting




**Fatigue → more than 10 millions cycles**

a full description of the load cases, driven by the various environmental conditions, **<u>can require around 1 million calculations:</u>**

**Description of a FLS case study, according to the *IEC- 61400-3***

•**<u>Wind</u>: *360 different winds***

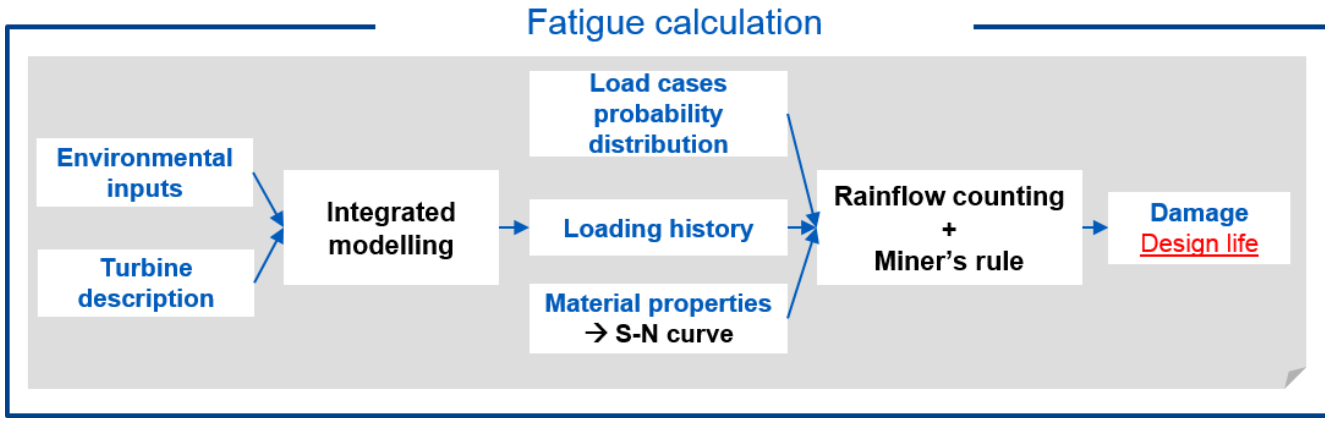
- $V_{in} < V < V_{out}$
- bin: 1-2m/s
- 6 seeds of wind to account for variability of turbulence
- yaw misalignment (+/- 8°)

•**<u>Waves</u>: *80 different sea states***

- Described by wave height/ period (Hs, Tp)

•**<u>Wind-Wave misalignment</u>: *12 directions***

•**<u>Tide</u>: *3 levels of tide***

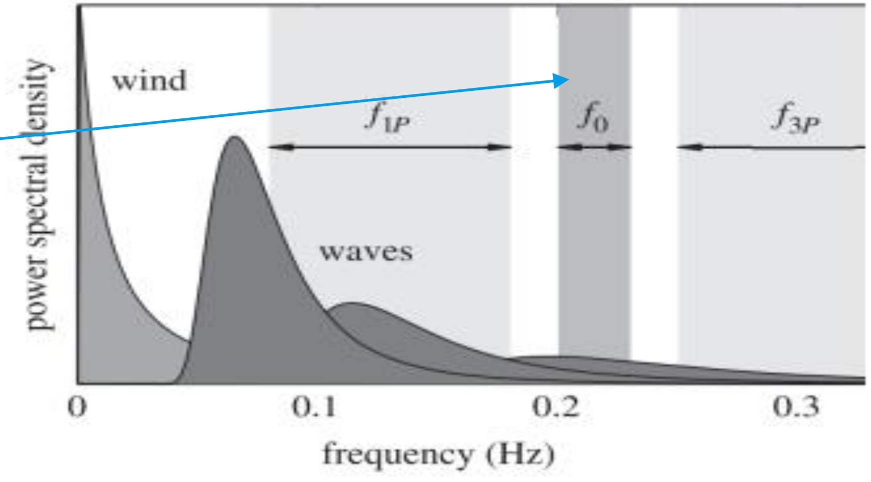


# Design of tower-foundation interface

- **Tower-foundation interface design [IEC61400-3]: Criteria:**

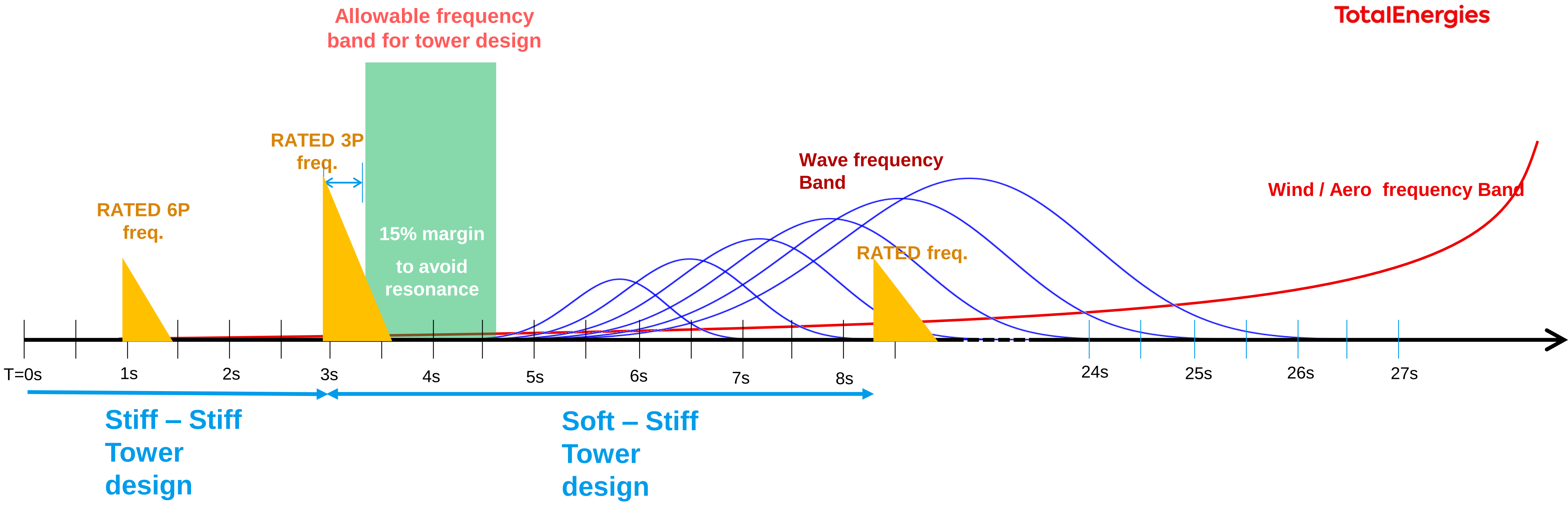
1. Structure remains within the elastic limit ($\sigma_{eq}\ SF\ < \sigma_y$) SF ( DLC ) = [1.1 ; 1.35]
2. Structure does not encounter local and global instabilities (buckling)
3. During the lifetime, structure cumulates fatigue damage within the limit (SF = 3.0)
4. Spectrum of the structure does not cross loads main spectra

1st nat. freq.
Soft-stiff design




Kallehave *et al.* (2015)

# System spectra



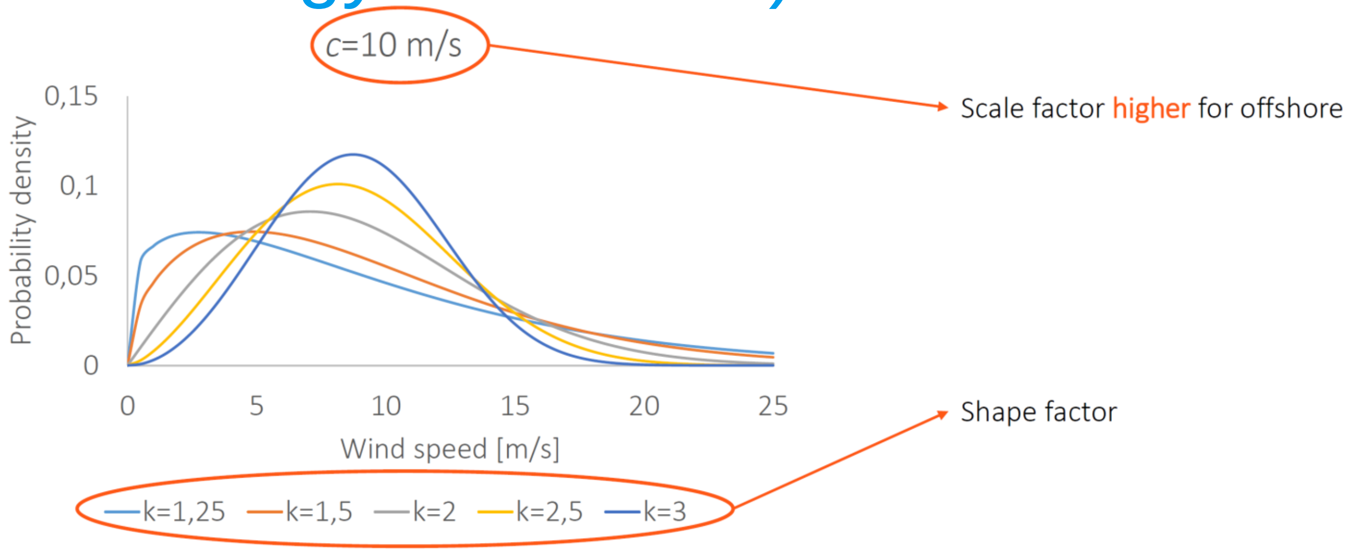
# 03.

# Multi-physics modelling

# Wind model (ref. Jenkins, Wind Energy Handbook)

Mean wind:

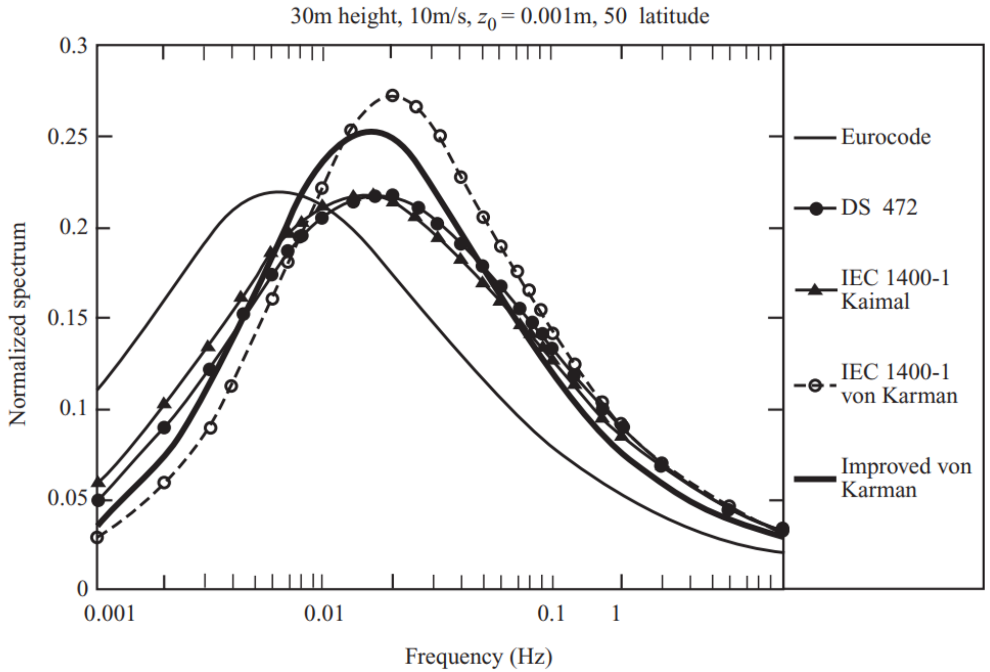
$$p(\overline{U}) = k\frac{U^{k-1}}{c^k}\ e^{\left(-\frac{U}{c}\right)^k}$$




Turbulence around mean:

- pseudo-stochastic model
1 Integer value determine the initial condition of the turbulent time-series

$$T.I. = \frac{\sigma}{\overline{U}}$$



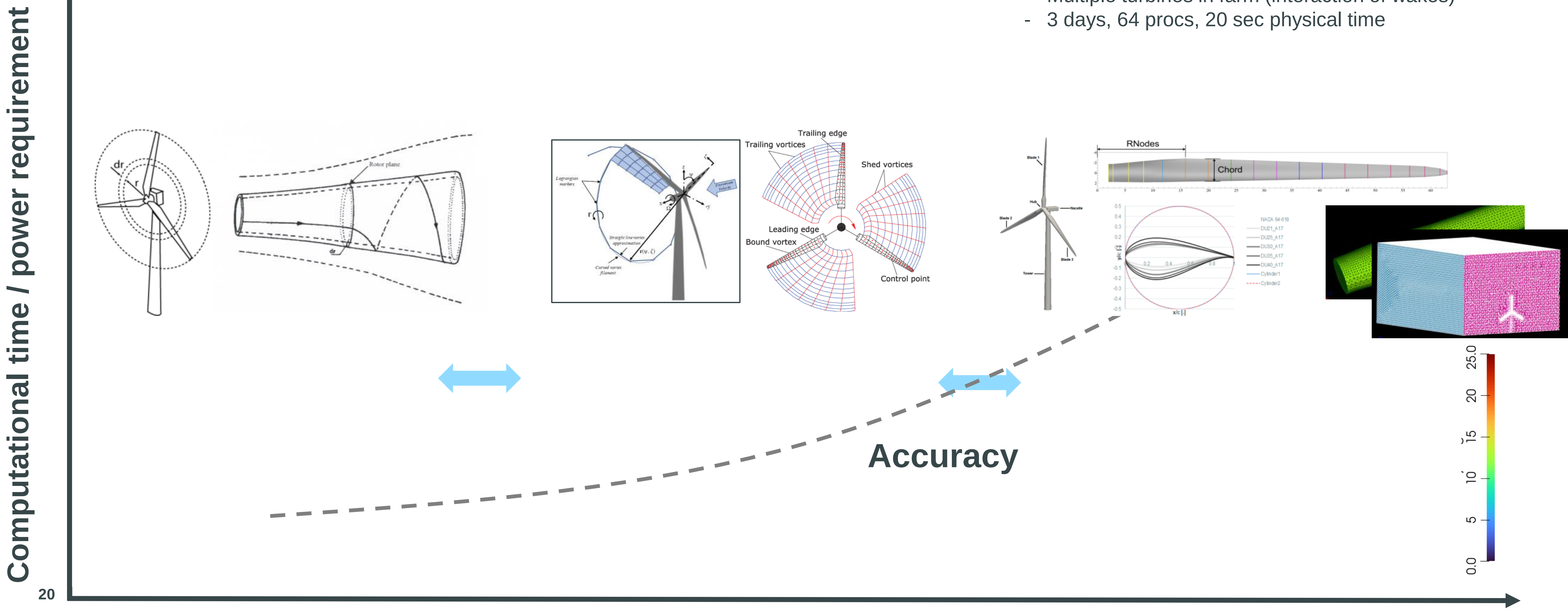
# Aerodynamic loads

ExaWind: OpenFAST + Nalu-Wind

**Low-fidelity simulation: Blade Element Momentum**
- Steady state wake
- Direct inflow of wind
- Small rotor diameter (small capacity turbines)
- Single turbine (no-interaction with other turbines)
- 5-10 minutes, 1 CPU

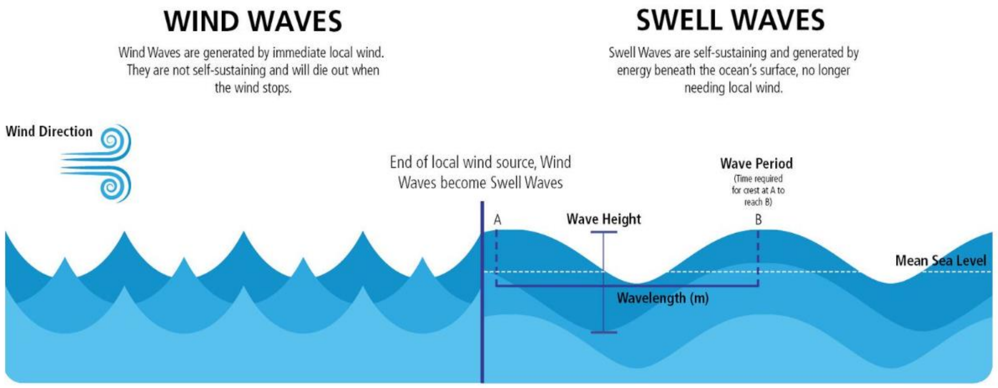
**Medium-fidelity simulation: Free Vortex Wake**
- Steady / non-steady wake
- Direct / Skewed inflow of wind
- Large rotor diameter (higher capapcity turbines)
- Multiple turbines in farm (interaction of wakes)
- 1-2 hours, 1 CPU

**High-fidelity simulation: Blade Resolved Large Eddy Simulation**
- Understand complex multi-physics using fundamental
- Direct / Skewed inflow of wind
- Large rotor diameter (higher capapcity turbines)
- Multiple turbines in farm (interaction of wakes)
- 3 days, 64 procs, 20 sec physical time

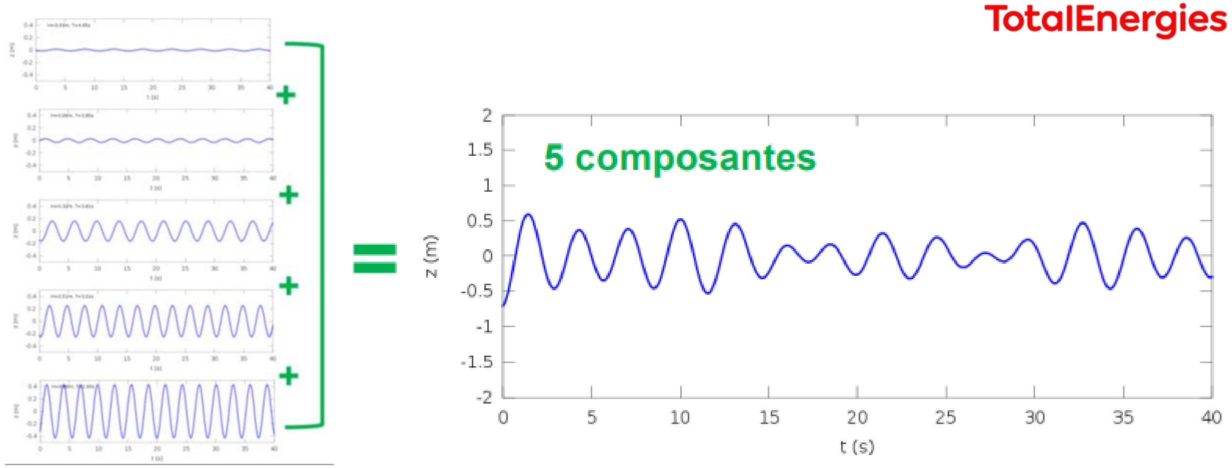


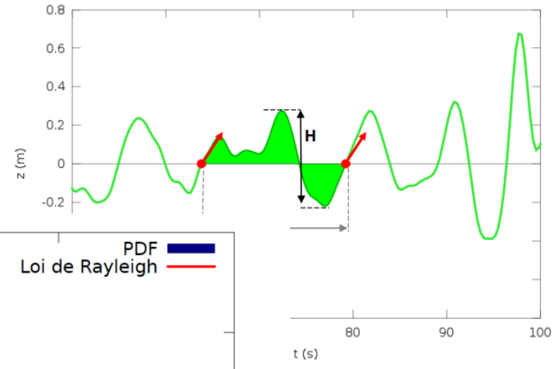
# Wave model (ref. Bernard Molin)

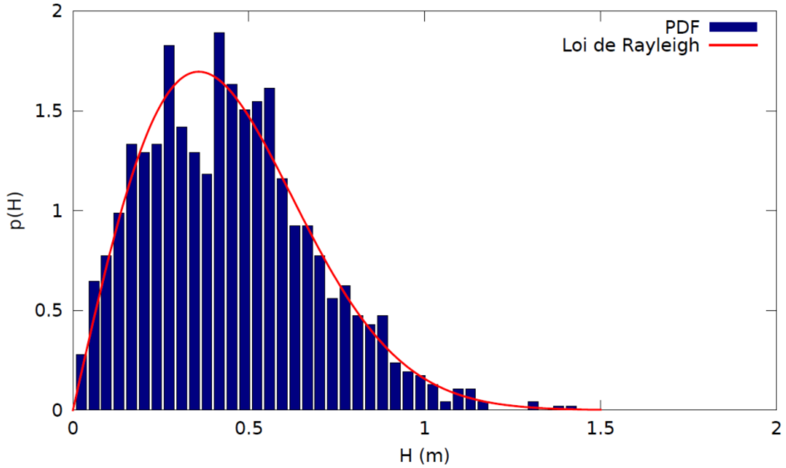
- Wind waves: 1 – 5 sec. ; 2 – 8 sec.
- Swell: 10 – 25 seconds




Fetch zone

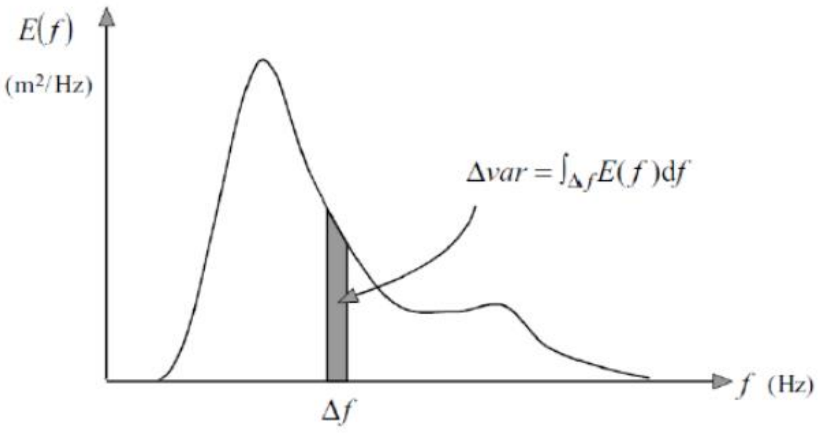


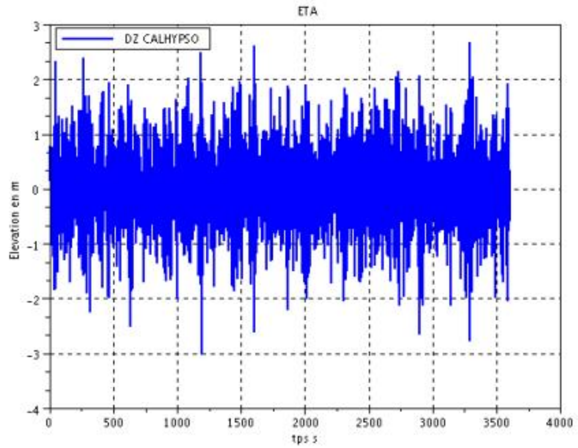




- $\eta(x,t) = a\sin(\phi\,(x,t))$
- $\phi = 2\,\pi\,\left(\frac{x}{\lambda} - \frac{t}{T}\right) = kx\, - \omega t$
- $\lambda$ wavelength (m); $t$ period (s);
  $k$ wavenumber (rad / m); $\omega$ angular freq. (rad / s);

# Wave model (ref. Bernard Molin)



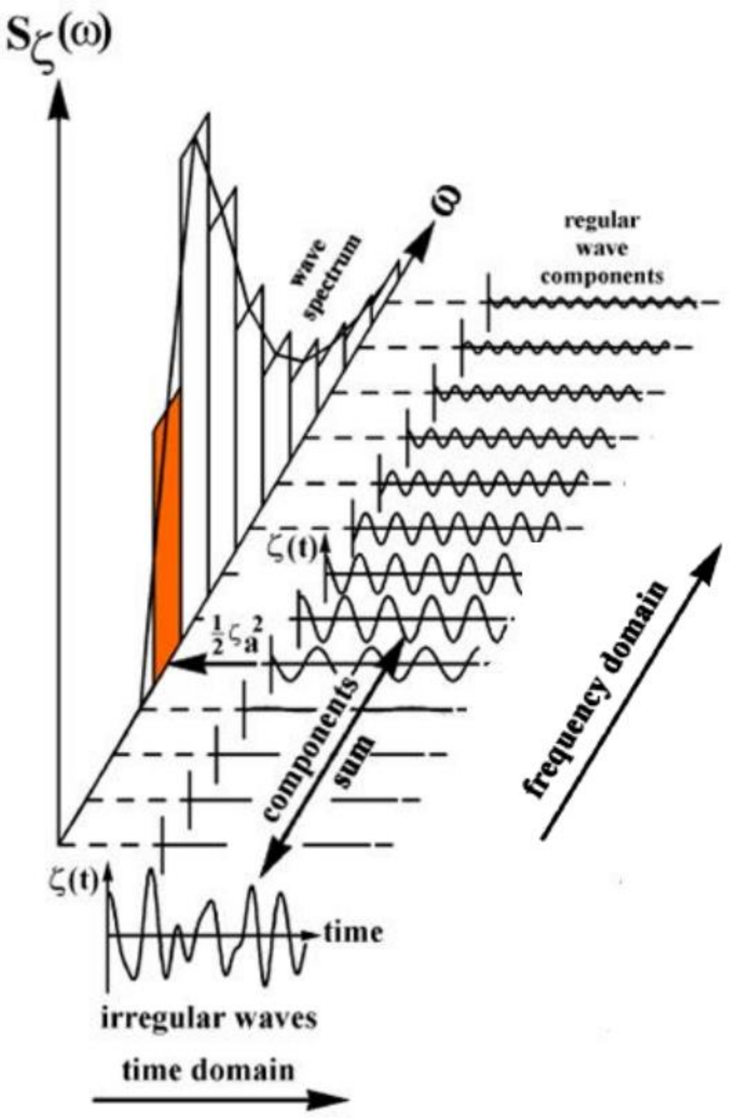

FFT




$$S(\omega)d\omega$$

$$S(\omega)d\omega = \frac{A_i^2}{2}$$

$$\eta(t) = \sum A_i \cos(\omega_i t + \varphi_i)$$




$$R(\tau) = E\{\eta(t)\ \eta(t+\tau)\} = \int_{-\infty}^{+\infty} \eta(t)\ \eta(t+\tau)\ dt$$

$$R(\tau) = \int_{0}^{+\infty} S(\infty)\ cos\ \omega\tau\ dt$$

# Hydrodynamics loads

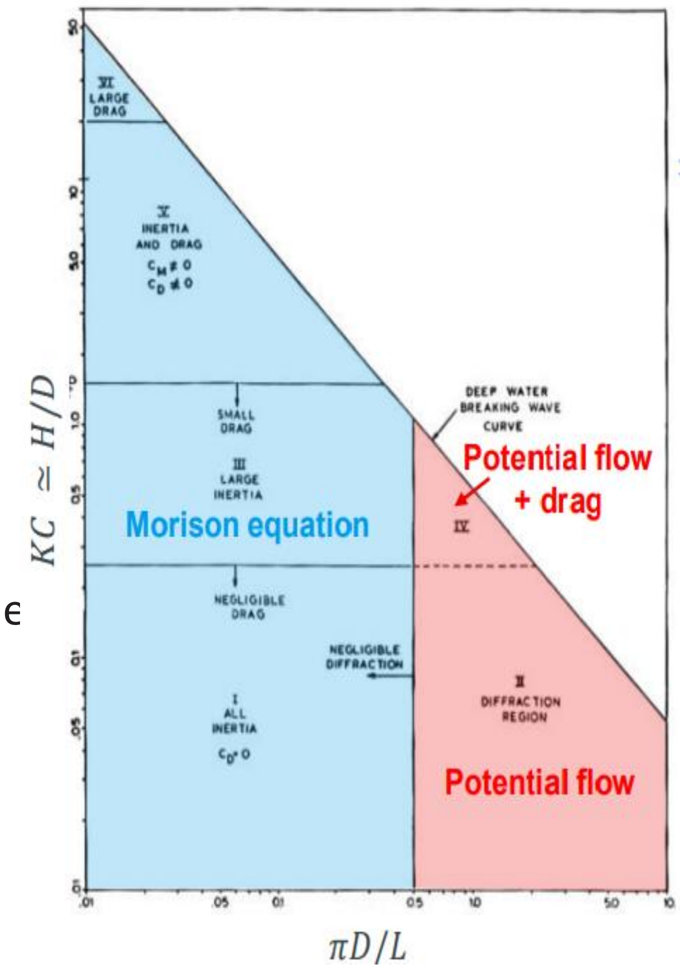
$$F_x \;=\; \rho\pi\frac{D^2}{4}\dot{u} \;+\; \rho\,(1+C_m)\pi\frac{D^2}{4}\,\dot{u} \;+\; \frac{1}{2}\,\rho\,C_D\,D\,u\,|u|$$

Froude-Krylov Added mass Drag

$$\phi = \phi_I + \phi_D + \phi_R$$

Drag term ($C_D \approx 1.0 - 1.2$) ; inertial term ($C_m \approx 0.7 - 1.0$)

They depend on Reynolds $R_e$, Keulegan-Carpenter $K_c$ and Stokes param. $\beta_S$




For large and moving components, only Morison's drag term is included to account for viscous e

the inertial term is accounted for by the more appropriate first order potential solution:

- Froude-Krylov load: pressure of the undisturbed wave on the body
- Diffraction load: pressure of the disturbed waves on the body
- Radiation load: pressure of the fluid induced by the movements of the body

They are calculated by the "Potential flow theory" (linearity), Boundary Elements Method.

The force are calculated for the body in the frequency domain (linear) → Hydrodynamic database (OFFLINE)

For time-domain simulation they are recombined to give the right force on the COG of the body for the given waves. (ONLINE)

# Structural model: Spinning finite elements

A wind turbine has a rotating body → multi-body dynamics:

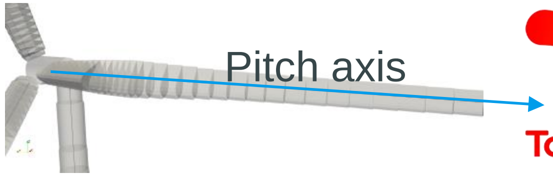
A multibody system is a mechanical system consisting of a number of interconnected components, or parts, performing motions that may involve **large translations and rotations** as well as small displacements such as vibrations.

The rotating part implies the description of the mechanics in **non-inertial frames: explicit expressions of Coriolis and inertial forces need to be considered**

M.M. Sajeer et al.,  Mechanical Systems and Signal Processing 145 (2020), https://doi.org/10.1016/j.ymssp.2020.106924

Leung and Fung, Spinning finite elements, Journal of Sound and Vibration 125 (1988), https://doi.org/10.1016/0022-460X(88)90259-3

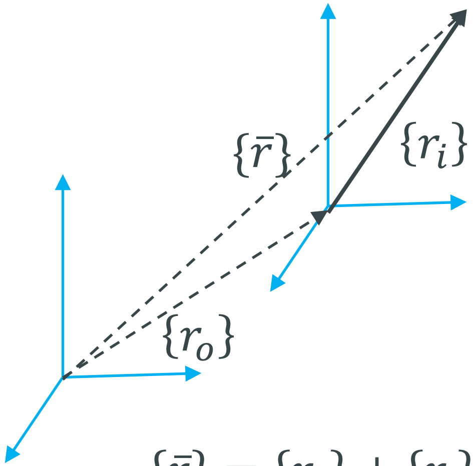
Kinematics description of the rotor:




- NO SPIN with respect to blade pitch axis
  → torsional stiffness is same as non-spinning beam and is assumed to be uncoupled with the bending and axial def.

- Rotor rotates around an axis $y' // Y$ . The rotation vector is assumed to be constant: gyroscopic effect couples rotational dofs perpendicular to the spinning axis

$$[\Omega] = \Omega \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

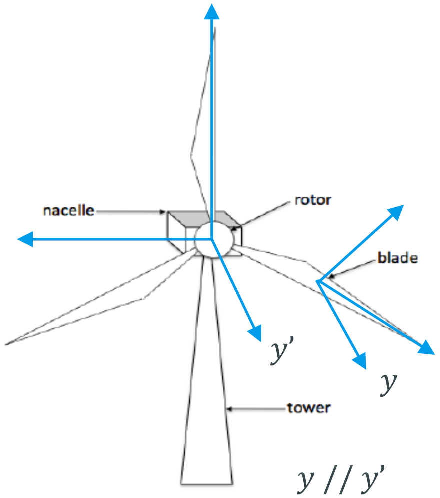


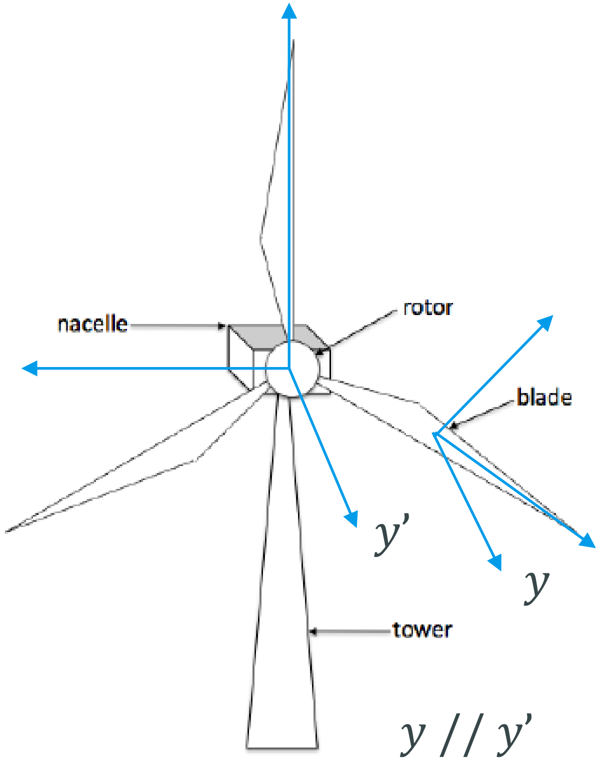

$$\{\bar{r}\} = \{r_o\} + \{r_i\}$$

- The velocity, in the inertial frame, of any point of the blade: $\{v\} = \{\dot{r_o}\} + [\Omega]\{r_i\}$

- The acceleration, in the inertial frame, of any point of the blade: $\{a\} = \{\ddot{r_o}\} + [\dot{\Omega}]\{r_i\} + [\Omega][\Omega]\{r_i\}$

$\{\dot{r_o}\}$ is the translational vel. of the local frame wrt the inertial one
$[\Omega]$ is the rotational vel. of the local frame wrt the inertial one
$\{r_i\}$ is the position vect. of a point on the blade wrt the local ref. frame






From Lagragian equation:

$$\frac{d}{dt}\left(\frac{\delta T}{\delta\{\dot{u}\}}\right) - \frac{\delta T}{\delta\{u\}} + \frac{\delta U}{\delta\{u\}} = \{F\}$$

By defining finite elements, and finite elements shape functions (for beams) $N$, it leads to:

$$M\ \ddot{q} \ + 2\ G\ \dot{q} + \ (K_e \ + K_g \ - K_\Omega)\ q \ = \ F(t) \ + \int \rho N^T \ (\ddot{s} \ + \dot{\Omega}\ x + \Omega^2\ x)\ ds$$

Skew-symmetric gyro damping matrix

Geom. stiff

Spinning softning

Rigid body motion inertias

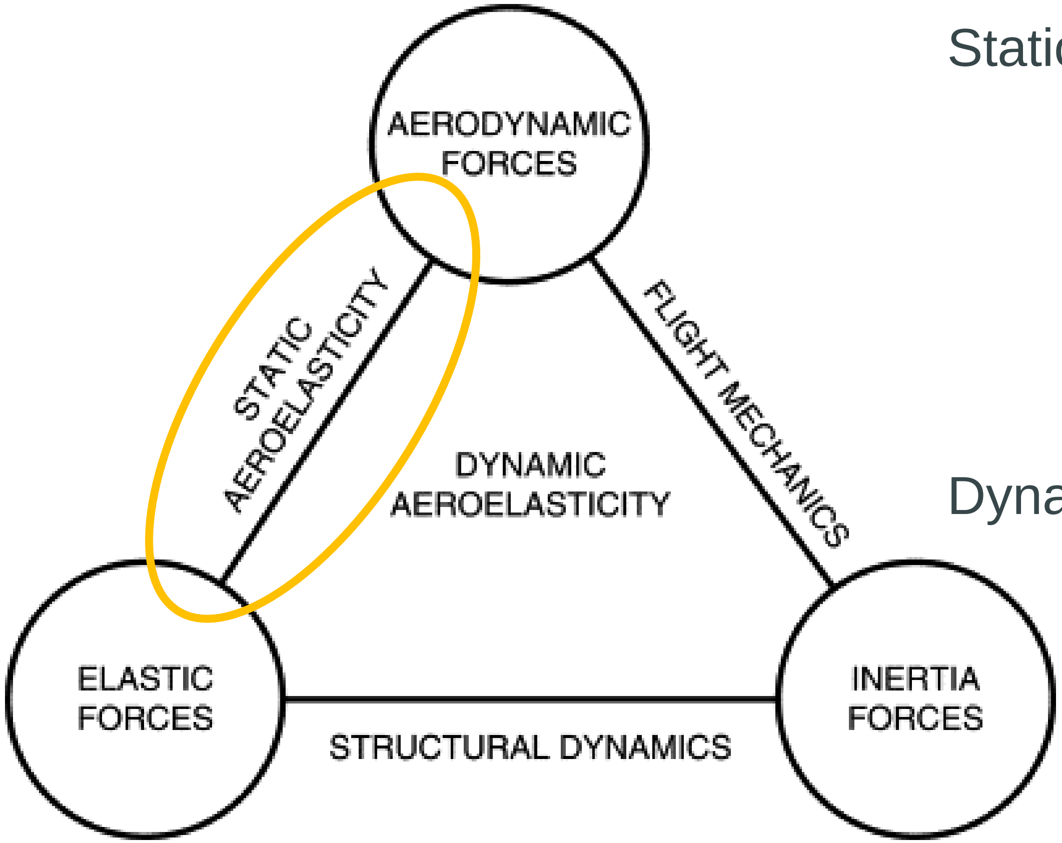
In $F(t)$ there are aerodynamic and gravitational loads. The inertial loads are taken:
at left for the vibrations and on the right (integrated) for the rigid body motion loads

A Newmark integration scheme allows to obtain at each time step the displacement, the velocity and the acceleration at each node of the finite elements mesh.

It allows also to obtain the internal loads in the structure
Material properties (elastic limit; fatigue behaviour) -- > Check the criteria

# Aeroelasticity

Aeroelasticity studies the interactions between the inertial, elastic, and aerodynamic forces occurring while an elastic body is exposed to a fluid flow




Static aeroelasticity:

– Interaction of aerodynamic and structural force

– Insensitive to acceleration of structural deflection

– Effect of elastic deformation on the aeroloads

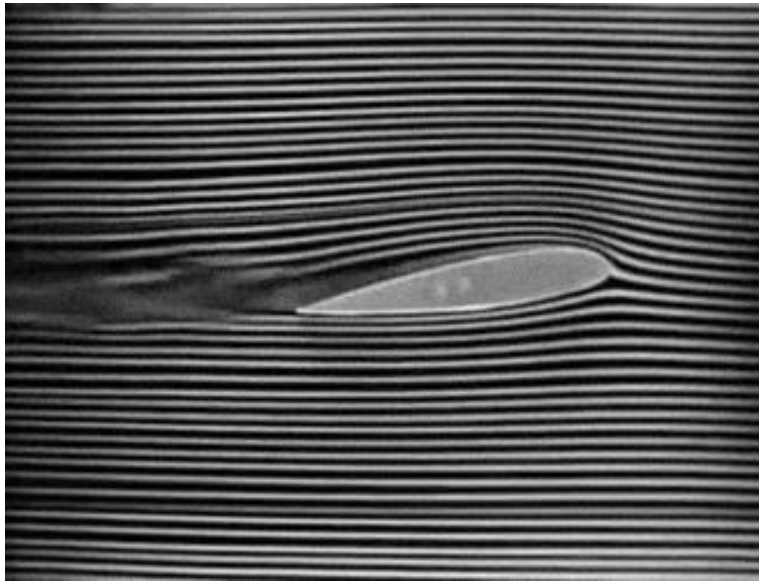
Dynamic aeroelasticity:

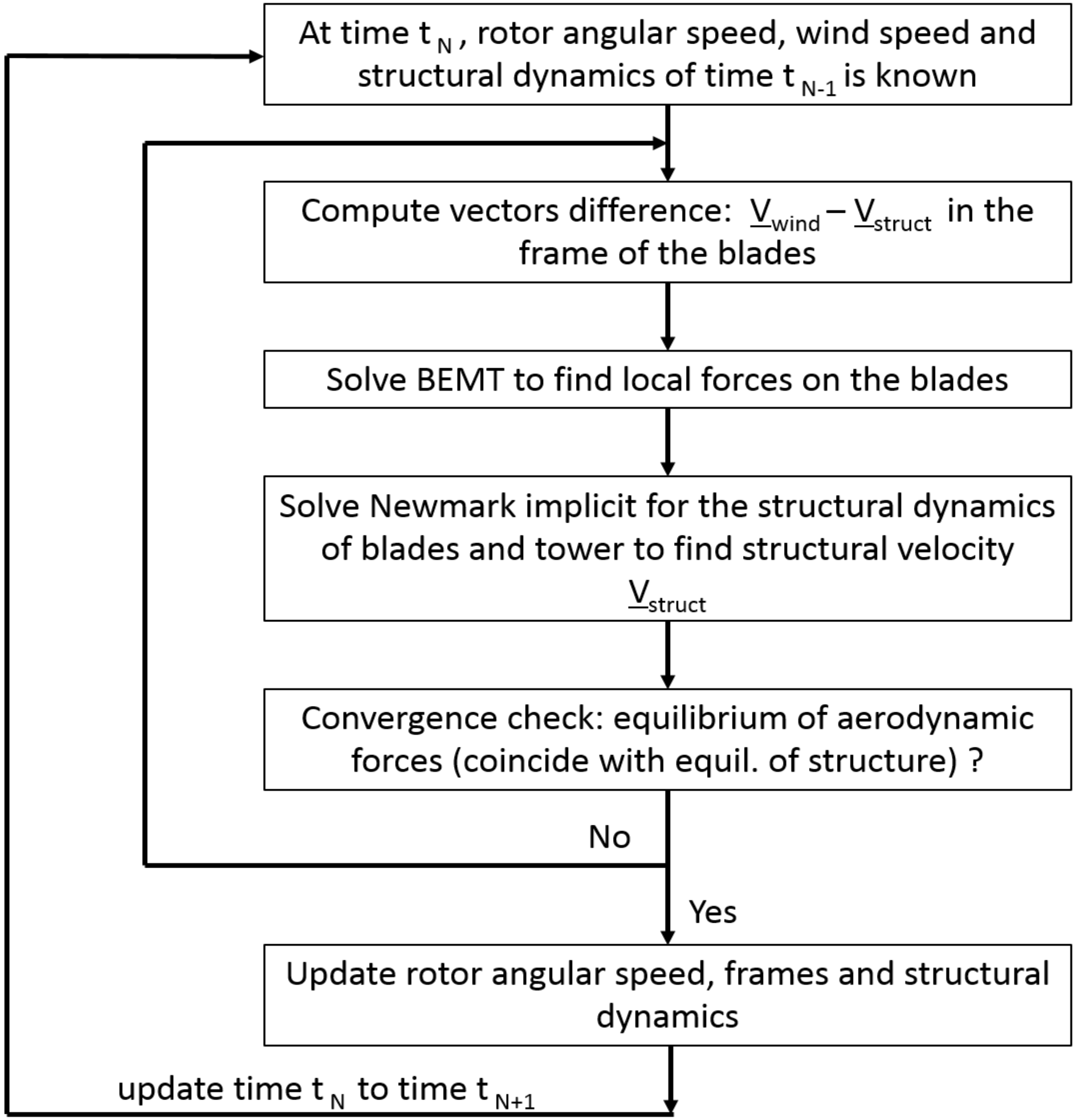
- Fluttering

# Aeroelastic algo

aero-elasticity – nonlinear phenomenon

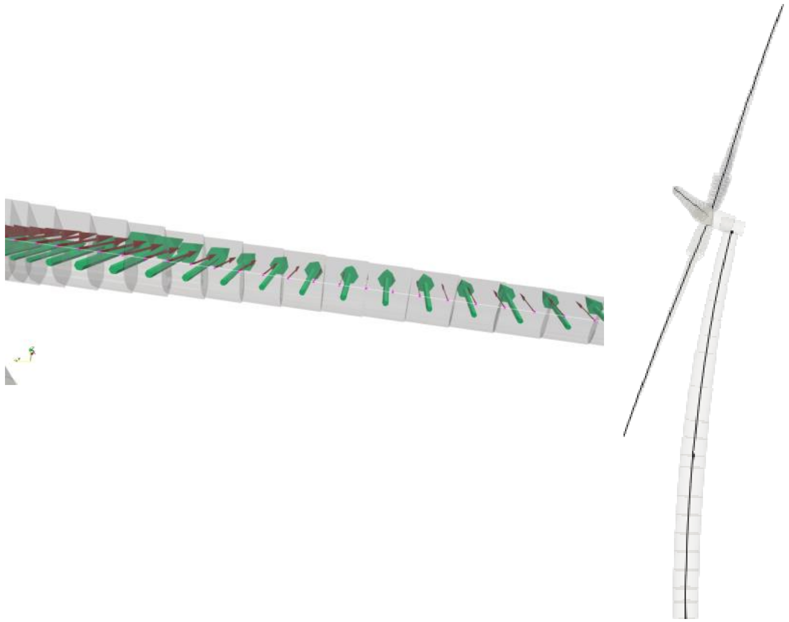
Fluid deforms the structure
This deformation changes the fluid flow
The change in fluid flow changes the structural deformation





# Structural description

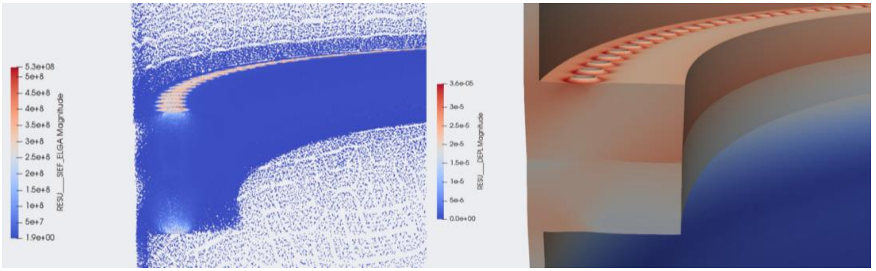
When the engineering phase progresses, the fidelity in the structural checks increases:

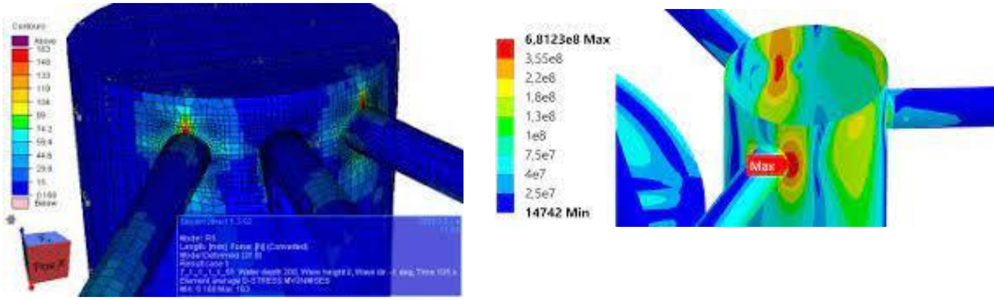


Beam model to have an integrated multi-physics resolution

6 dofs output of internal loads
Drop a scale

3D models with local (event. nonlinear) effects

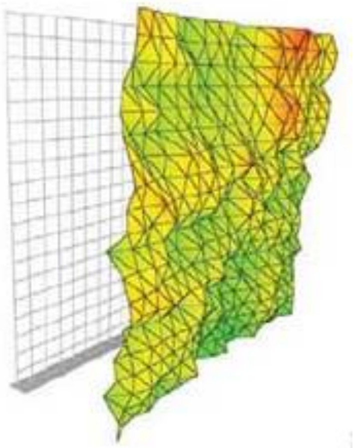




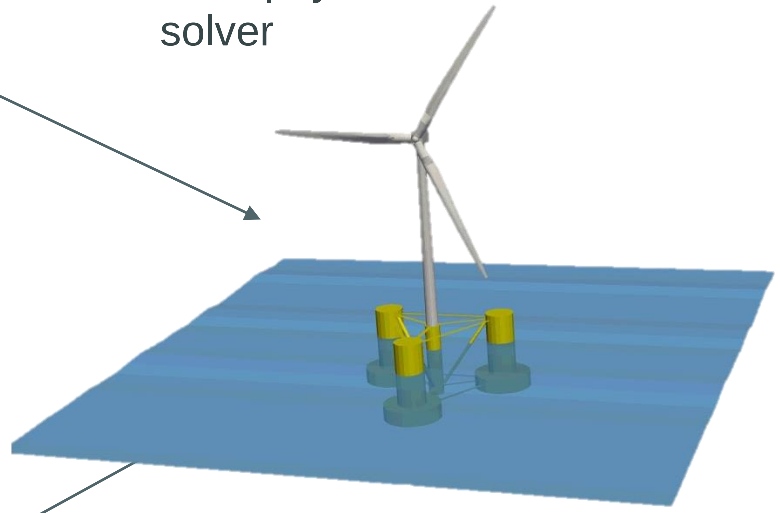
# Multi-physics num. simulation

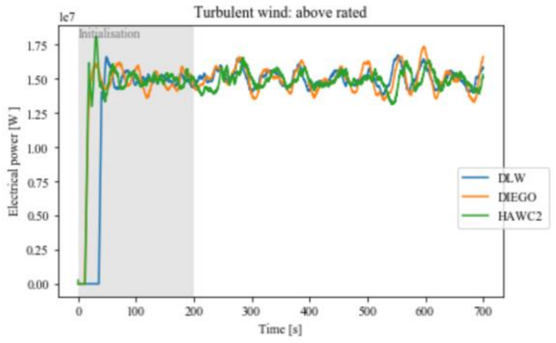
Time-series outputs
- Performances
- Beams Internal forces

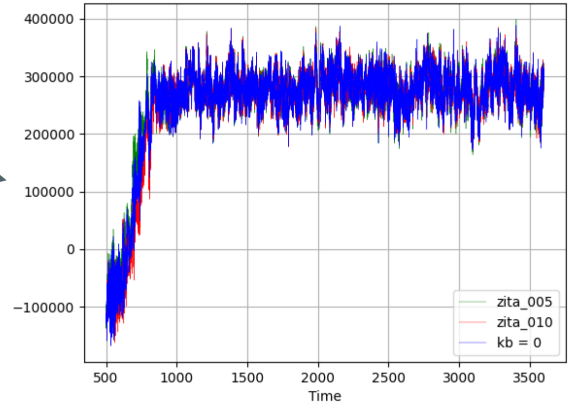
6 stochastic seeds of 10min



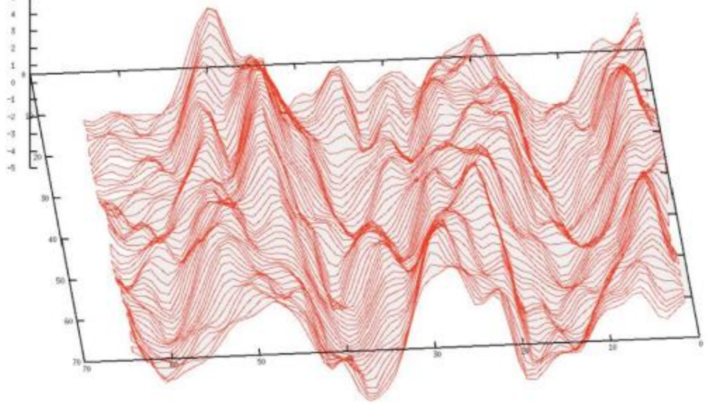
Multi-physics
solver

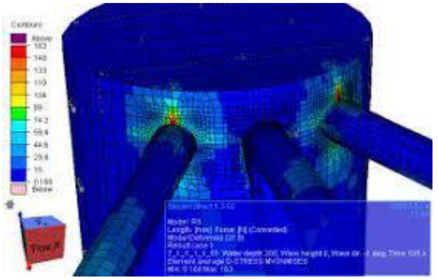




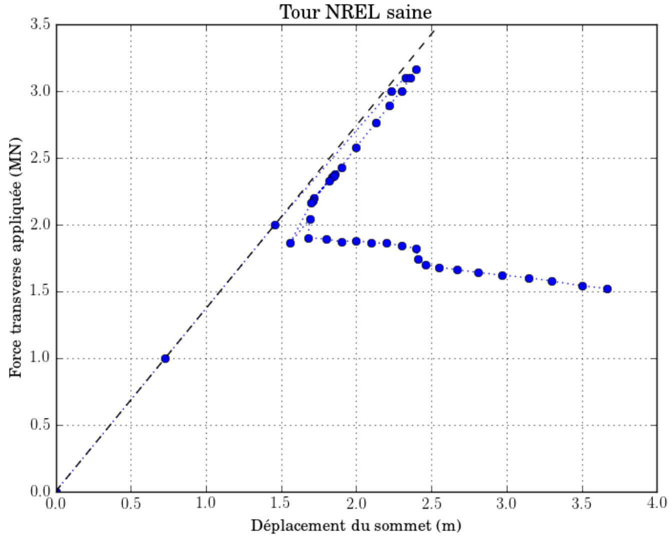




6 time-series of 1 hours





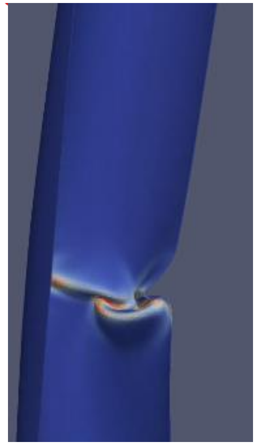
# Models for operation issues




A : instability point
Enough to assess the collapse

B : snap-back

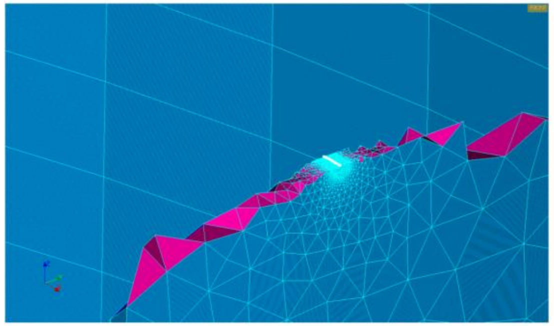
C : post-buckling

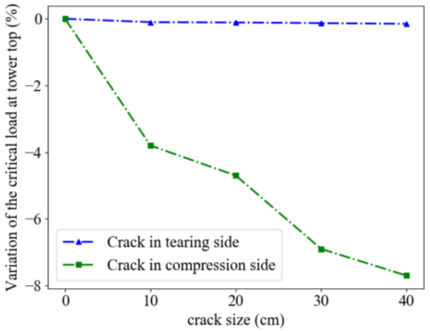


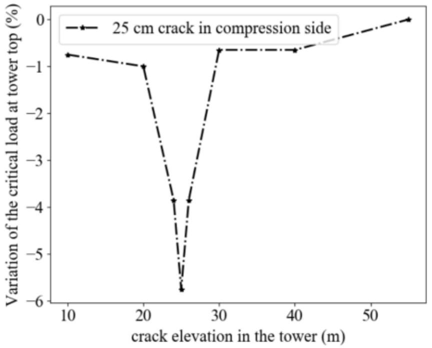
$$F = F_{impo} + \eta\, F_{pilo} = W_{RNA} + \eta\, F_{RNA}$$

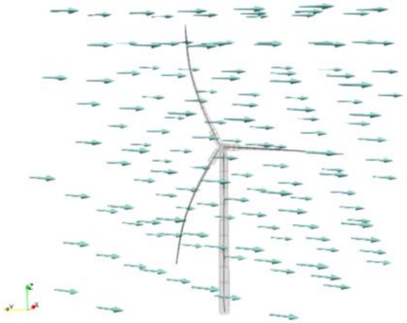
$$f\left(\underline{\sigma}, p_n\right) = \sigma_n^{eq} - R(p_n) \leq 0$$

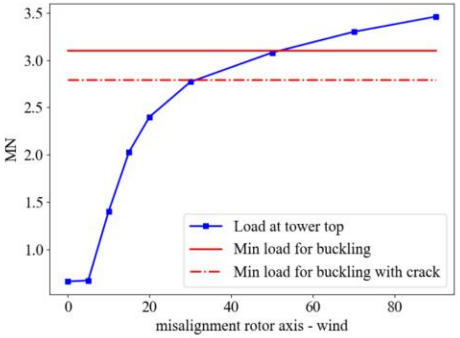
$$\max f^{elas}\left(\underline{\sigma}\right) = \Delta\tau$$








M. Capaldo *et al* 2020 *J. Phys.: Conf. Ser.* **1618** 022001
Influence of cracks on the buckling of wind turbine towers

# 04.

# On-going challenges

# On-going challenges

Multi-fidelity approach

Digital twins

Blade

Wind farm modelling

# Digital Twins

- Digital twin combines physical models and data coming from operation
- The massive increase of wind turbines in operation will allow to rely on big data
- For operations needs, to extend wind farm lifetime, to improve production estimation, etc.
- To optimize operations, digital twins will play a key role

# Blade

- Blades goes towards 100 – 120 meters of lenght

- A question is: a defect found, how much time we can continue produce before criticity ?

- In order to captures local phenomena the size of the mesh element needs to be adapted cracks of 20 cm

- The number of dofs can reach 1 billion with nonlinear composite mechanics

- Multi-scale strategies to be set → boundary conditions consistance can be challenging

Merci.

# Avertissement - Propriété intellectuelle

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