REAL WORLD LOADS

WIND LOADS

WAVE LOADS

ROTATING MACHINERY

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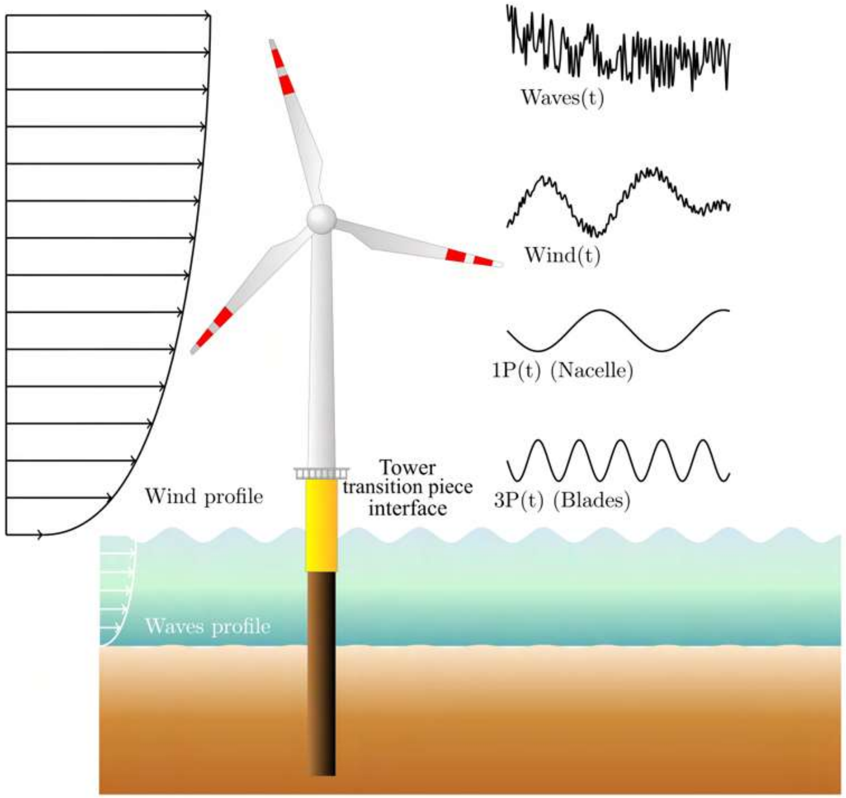
LOADS ACTING ON AN OFFSHORE WIND TURBINE

Where it all comes together

- Offshore wind turbines are subjected to a variety of loads
  - Gravitational and inertial loads (self-weight)
  - Aerodynamic loads (mean wind speed, gusts, turbulence)
  - Hydrodynamic loads (waves, currents)
  - Actuation or operational loads (braking, 1P/3P, yawing)
  - Other loads that may occur e g. wake or impact loads



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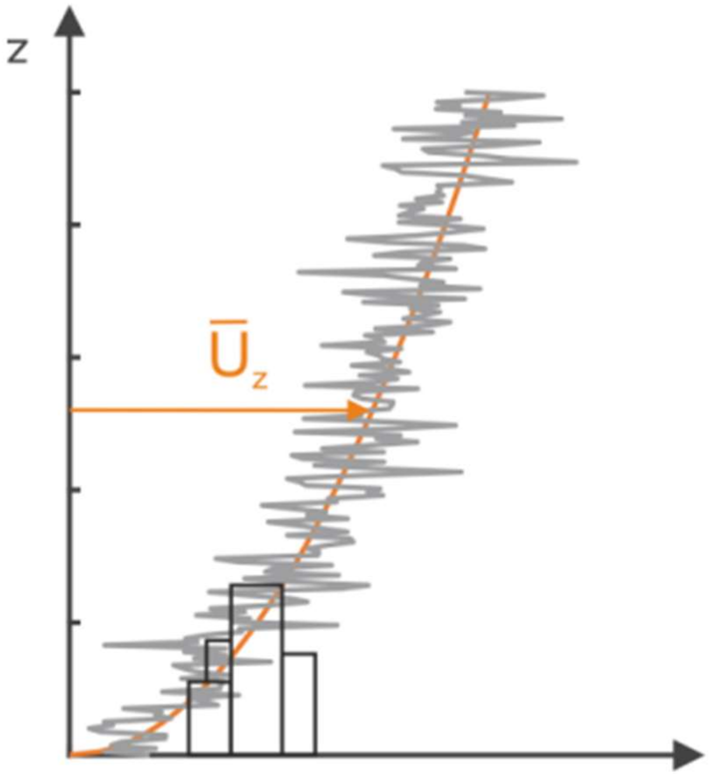
REAL WORLD LOADS

WIND LOADS

WIND EXCITATION PROFILE

Constant wind and turbulence



- Wind forces:

$$f_{tot}(t) = \frac{1}{2}\rho C_d \Omega [U + u(t)]^2$$

$$\approx \underbrace{\frac{1}{2}\rho C_d \Omega U^2}_{\text{constant}} + \underbrace{\rho C_d \Omega U u(t)}_{\text{turbulent}}$$

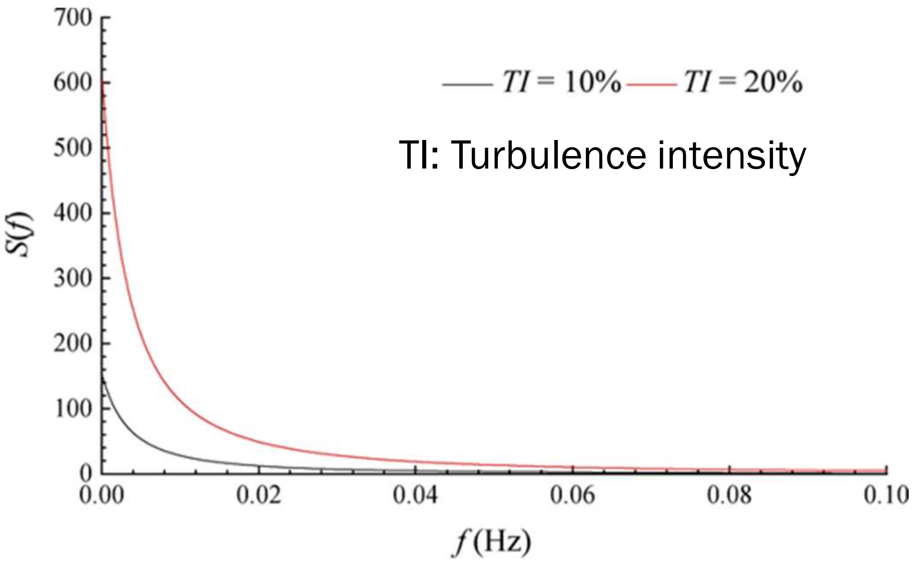
AERODYNAMIC FORCES

- Constant flow
  - Constant inflow conditions
  - Baseline constant force
  - But dynamics excitation can still originate
    - Dynamic vortex excitation
    - Self-excited vibrations
      - Inflow itself is contant but moving body influences forces

- Turbulent flow
  - Dynamic force
  - Resonance

SPECTRAL CONTENT WIND LOADS

- Reference wind speeds, e.g. for design, are typically represented as **Power Spectral Density** ($S_f(f)$)
  - Surface area represents the energy in a given frequency band
  - **E.g. Kaimal Spectrum** (Wind energy) , Davenport spectrum
- **This is the spectrum of the windspeed, not the resulting force!**
  - You'll need to pass through the equations listed before to get the forces
  - But these don't influence the frequency of the load
- Wind loads are typically low frequency (<0.1Hz) loads and "*white*"
  - However, gusts may result in impulse like loads



ADDITIONAL SOURCES OF TURBULENCE

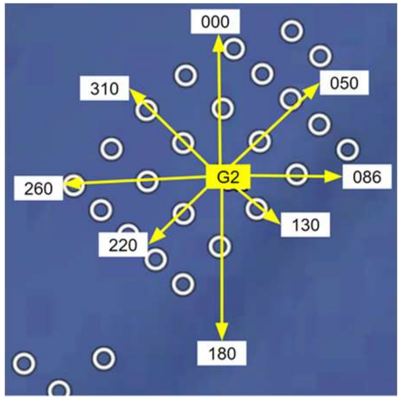
Wake effects

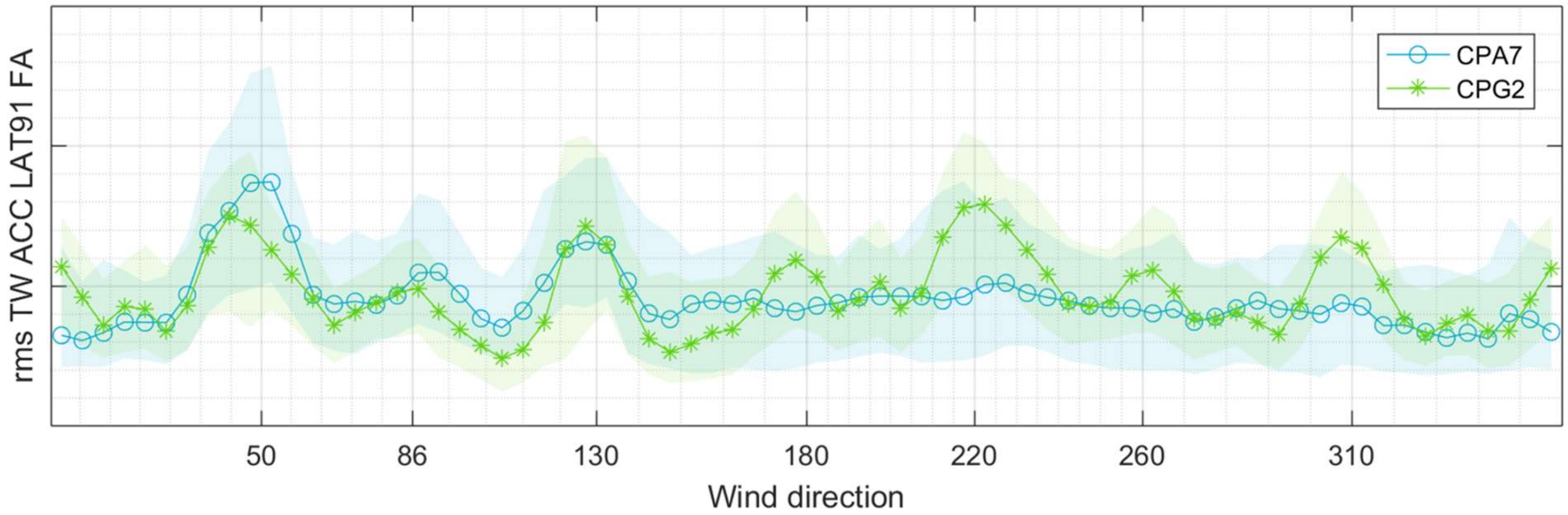
- Reference spectra are typically for free inflow conditions
- **Wake effects** can result in increased turbulence intensities
  - Tall buildings : **vortex shedding**
  - Wind turbines in the wake of another wind turbine
- Turbulence from wake effects is not necessarily white noise
  - Force resulting can therefor be tonal

ADDITIONAL SOURCES OF TURBULENCE

Wake effects

- Example from the field



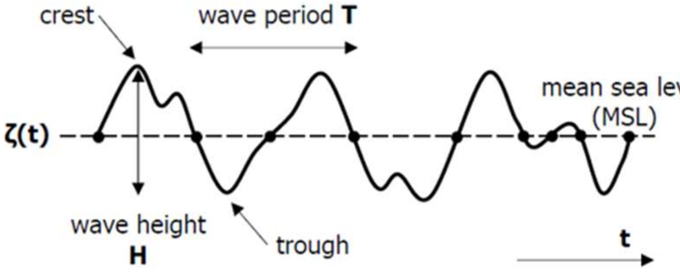


REAL WORLD LOADS

WAVE LOADS

SPECTRAL CONTENT OF WAVE LOADS

- At sea waves play a vital role in dynamic loading
- Waves are not sinoids
  - Complex interaction of long ‘low-frequent’ waves
  - Shorter high frequent waves
  - Complex loading patterns for e.g. breaking waves (more like impulses)



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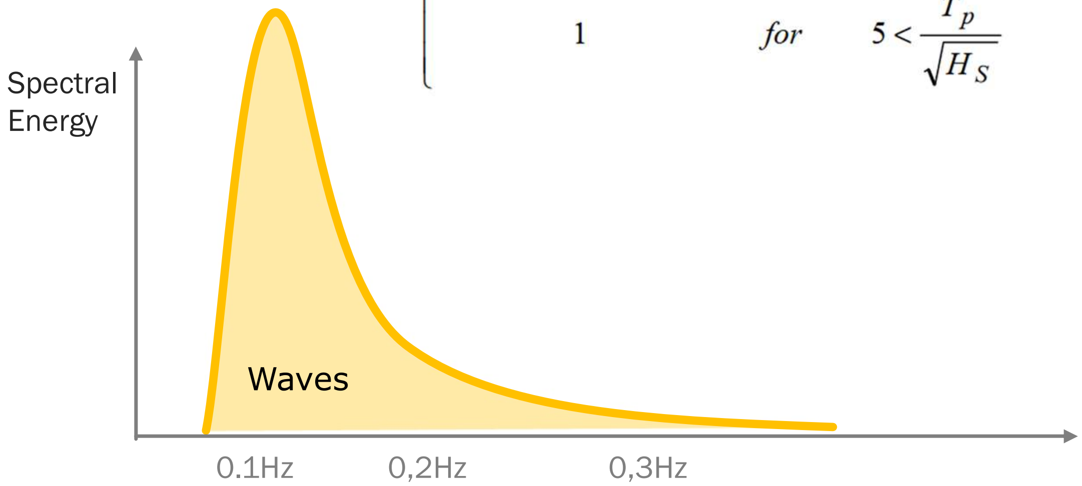
SPECTRAL CONTENT OF WAVE LOADS

JONSWAP spectrum

- Much like wind loads a reference spectrum is used to define the spectral content of the waves
  - Pierson-Moskowitz (Fully developed sea)
  - JONSWAP (DNV OS J101 : Standard wave spectrum)
- The JONSWAP is composed based on a given sea-state (e.g. T_p is wave's peak period)
- The JONSWAP is not the force spectrum, but the sea elevation spectrum for a given sea state

$$S(f) = \frac{\alpha g^2}{(2\pi)^4} f^{-5} \exp\left(-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right) \gamma^{\exp\left(-0.5\left(\frac{f-f_p}{\sigma \cdot f_p}\right)^2\right)}$$

$$\gamma = \begin{cases} 5 & \text{for } \frac{T_p}{\sqrt{H_S}} \leq 3.6 \\ \exp(5.75 - 1.15 \frac{T_p}{\sqrt{H_S}}) & \text{for } 3.6 < \frac{T_p}{\sqrt{H_S}} \leq 5 \\ 1 & \text{for } 5 < \frac{T_p}{\sqrt{H_S}} \end{cases}$$



SPECTRAL CONTENT OF WAVE LOADS

Transforming it into a load

- Use the wave spectrum to construct a water elevation timeseries
- Use the wave kinematics models (e.g. Airy wave) to calculate horizontal flow speed and acceleration
- Introducing the Morison Equation for a body moving in (horizontal) flow*

$$F = \rho V \dot{u} + \rho C_a V(\dot{u} - \dot{x}) + \frac{1}{2}\rho C_d A(u - x)|x - v|$$

- Includes the flow speed (u) and the flow acceleration ($\dot{u}$) as well as the position and velocity of the system in the flow (x)
- Important hydrodynamic factors are the Coefficients of mass ($C_a = 1 + C_m$) and drag C_d

**For today's size of wind turbines Morison equation is not fully valid anymore, a diffraction correction needs to be applied*

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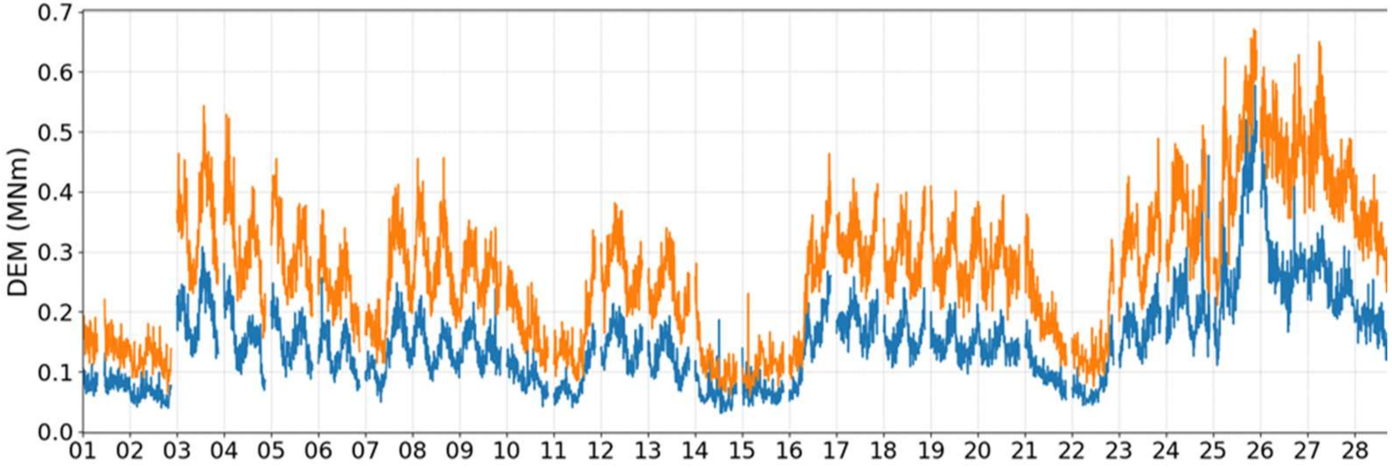
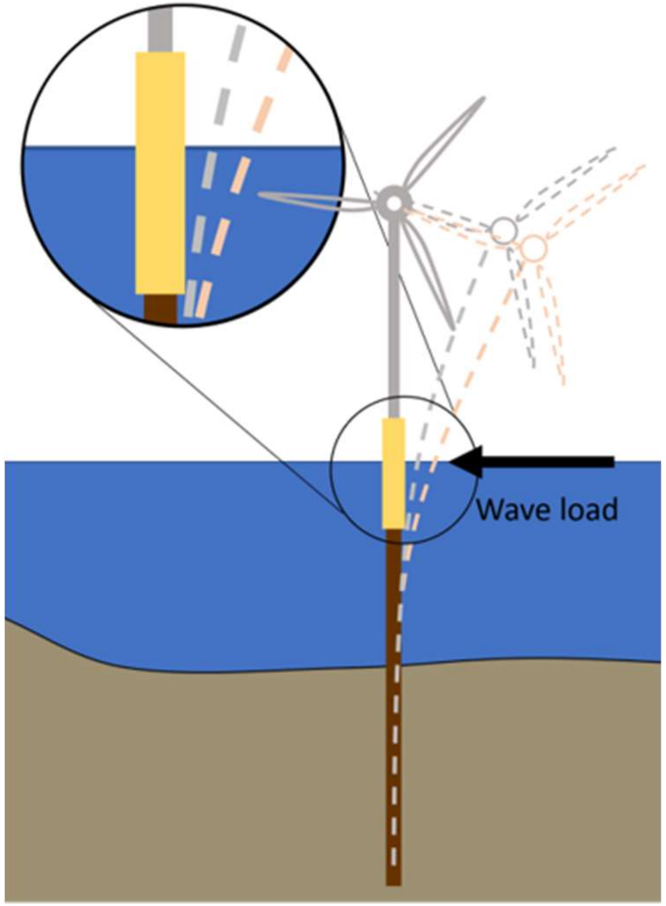
WAVE LOADING

Consider the wave load location

- Vibration levels vary along with the tides!
  - A ±12h cycle





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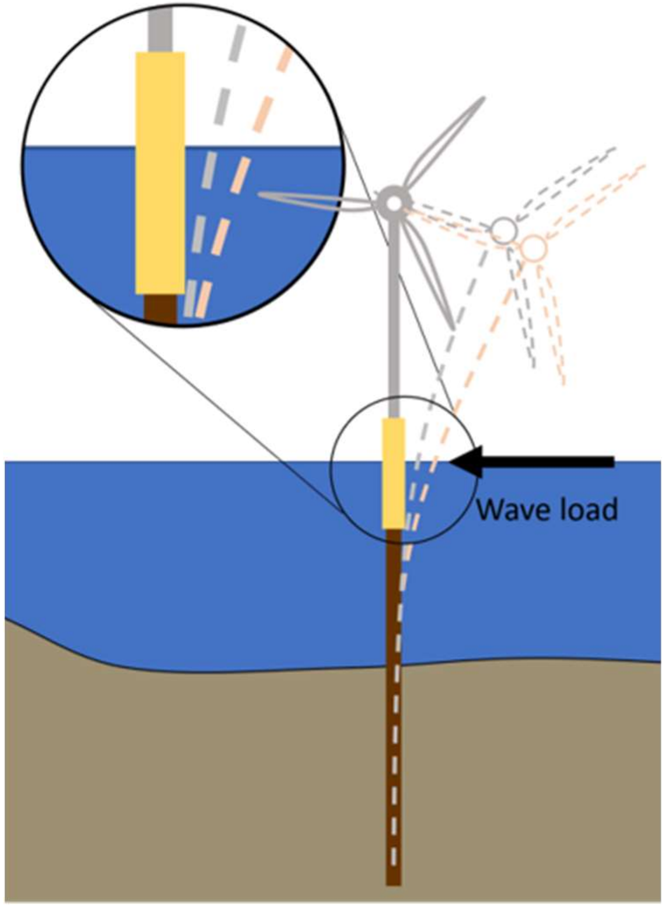
WAVE LOADING

Consider the wave load location

- Waves introduce the largest loads close to the water surface
- When projecting the dynamics into the modal space we learn from the modal excitation:

$$F_i = \psi_i^T F$$

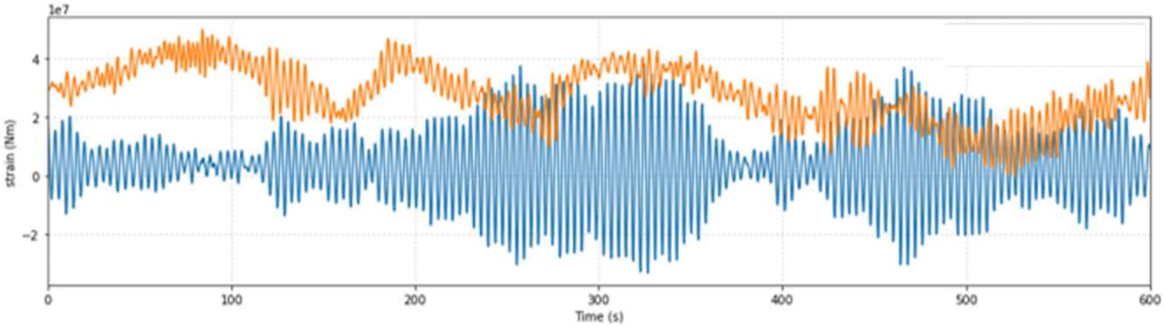
- The modal excitation will depend on the water level, so the tides influence the amount of vibration!

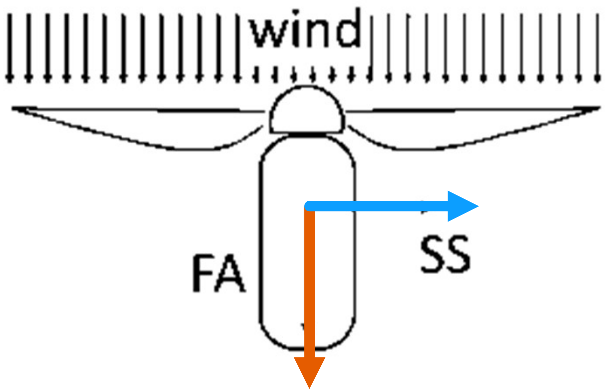


WAVE LOADING

Consider the wave load location

- Waves do not necessarily come from a single direction
- Waves also don't necessarily come from the same direction as the wind direction : Wind-Wave misalignment





REAL WORLD LOADS

ROTATING MACHINERY

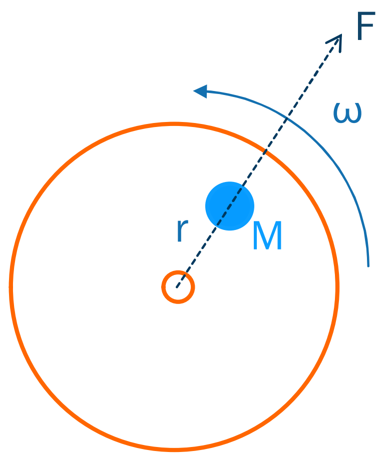
ROTATING MACHINERY

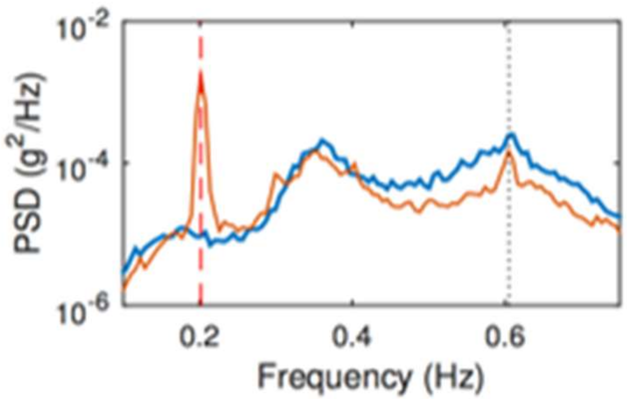
Forces originating from a rotating machinery

- Common example: Mass unbalance
  - Center of gravity ≠ Axis of rotation

$$F = Mr\omega^2$$

- The resulting force is thus:
  - Proportional to the severity of the unbalance
    - Both in mass (M) or off-centricity (r)
  - Proportional to the square of the rotational speed
  - Tonal: at exactly the frequency of rotation (**1p**)
  - Force in the plane of rotation
- Permissible unbalance typically expressed through the Balancing Class of the machine (ISO 21940-3)

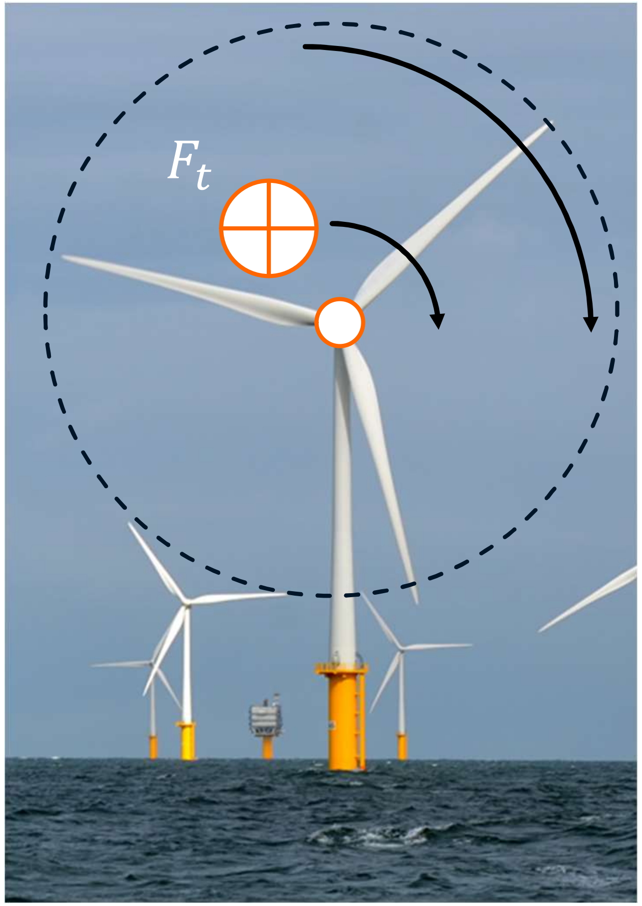




ROTATING MACHINERY

Not all unbalances are mass

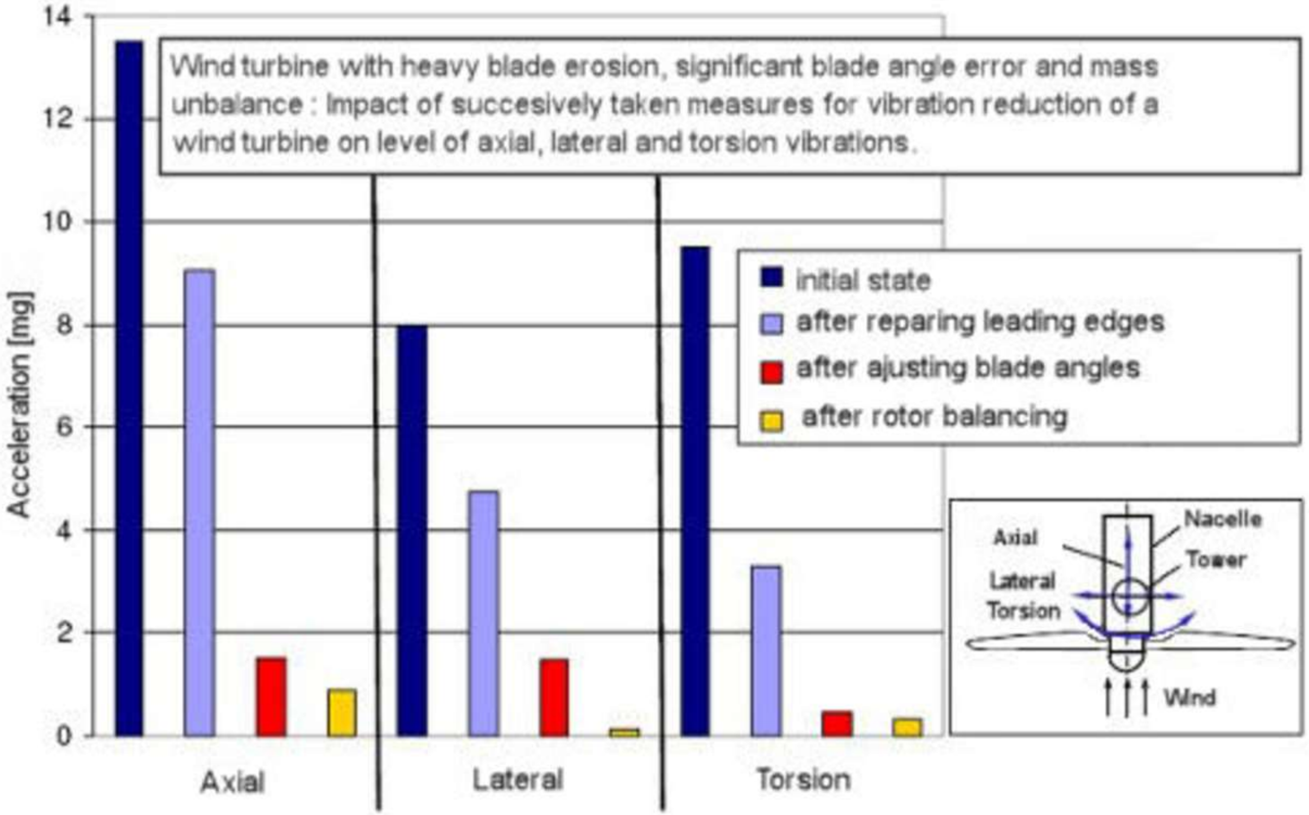
- Basically any unbalance in the forces can result in a periodical force at the rotational speed
- For wind turbines: e.g. Aerodynamic unbalance
  - Center of thrust ≠ Axis of rotation
  - Misaligned/damaged blade
- The resulting force is:
  - At the frequency of the rotor 1p
  - In the wind direction (orthogonal to the plane of rotation)
  - Dependent on the severity of the misalignment



ROTATING MACHINERY

The gain of running a balanced machine

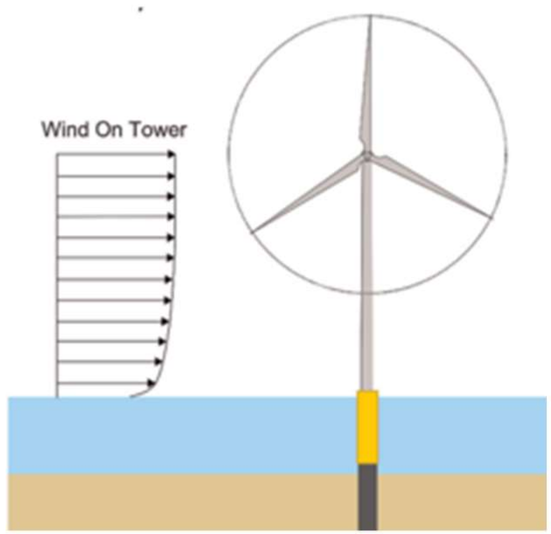
- Source: *Berlinwind*

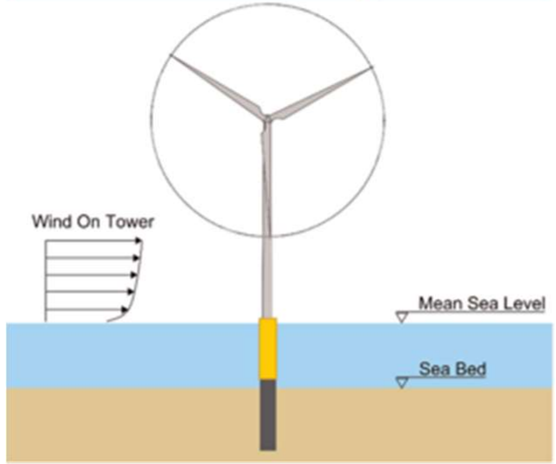


ROTATING MACHINERY

Tower shadowing effect

- For wind turbines an additional load comes from the so-called Tower/blade shadowing effect
- As a blade passes in front of the tower the wind load that acts on the tower is *caught* by the blade
- The resulting force is:
  - In the wind direction
  - At 3 times the rotor frequency (3p)
    - (Footnote) for a three bladed upwind turbine





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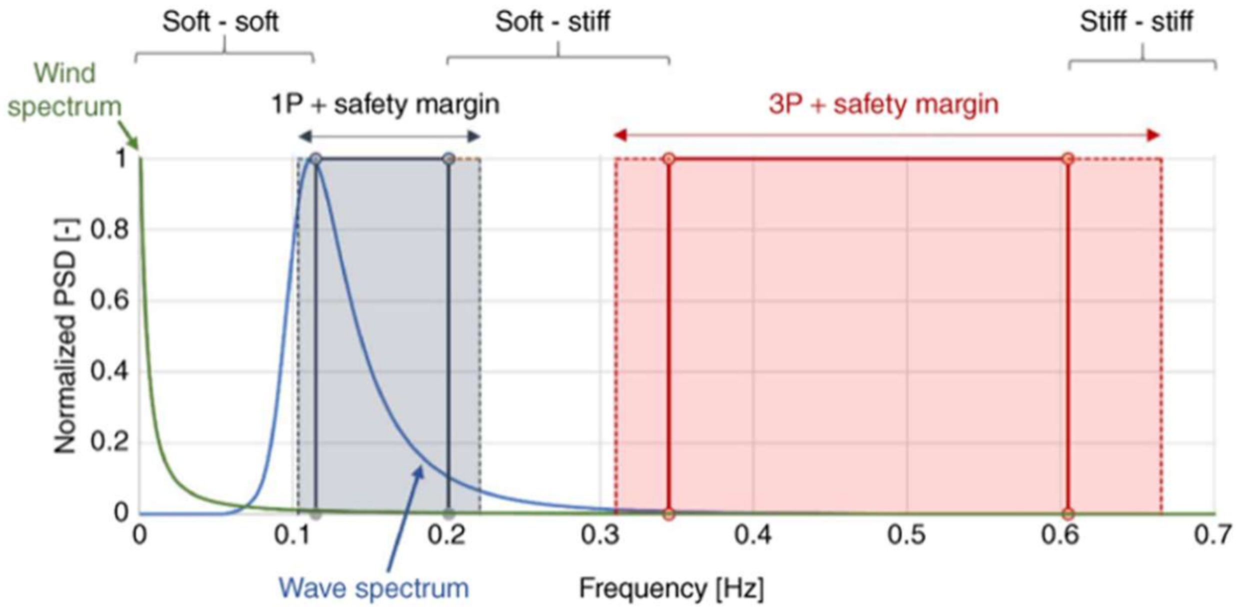
REAL WORLD LOADS

IMPACT ON DESIGN

IMPACT ON DESIGN

Balancing the various loads

- Designing the offshore wind turbine
- Loads:
  - Wind spectrum
  - Rotor/Aerodynamic unbalance
  - Blade shadowing effect
  - Wave loads



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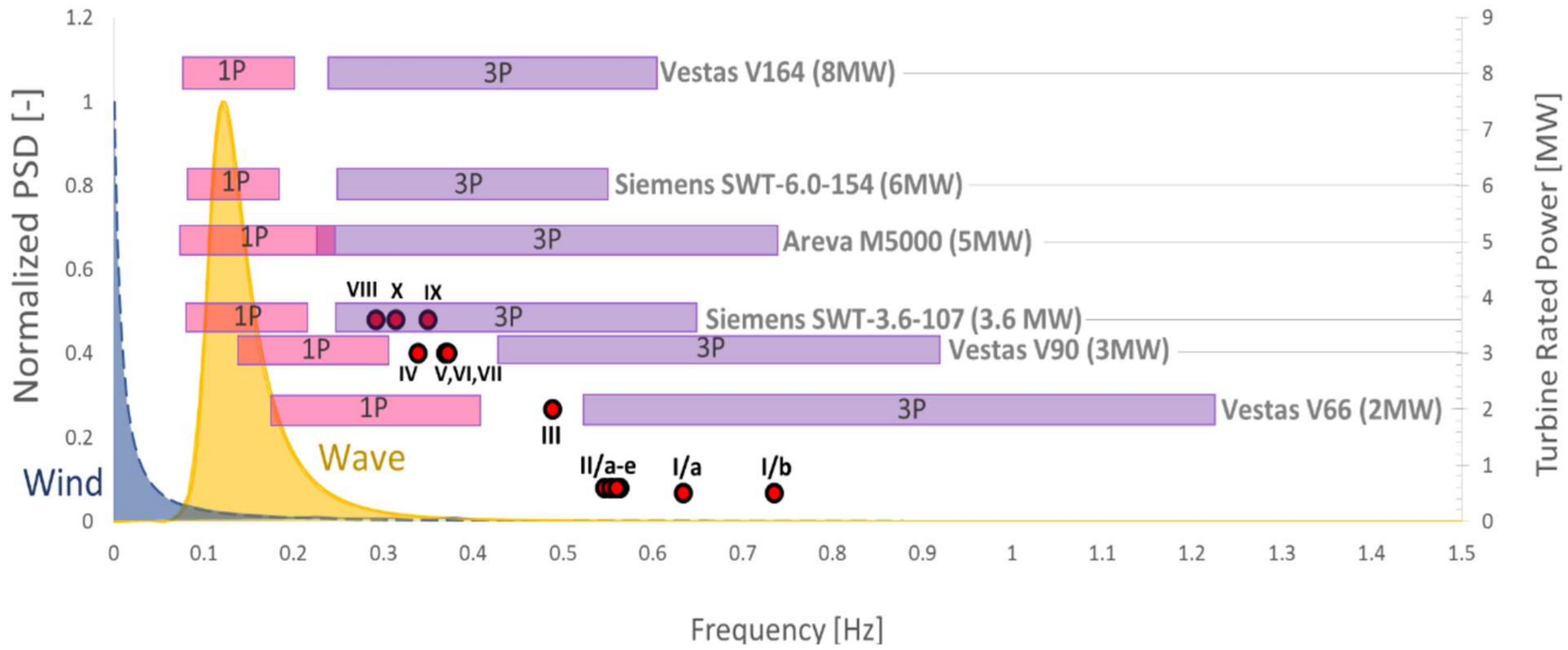
IMPACT ON DESIGN

Balancing the various loads

- The challenge with growing turbine sizes



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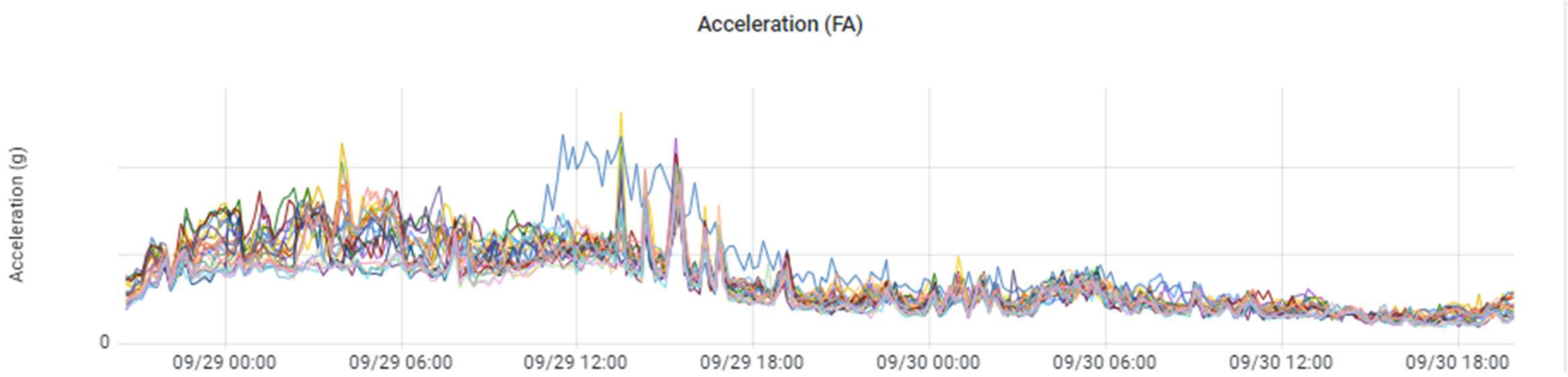
IMPACT ON DESIGN

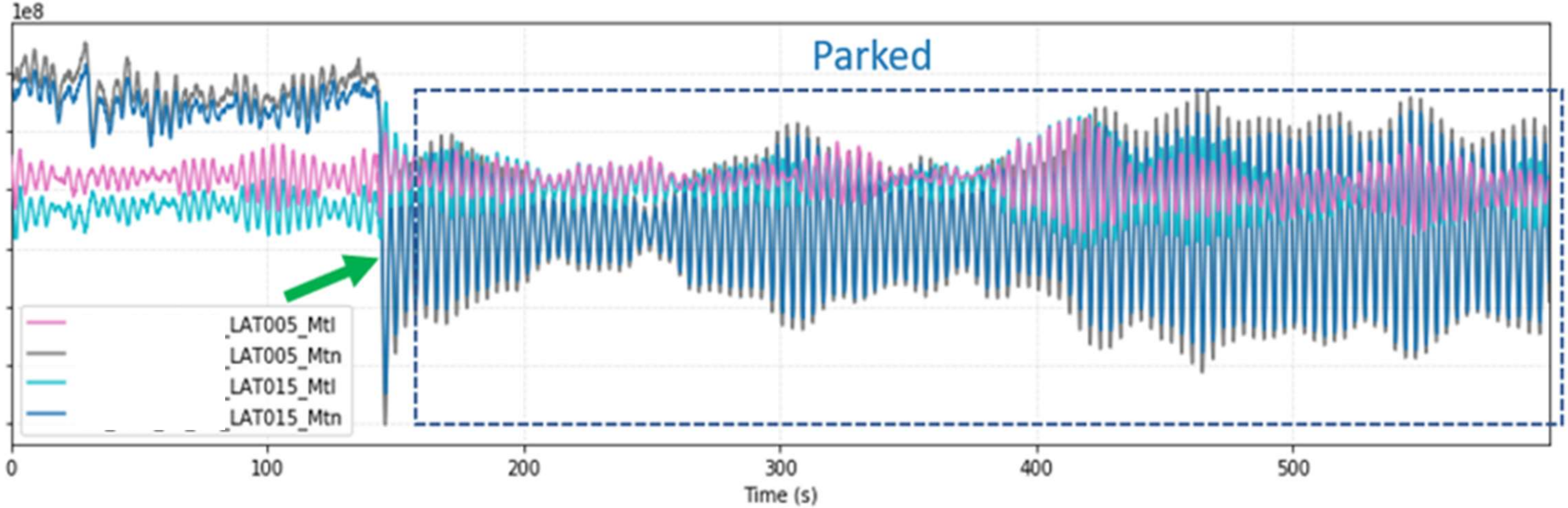
When parking your turbine hurts you

- The vibration levels of an entire wind farm are shown below for a period of 2 days
- One turbine (dark blue) stands out with elevated vibration levels



IMPACT ON DESIGN

When parking your turbine hurts you



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