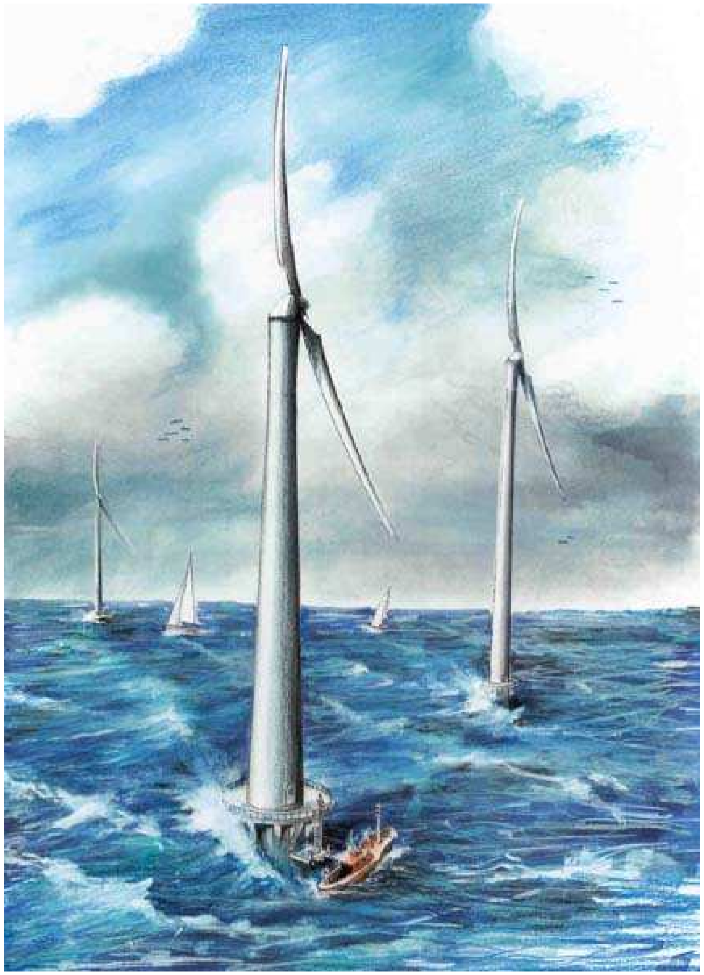
Loads, dynamics and structural design



Offshore Wind Farm Design

Michiel Zaaijer

2007-2008

DUWIND

Delft University of Technology

Overview

- Introduction
- Modelling offshore wind turbines
- Types of analysis and tools
- Loads and dynamics in design

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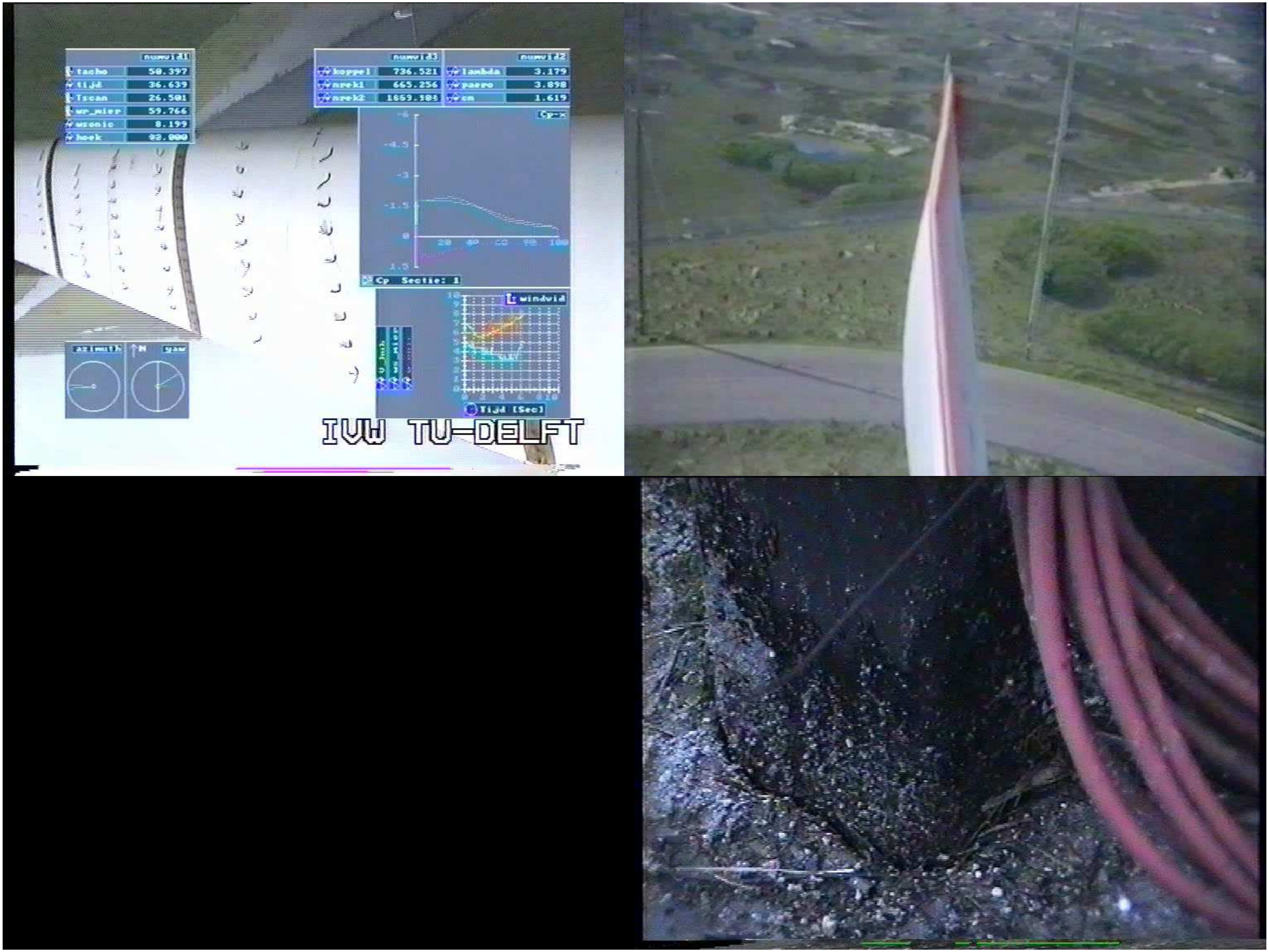
numvid1
tacho 58.397
tijd 36.639
Tscan 26.501
wr_mier 59.766
wsonic 8.199
numvid3
koppel 736.521
nrek1 665.256
numvid2
lambda 3.179
paero 3.898
cn 1.619
Cp-x
Cp Sectie: 1
windvid
Tijd [Sec]
azimuth
yaw
IVW TU-DELFT

Introduction

Loads, dynamics and structural design

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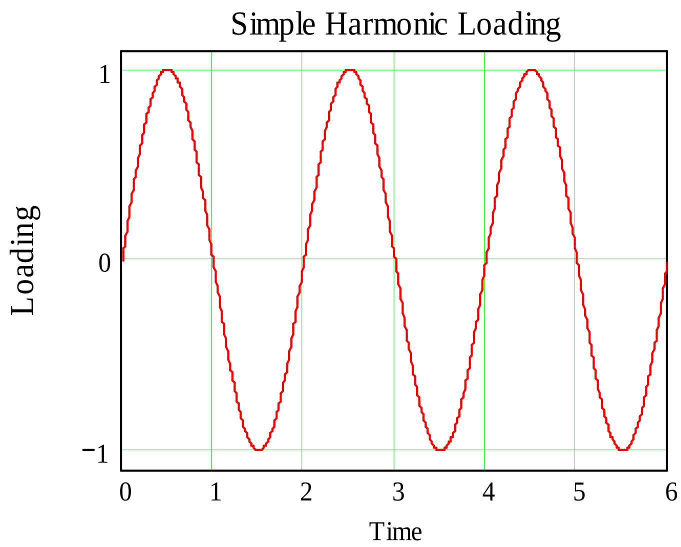
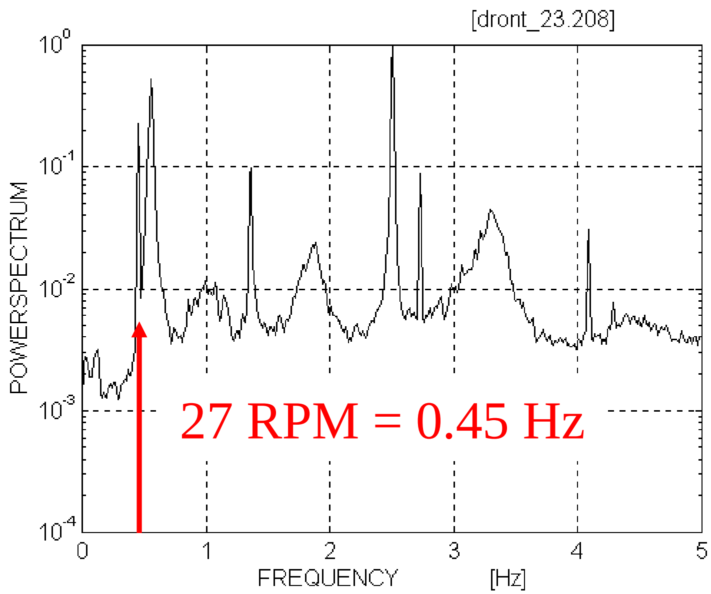
Harmonic loading



$$F(t) = \hat{F} \cdot \sin(\omega \cdot t + \varphi)$$



- Gravity loads on blades
- Mass imbalance rotor (1P)
- Aerodynamic imbalance (1P)
- Small regular waves

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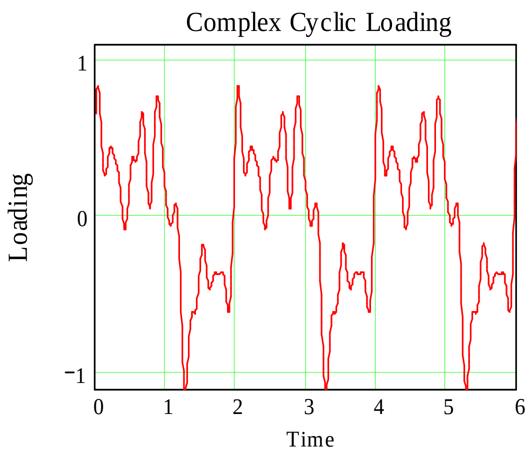
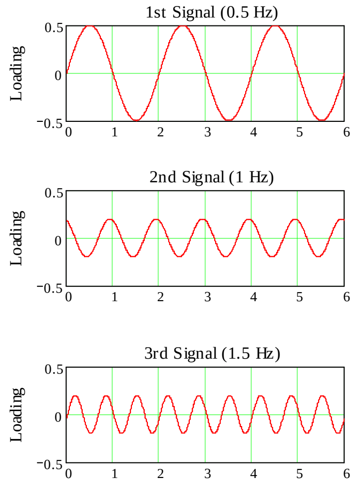
Non-harmonic periodic loading

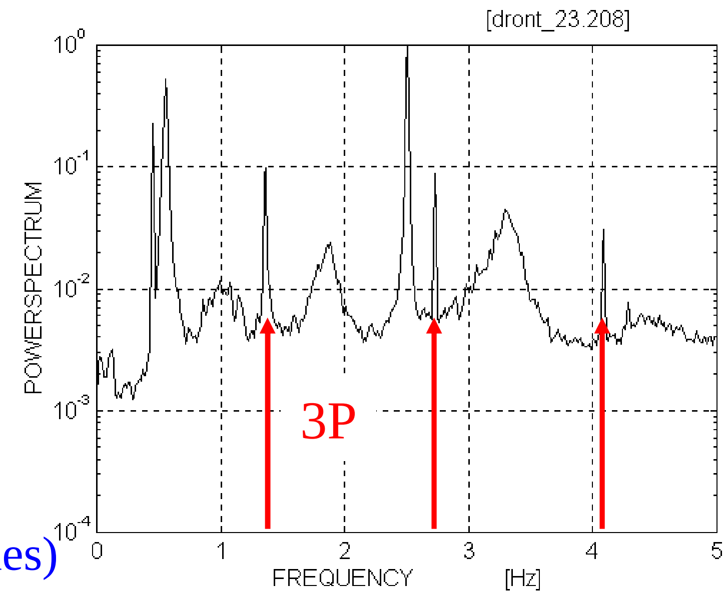




$$F(t) =$$

$$a_0 + \sum_{k}^{\infty} a_k \hat{F} \sin(k\omega t + \varphi_k)$$

- Wind-shear
- Yaw misalignment
- Tower shadow
- Rotational sampling of turbulence (all 2P or 3P and multiples)



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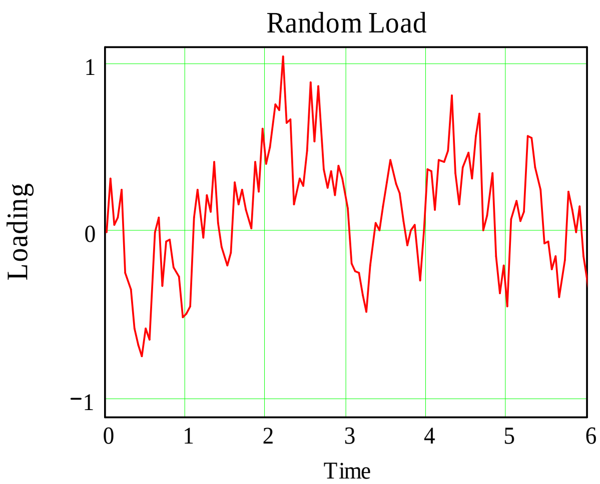
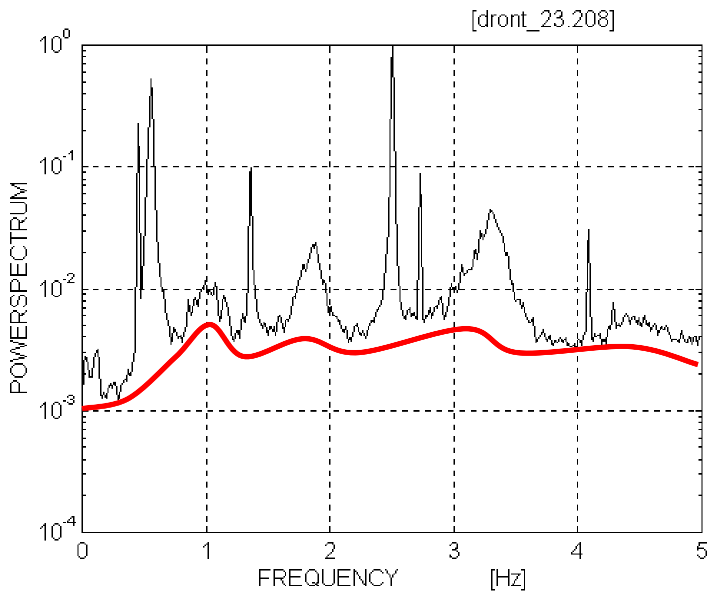
Non-periodic random loading

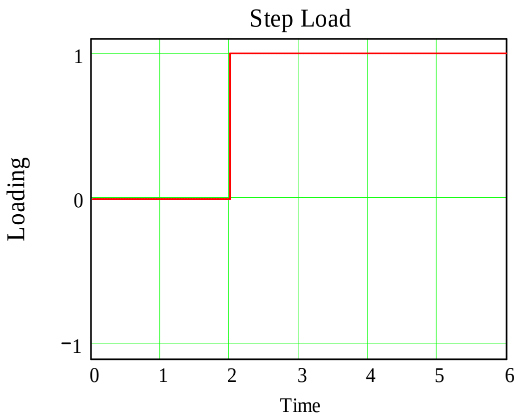


- Turbulence (small scale)
- Random waves



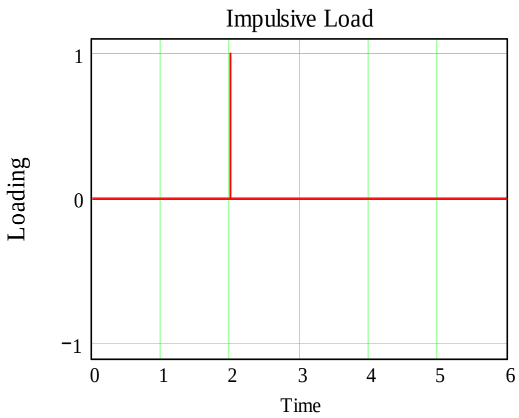
Other (non-periodic) loading

Transients



- Start/stop
- Turbine failures
- Storm front

Short events



- Extreme gust
- Extreme waves

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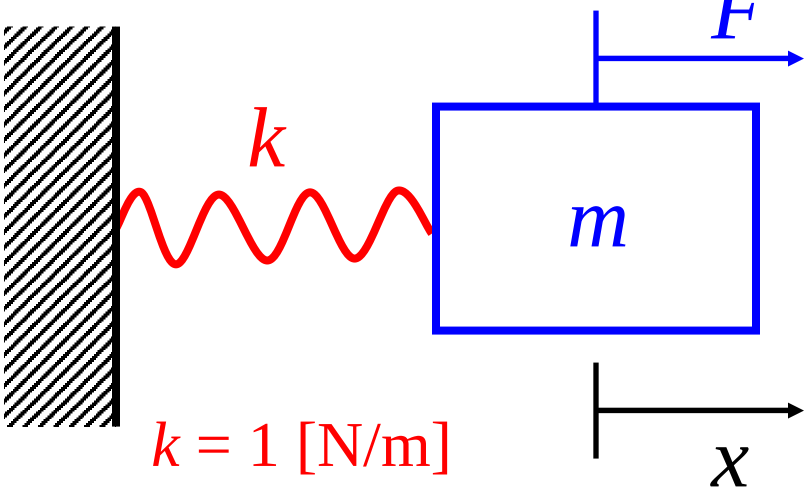
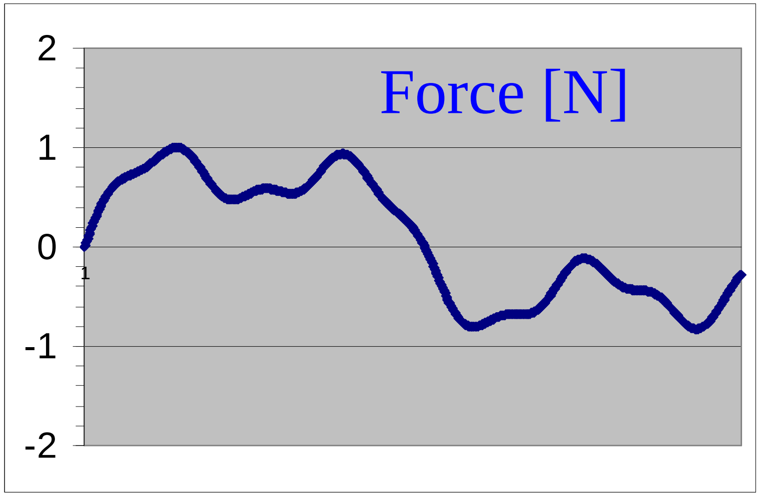
Introduction

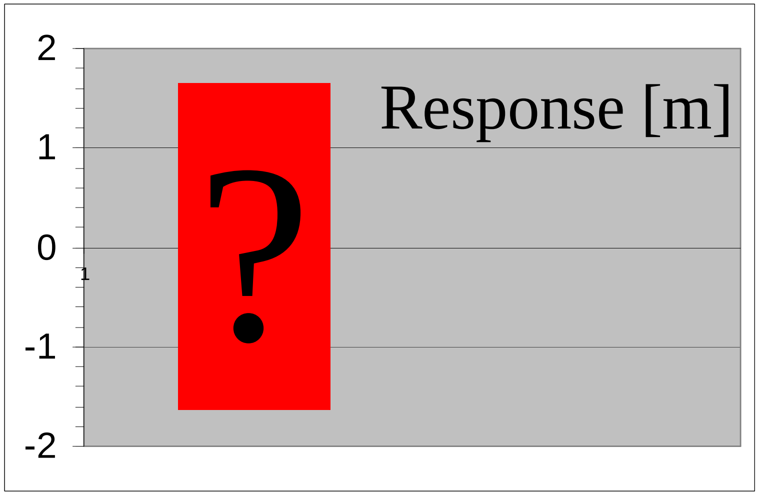
Loads, dynamics and structural design

2007-2008

The effect of dynamics







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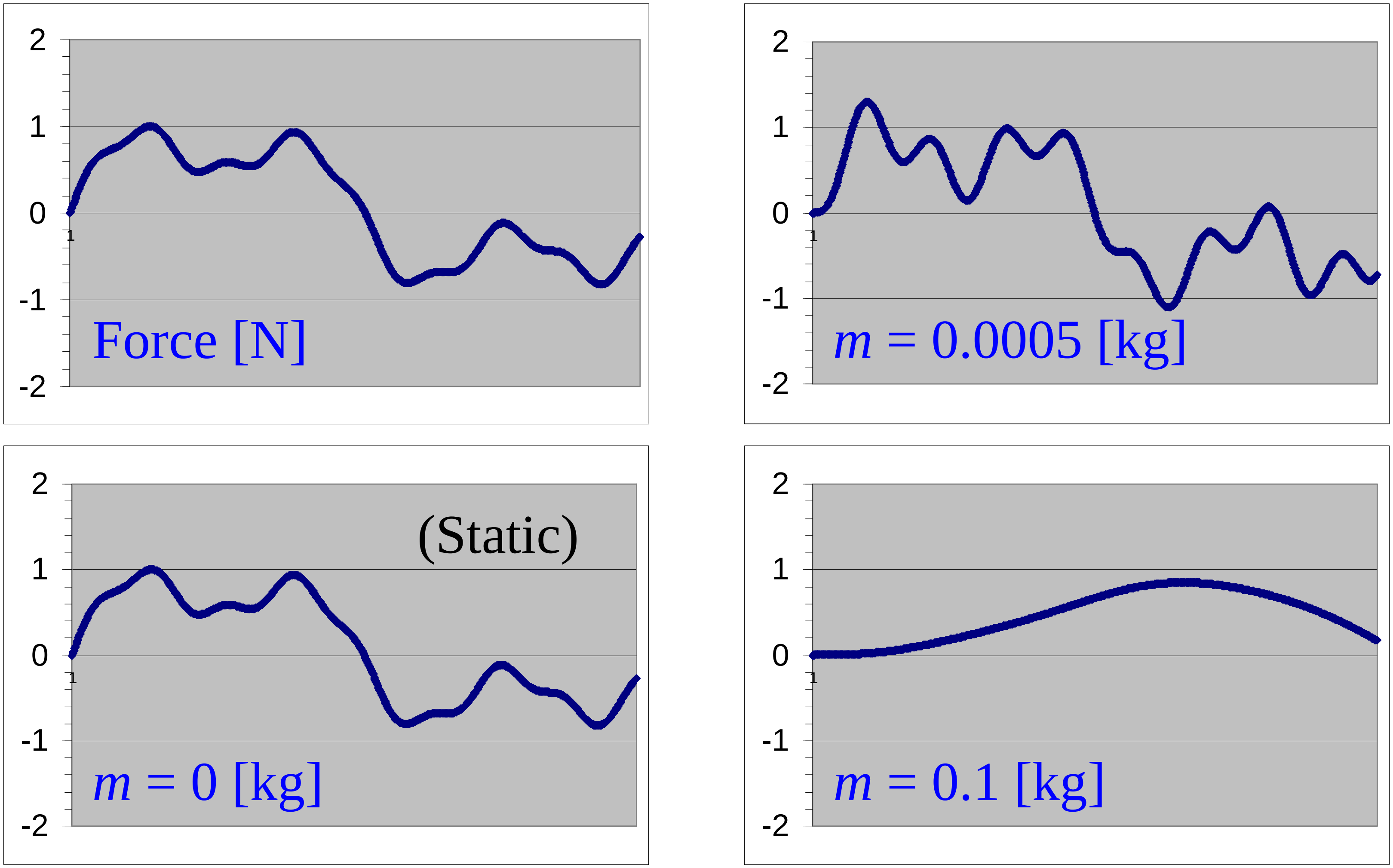
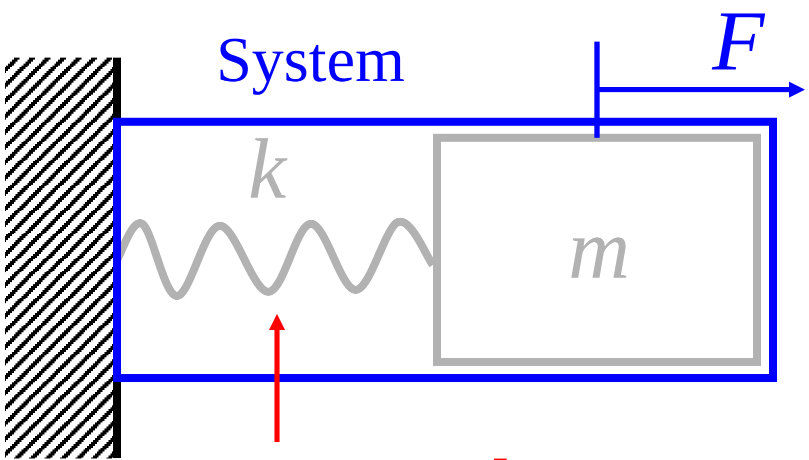
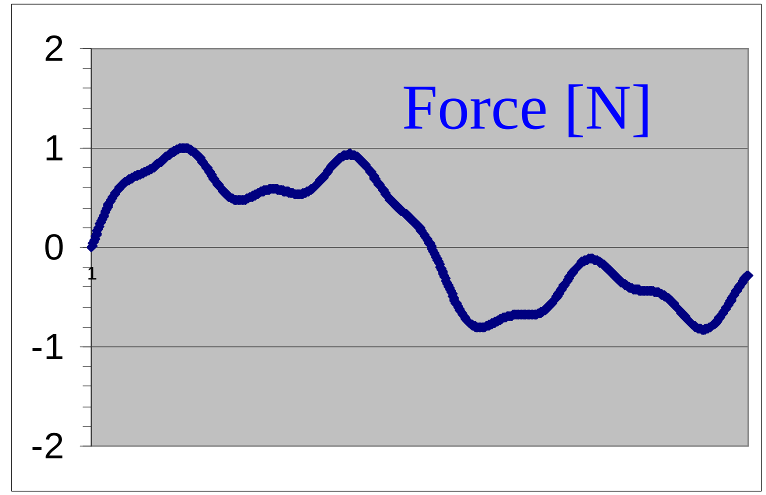
The effect of dynamics

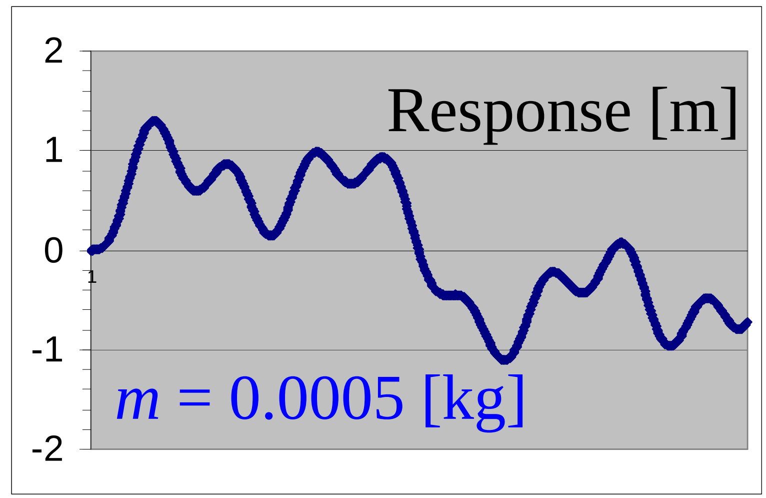


The effect of dynamics



$$F_{intern} = k \cdot x$$





Internal forces ≠ external forces due to dynamics

Internal forces drive the design, not external forces!

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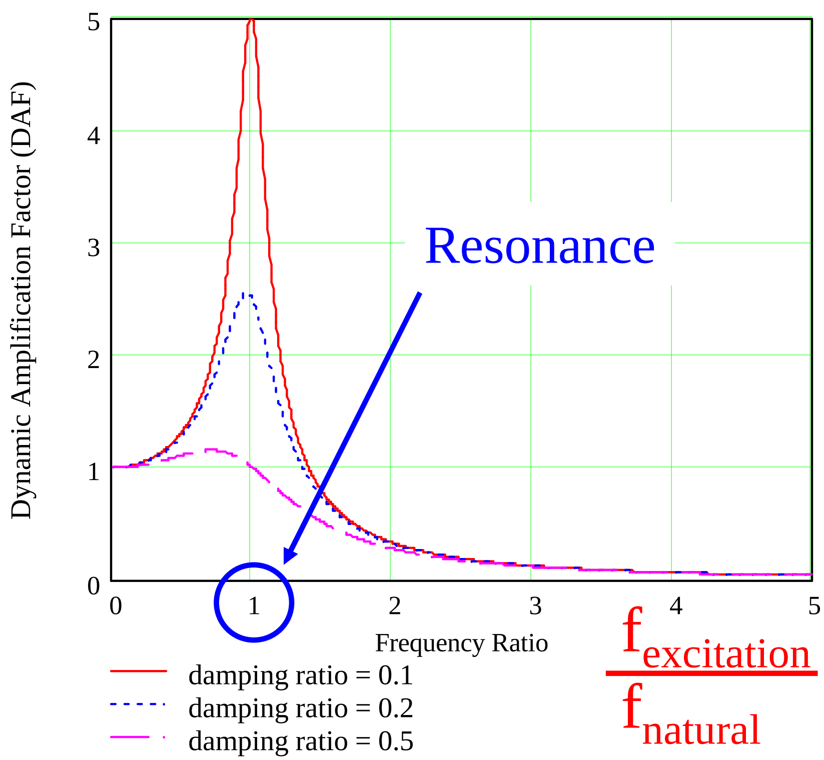
Dynamic amplification factor

$$\text{DAF} = \frac{\text{Dynamic amplitude}}{\text{Static deformation}}$$



$$\frac{f_{excitation}}{f_{natural}}$$

Note: the DAF is defined for harmonic excitation

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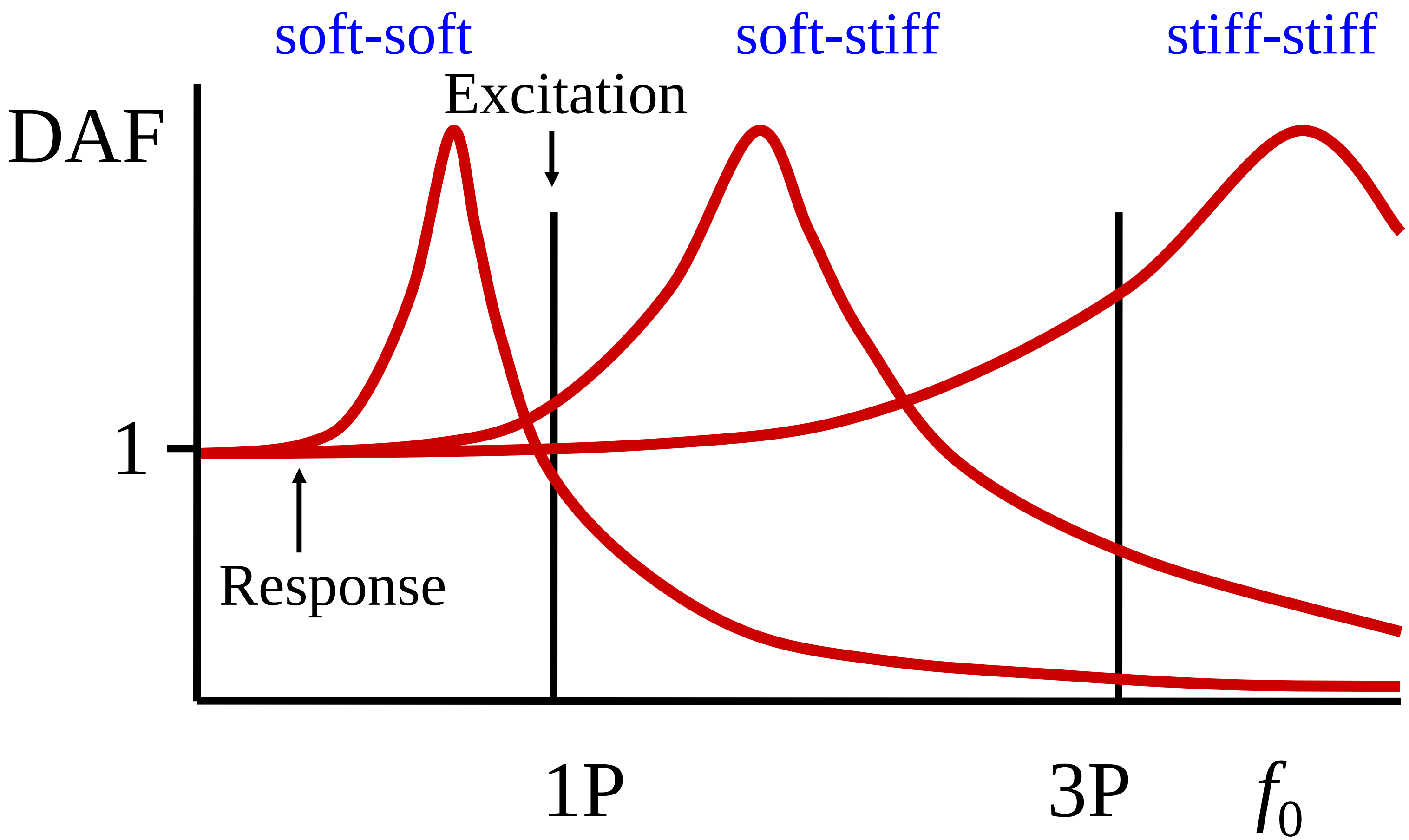
Character of resonance

- Excitation frequency ≈ natural frequency
- Large oscillations
- Fatigue damage (due to severe cyclic loading)
- Generally not destructive (anticipated in design)

Natural frequencies of wind turbine (-components) are close to several excitation frequencies

Classification for wind turbines



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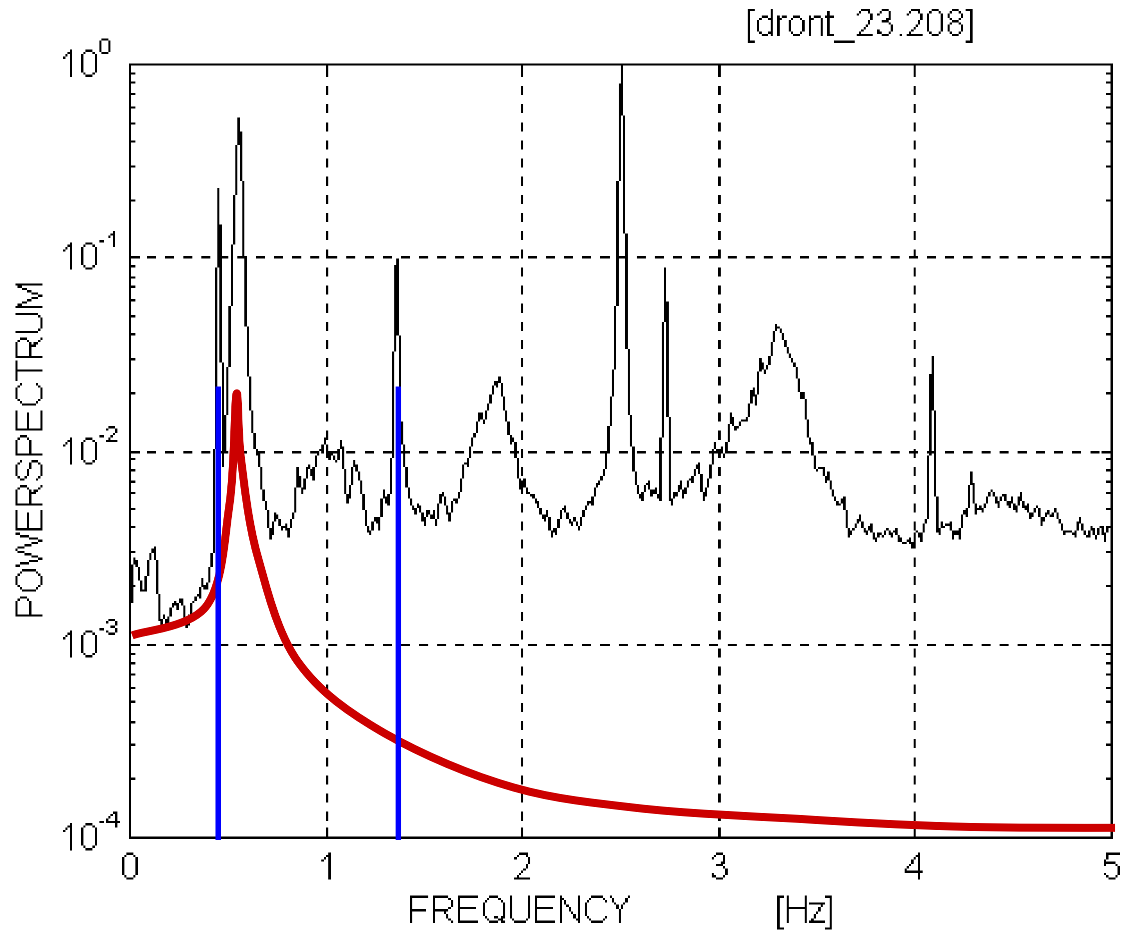
Soft-stiff example



1P = 0.45 Hz

$f_{natural}$ = 0.55 Hz

3P = 1.35 Hz

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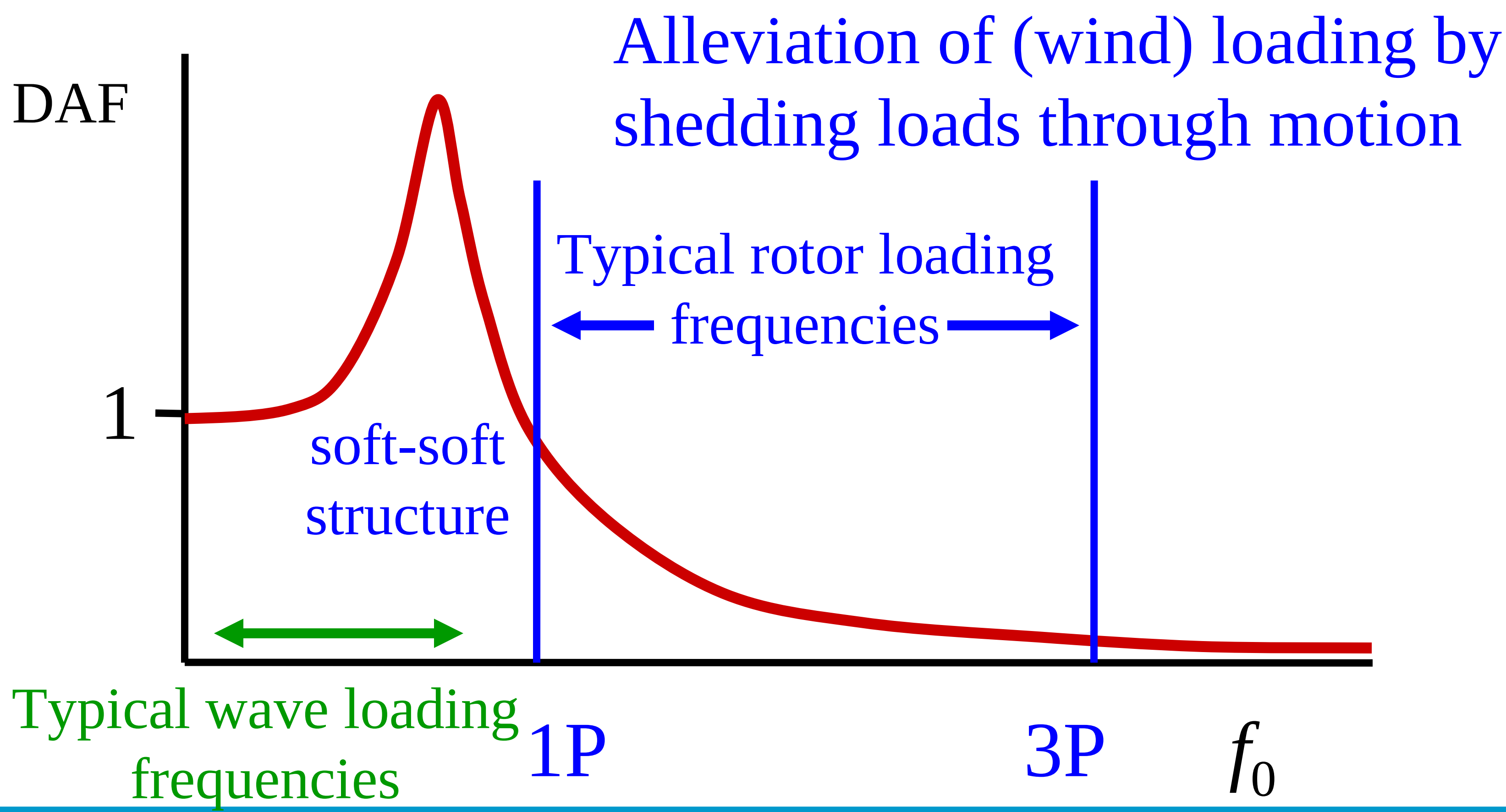
Reduced response to loading



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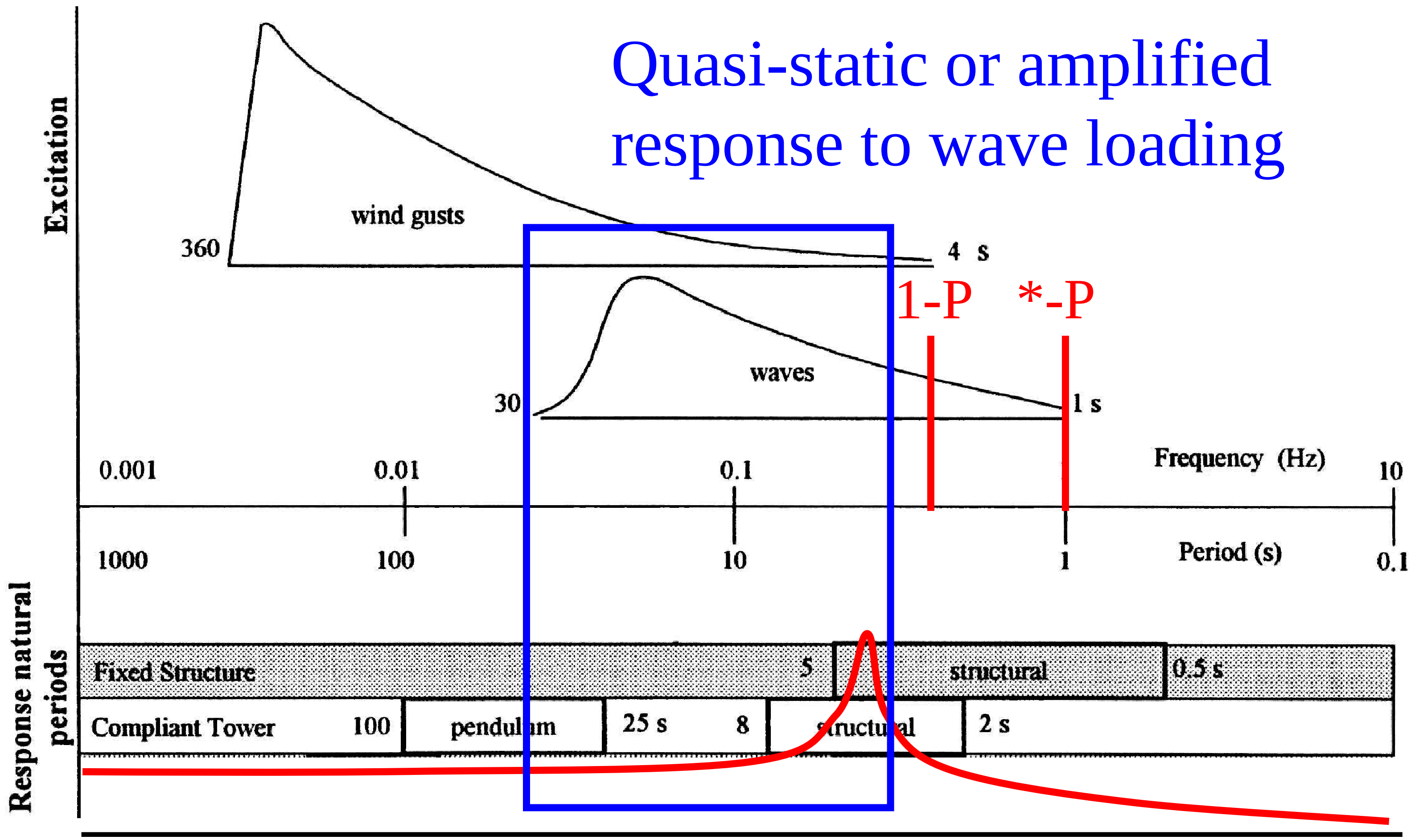
Increased response to loading



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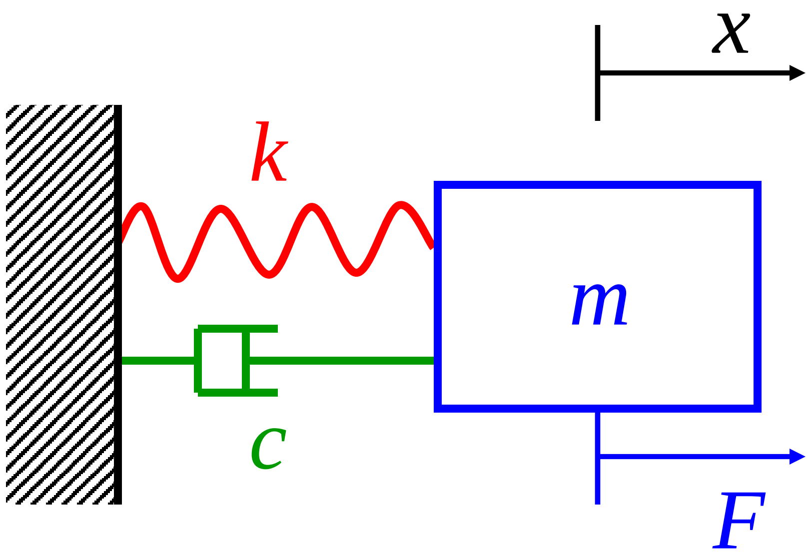
Single degree of freedom system



$$F = m \cdot \ddot{x} + k \cdot x + c \cdot \dot{x}$$

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Wind turbine characteristics

- Stiffness
  - Material properties / soil properties
  - Buoyancy of a floating structure
- Damping
  - Material properties / soil properties
  - Aerodynamic loading
  - Control
  - (Viscosity of water / radiation in soil)
- Inertia
  - Material properties
  - Hydrodynamic loading (water added mass)
  - Entrained water mass

Linear / non-linear systems

Linear system:

$a \cdot x_1(t) + b \cdot x_2(t)$ → $a \cdot y_1(t) + b \cdot y_2(t)$

Initial condition x_0: $x(t) + x_0$ → $y(t) + y_0$

Non-linear system:

- No superposition possible
- Possible dependency on initial conditions
- Possible variation in output statistics for the same input (statistics)

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Non-linearities for wind turbines

- Aerodynamic loading
- Hydrodynamic loading
  - extreme waves
  - waves and currents
- Speed and pitch control
  - some algorithms
  - settings for various wind speeds
- Extreme deformations (2^{nd} order effects)

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Introduction

Loads, dynamics and structural design

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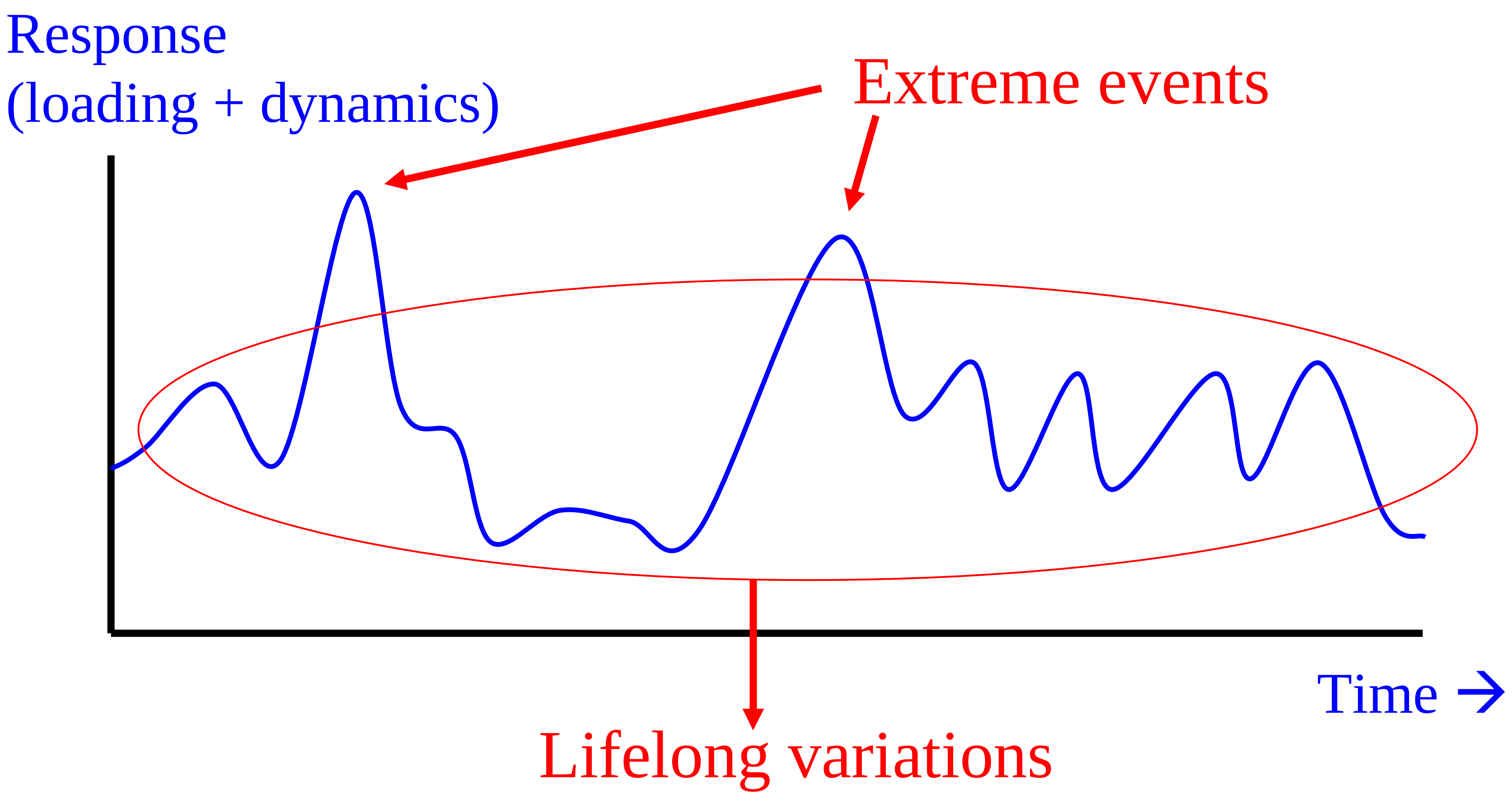
Lifelong response signal



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Effects of loads and dynamics

- Ultimate limit state (ULS)
  (maximum load carrying resistance)
  - Yield and buckling
  - Loss of bearing / overturning
  - Failure of critical components
- Fatigue limit state (FLS)
  (effect of cyclic loading)
  - Repeated wind and wave loading
  - Repeated gravity loading on blade

Effects of loads and dynamics

- Accidental limit state (ALS)
  (accidental event or operational failure, local damage or large displacements allowed)
  - Ship impact
- Serviceability limit state (SLS)
  (deformations/motion, tolerance for normal use)
  - Blade tip tower clearance
  - Vibrations that may damage equipment
  - Tilt of turbine due to differential settlement

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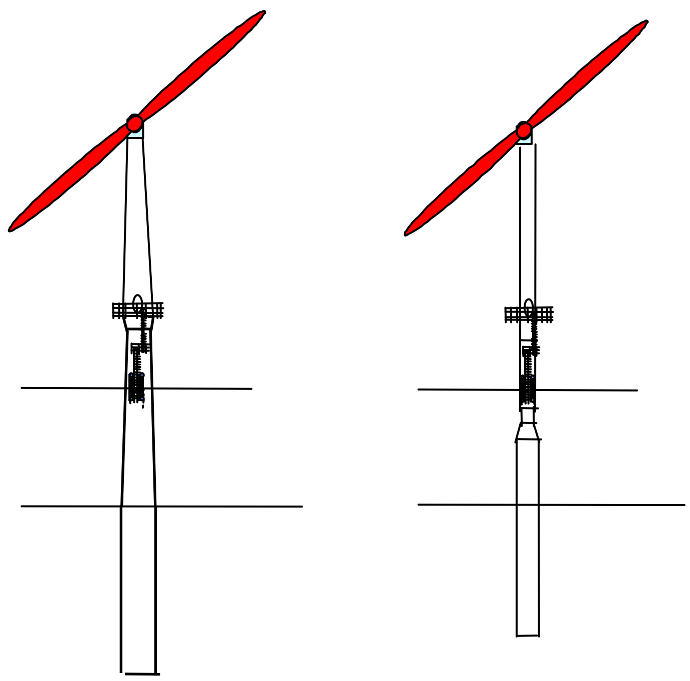
Design drivers of wind turbines

Component	Design drivers: Ultimate	Design drivers: Fatigue
Tower top	top mass	-
Tower	-	wind/wave
Submerged tower	wind/wave/current	wind/wave
Foundation	wind/wave/current	-

Importance of dynamics in design

- Increase or decrease of maximum load
  - Affects Ultimate Limit State conditions
- Increase or decrease of number of load cycles and their amplitudes
  - Affects Fatigue Limit State / Lifetime

Effect on structural design



Monopile
soft-stiff

Monopile
soft-soft

Support structure cost
Soft-stiff monopile ≈ 100 %
Soft-soft monopile ≈ 80 %

Energy cost
Soft-stiff monopile ≈ 100 %
Soft-soft monopile ≈ 95 %

Use of dynamic models

1.

Analyse system properties

↓

Avoid resonance and instabilities

2.

Reduce internal loads and match resistance

↓

Make lightest and cheapest structural design

3.

Assess lifelong loading

↓

Validate reliability and technical lifetime

Modelling of offshore wind turbines

Structural models of rotor, nacelle and support structure

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Flexibility of wind turbines

Rotor	- Rotation
Drive train	- Torsion
Blades	- Flapwise bending - Edgewise bending - Torsion
Tower	- Bending - Torsion
Foundation	- Rotation - Horizontal - Vertical

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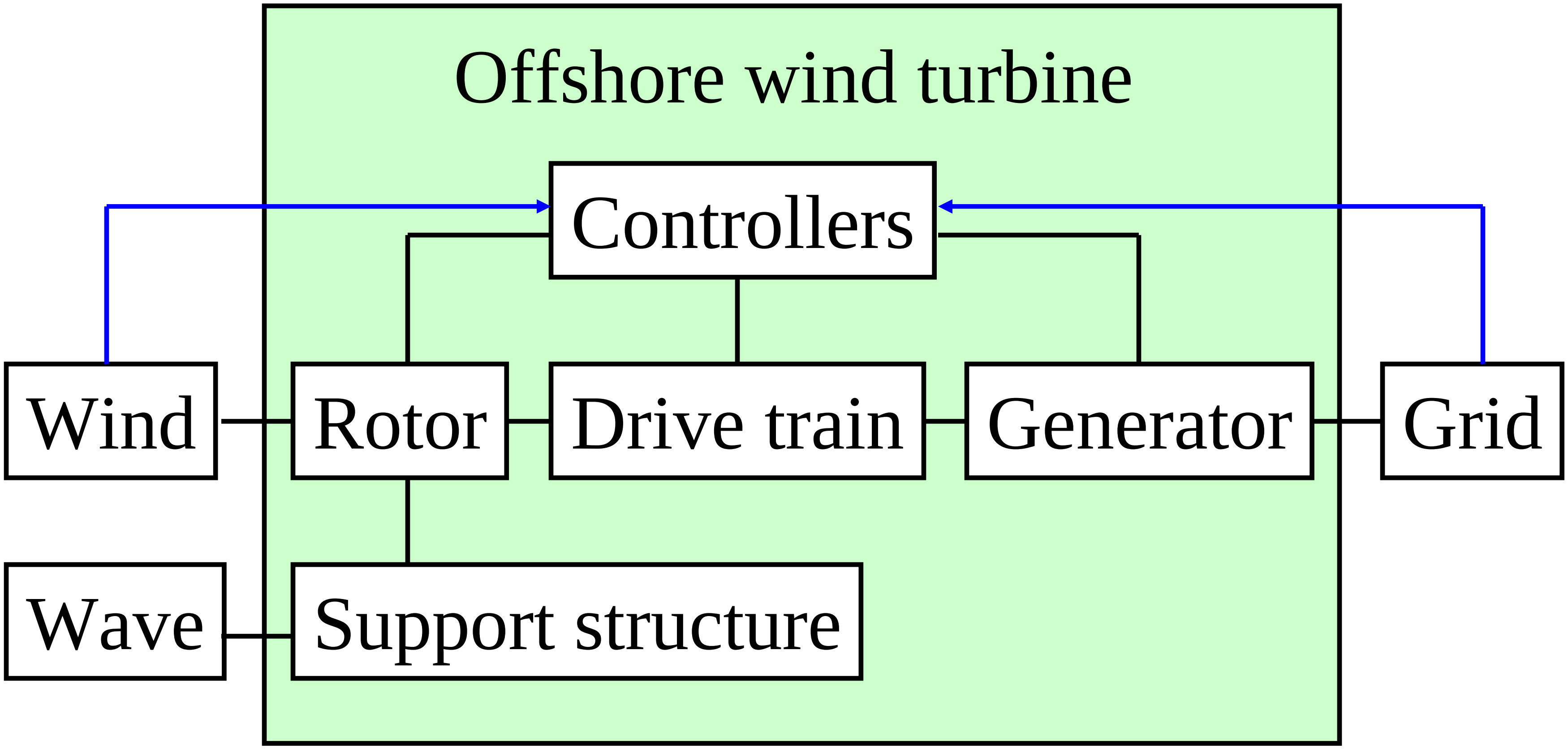
Integrated dynamic model



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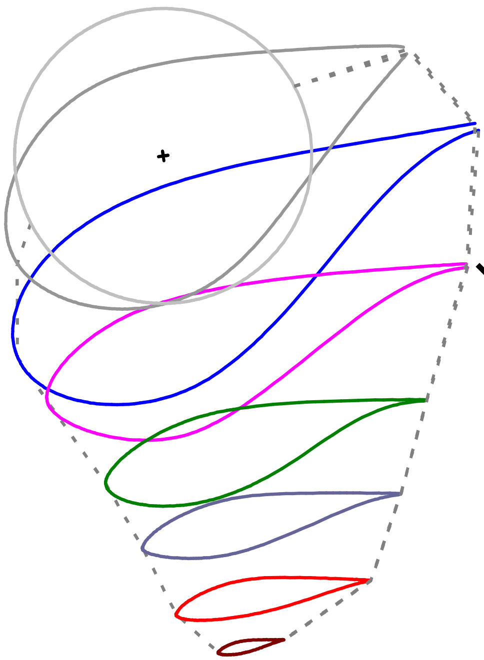
Rotor model

Aerodynamic properties



Tables

$C_l - \alpha$

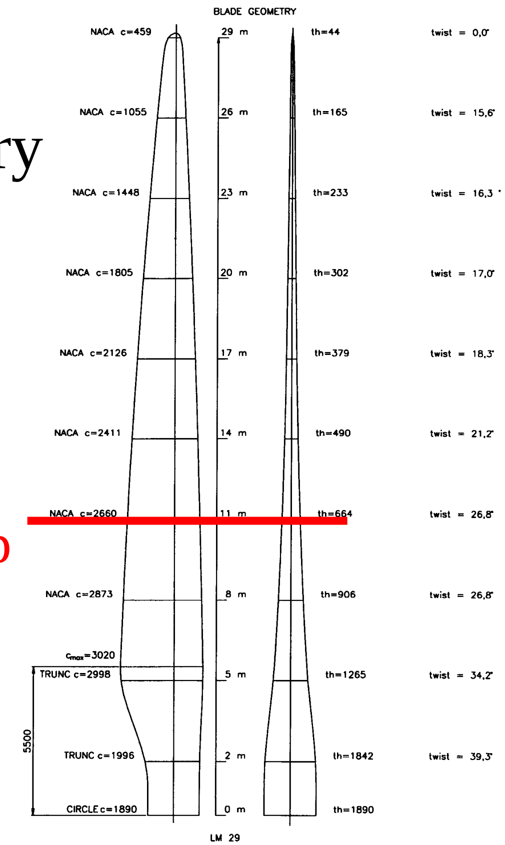
$C_d - \alpha$

Distributed mass-stiffness

Beam theory

FEM

μ, $EI_{x,y,p}$



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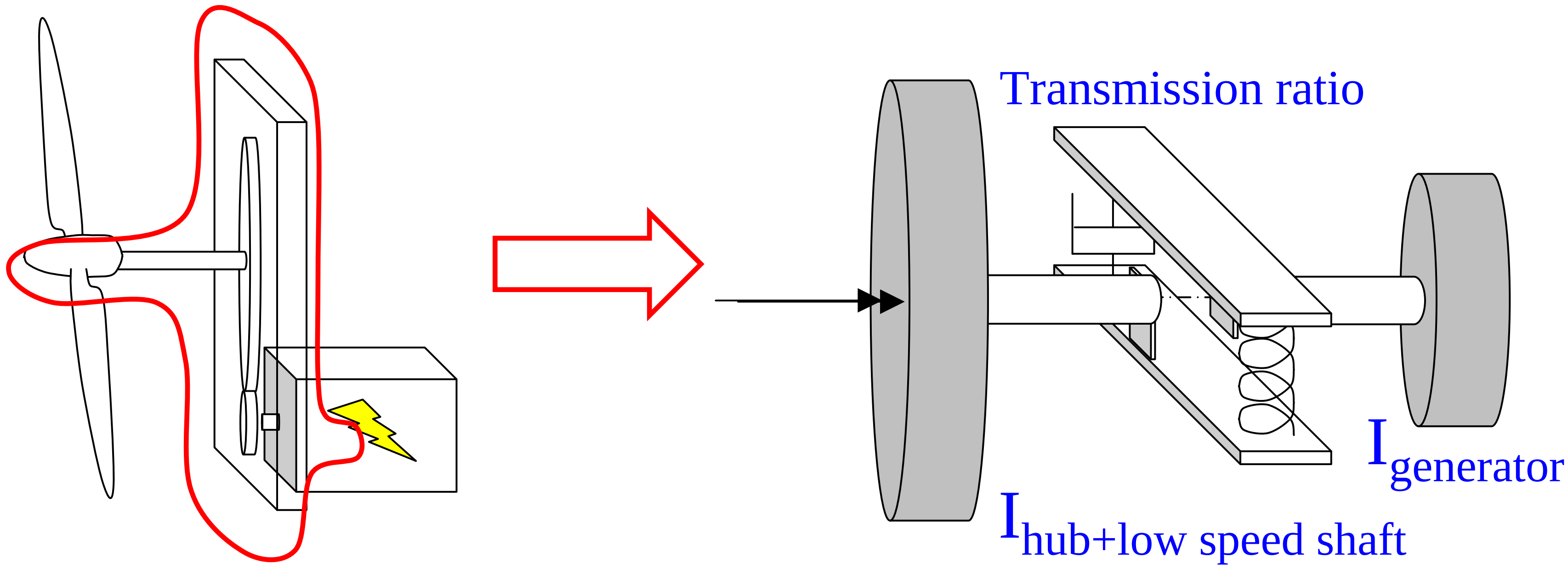
Drive train model



Stiffness torsion in transmission and main shaft; main shaft bending

Damping transmission suspension and generator torque control

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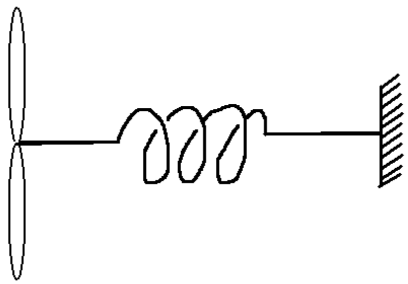
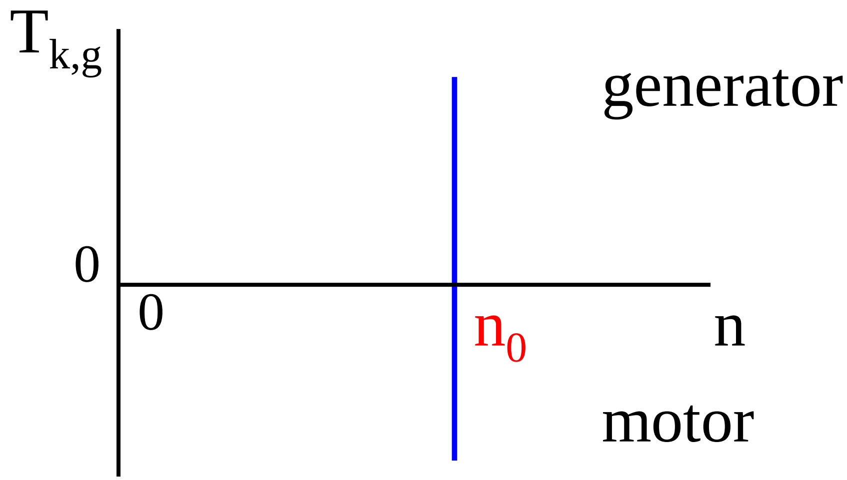
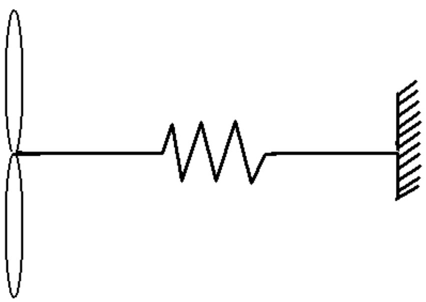
Generator model

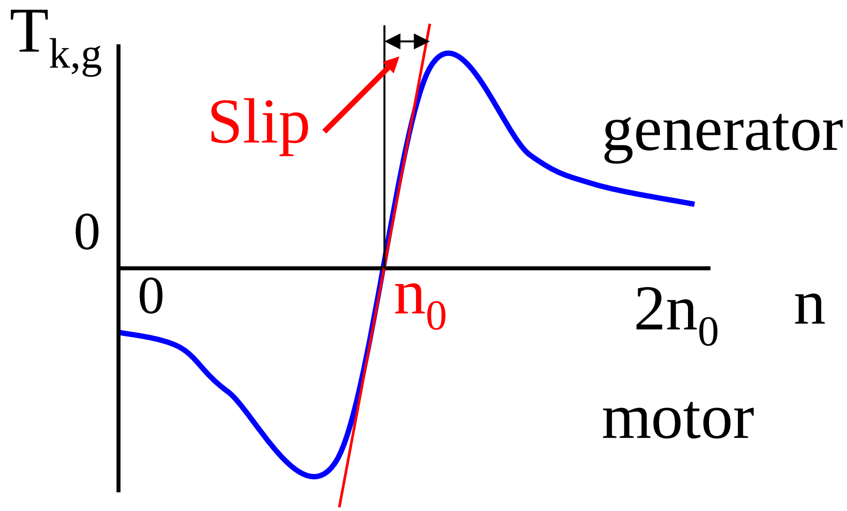
synchronous generator:





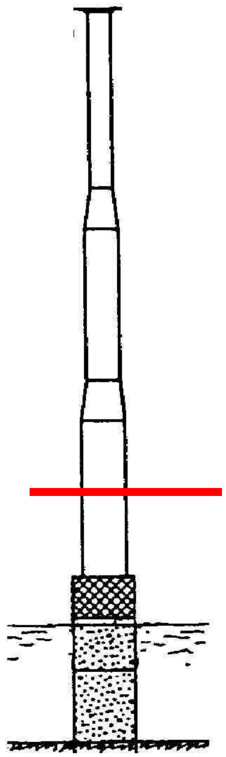
induction generator:





Tower model

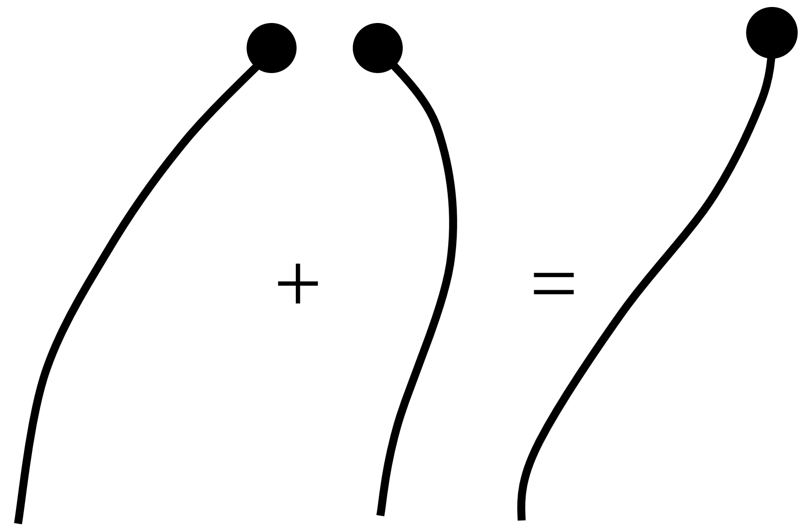
Distributed mass-stiffness



Beam theory
FEM

μ, $EI_{x,y,p}$

Modal representation



Deflection 1st mode | Deflection 2nd mode | "Total" deformation

Effective reduction of DOFs

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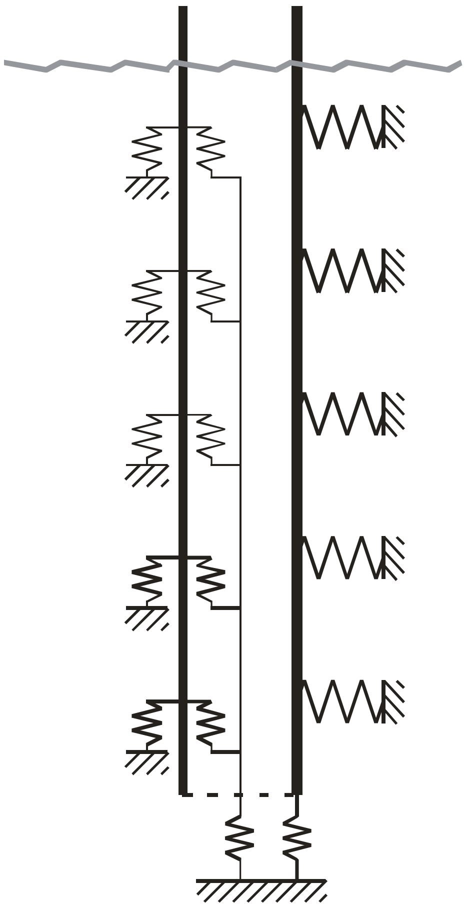
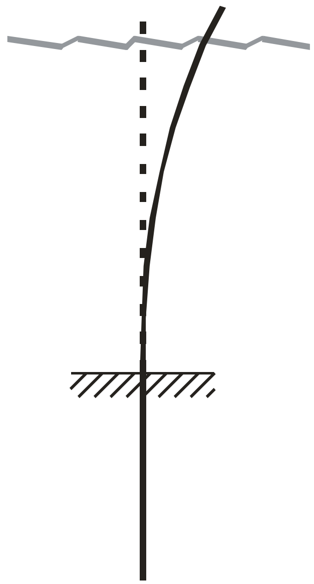
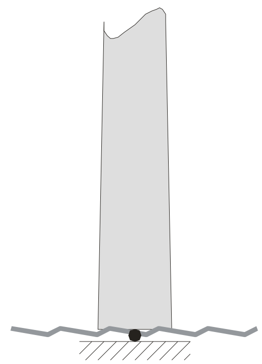
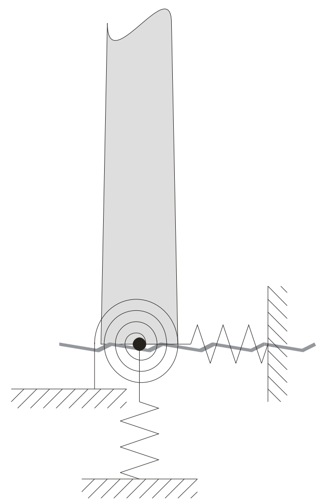
Foundation model

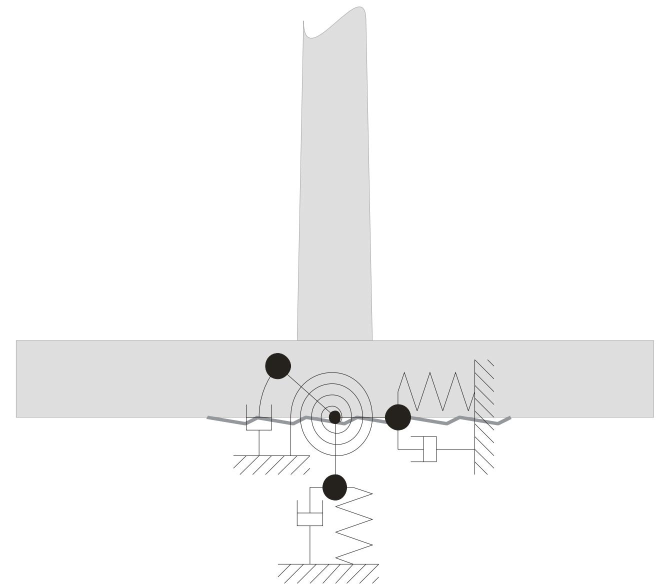






$$\begin{bmatrix} H \\ M \end{bmatrix} = \begin{bmatrix} k_{xx} & k_{x\theta} \\ k_{\theta x} & k_{\theta\theta} \end{bmatrix} \cdot \begin{bmatrix} u \\ \theta \end{bmatrix}$$





Modelling of offshore wind turbines

Deriving parameters for foundation models

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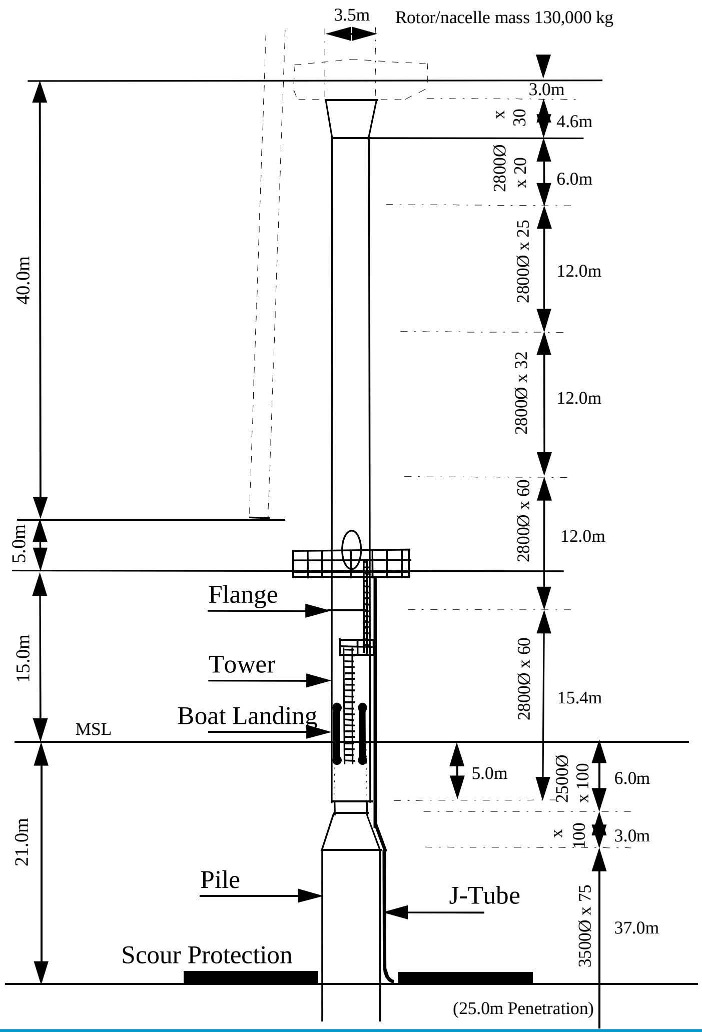
Importance of foundation model



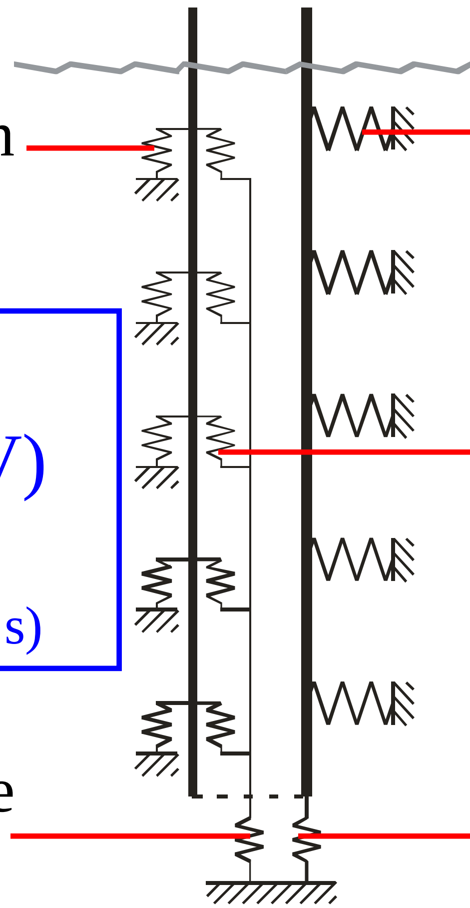
First natural frequency (Hz)

without foundation	0.34627
with foundation	0.29055
with scour	0.28219

Second natural frequency (Hz)

without foundation	2.2006
with foundation	1.3328
with scour	1.2508

Enhanced foundation model



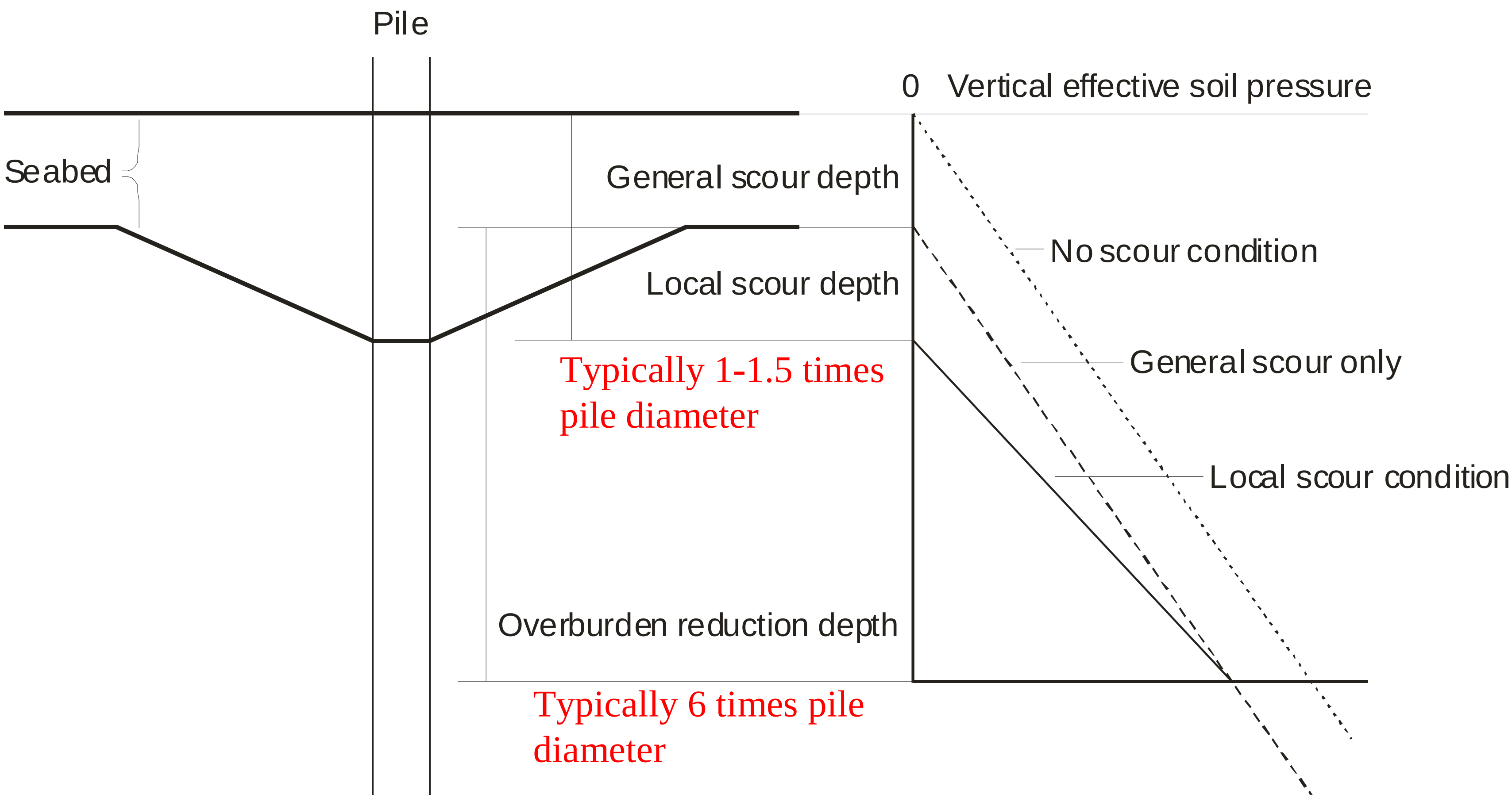
Use:

Standards (API/DNV)

Existing software

(In exercise: ANSYS Macro's)

Scour



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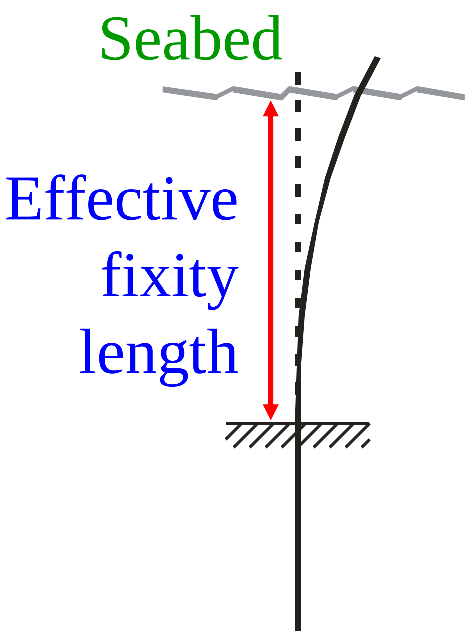
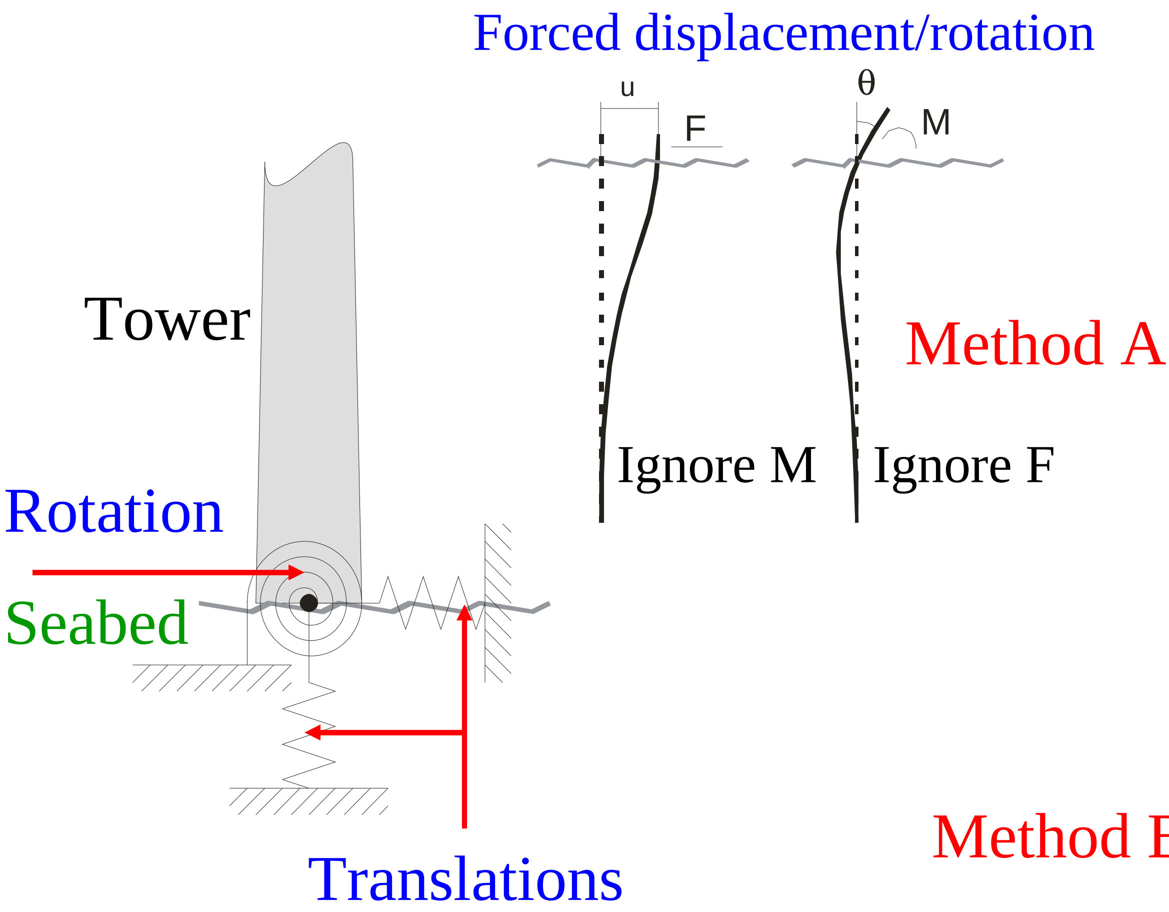
Effective fixity length

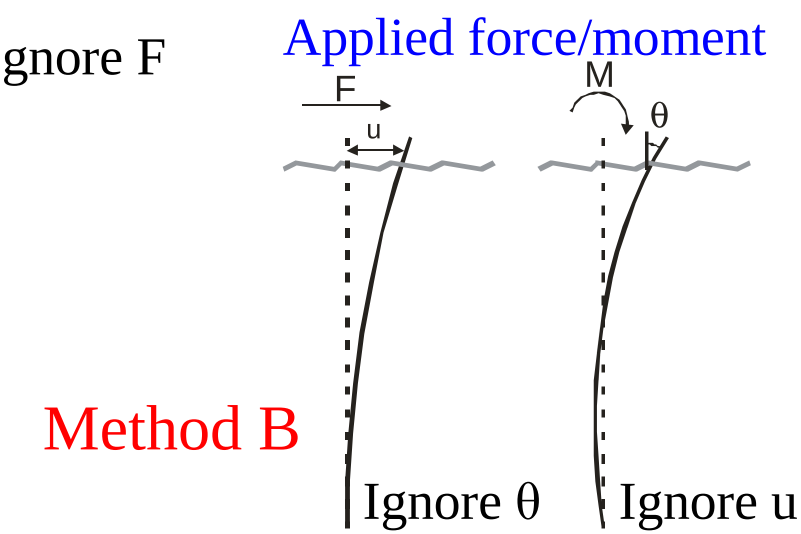


Configuration	*Effective fixity length*
Stiff clay	3.5 D – 4.5 D
Very soft silt	7 D – 8 D
General calculations	6 D
Experience with offshore turbines	3.3 D – 3.7 D

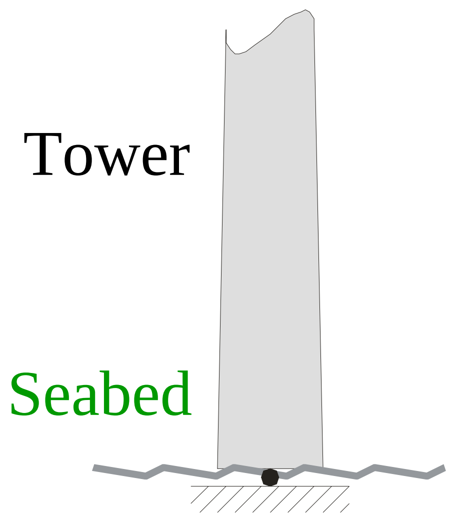
Uncoupled springs



In exercise: Use ANSYS Macro's and method B for a monopile



Stiffness matrix



$$\begin{bmatrix} H \\ M \end{bmatrix} = \begin{bmatrix} k_{xx} & k_{x\theta} \\ k_{\theta x} & k_{\theta\theta} \end{bmatrix} \cdot \begin{bmatrix} u \\ \theta \end{bmatrix}$$

Stiffness matrix

Run two load cases with FEM model with py-curves

(See next slide)

FEM-based pile-head stiffness

1. Solve FEM for F_1, M_1

   (F_1, M_1 near loading situation of interest)

$$F_1 = k_{xx} \cdot u_1 + k_{x\theta} \cdot \theta_1$$

$$M_1 = k_{\theta x} \cdot u_1 + k_{\theta\theta} \cdot \theta_1$$

2. Solve FEM for F_2, M_2

   (F_2, M_2 near loading situation of interest)

$$F_2 = k_{xx} \cdot u_2 + k_{x\theta} \cdot \theta_2$$

$$\sout{M_2 = k_{\theta x} \cdot u_2 + k_{\theta\theta} \cdot \theta_2}$$

3. Scratch one equation and solve k_{xx}, $k_{x\theta}$, $k_{\theta\theta}$

   ($k_{\theta x} = k_{x\theta}$, assume matrix equal for both loads)

4. Check assumption with another FEM solution

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Selection of pile foundation models

- Foundation flexibility significant enough to require close consideration of modelling
- Effective fixity length model dissuaded
- Stiffness matrix much more favourable than uncoupled springs
  For exercise: Monopile in Bladed modeled with uncoupled springs (unfortunately)

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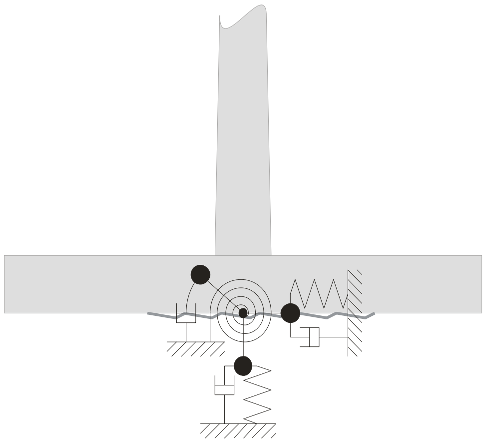
Documented GBS model parameters

GBS	Spring stiffness	Viscous damping	Inertia
Rocking	$\frac{G \cdot D^3}{3 \cdot (1-\nu)}$	$0.65 \frac{D^4 \cdot \sqrt{\rho \cdot G}}{32 \cdot (1-\nu)}$	$0.64 \frac{\rho \cdot D^5}{32 \cdot (1-\nu)}$
Horizontal	$\frac{16G \cdot D \cdot (1-\nu)}{7-8\nu}$	$4.6 \frac{D^2 \cdot \sqrt{\rho \cdot G}}{4 \cdot (2-\nu)}$	$0.76 \frac{\rho \cdot D^3}{8 \cdot (2-\nu)}$
Vertical	$\frac{2G \cdot D}{1-\nu}$	$3.4 \frac{D^2 \cdot \sqrt{\rho \cdot G}}{4 \cdot (1-\nu)}$	$1.08 \frac{\rho \cdot D^3}{8 \cdot (1-\nu)}$

Lumped springs and dashpots for:
- Horizontal
- Vertical
- Rocking



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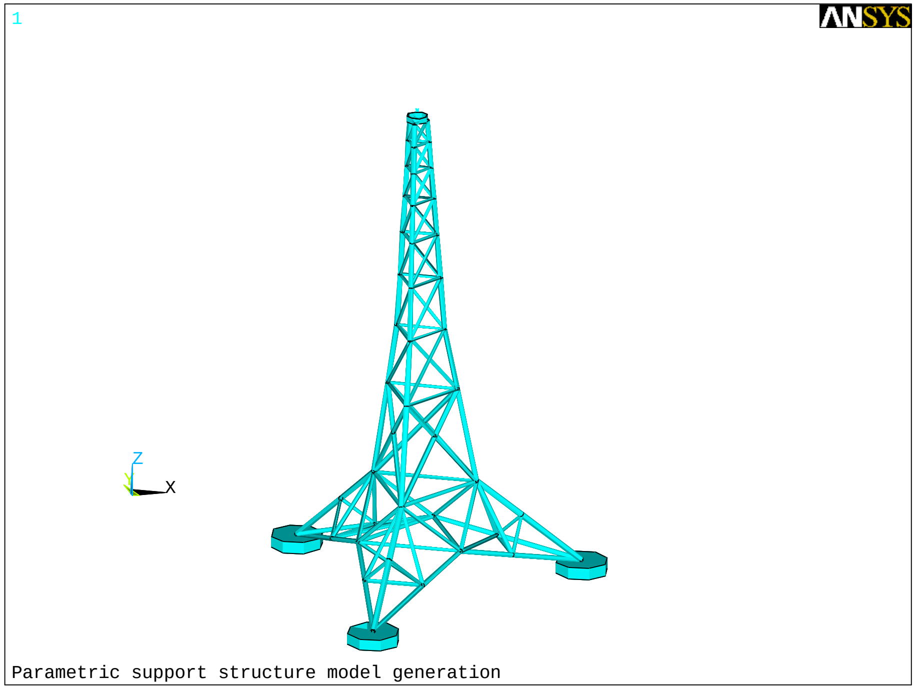
Types of analysis and tools

Natural frequency and mode analysis

FEM modal analysis



FEM analysis provides:

- Natural frequencies
- Mode shapes
- (Pre-processed) matrices of structural properties:
    - Mass
    - Stiffness
    - Damping

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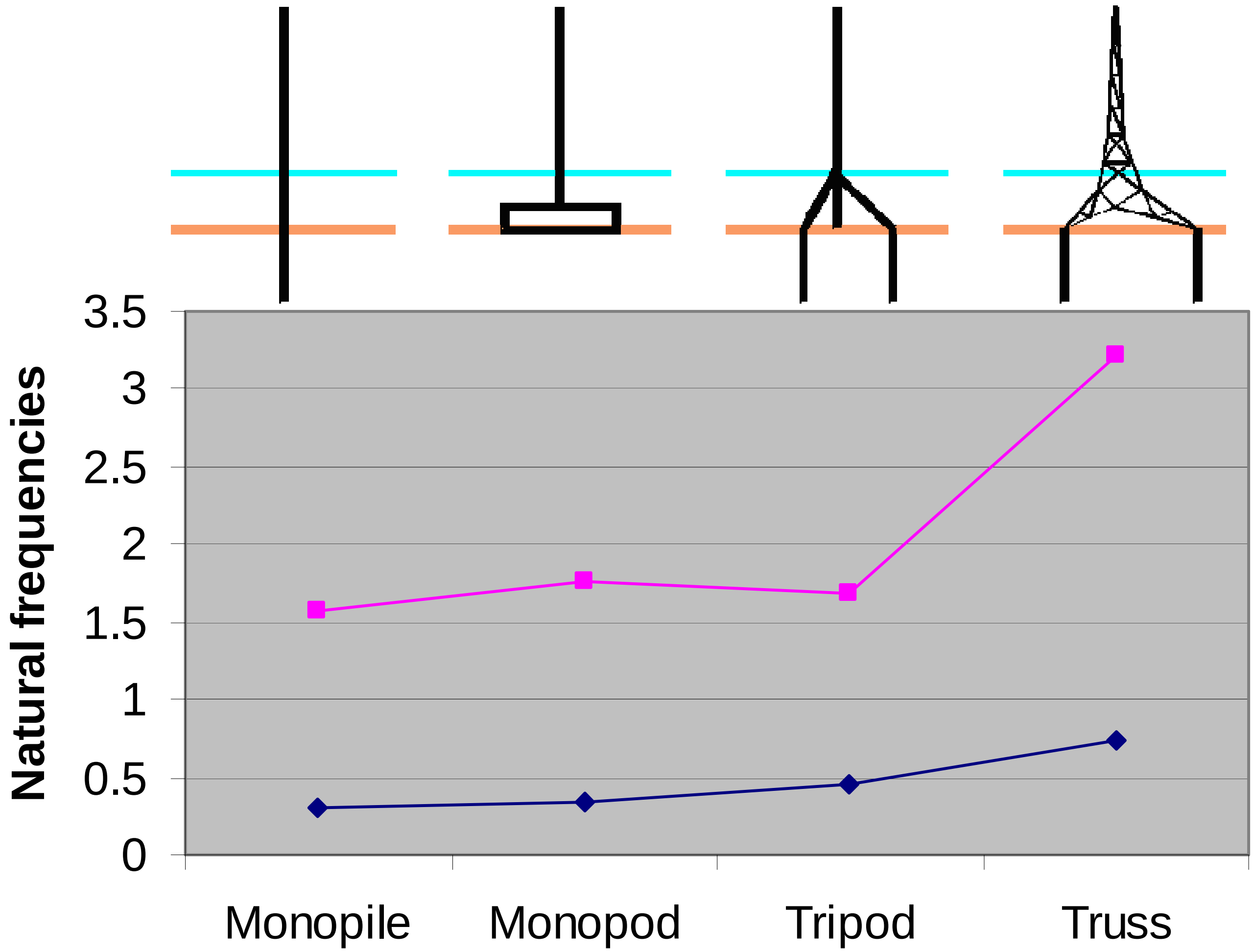
Natural frequencies



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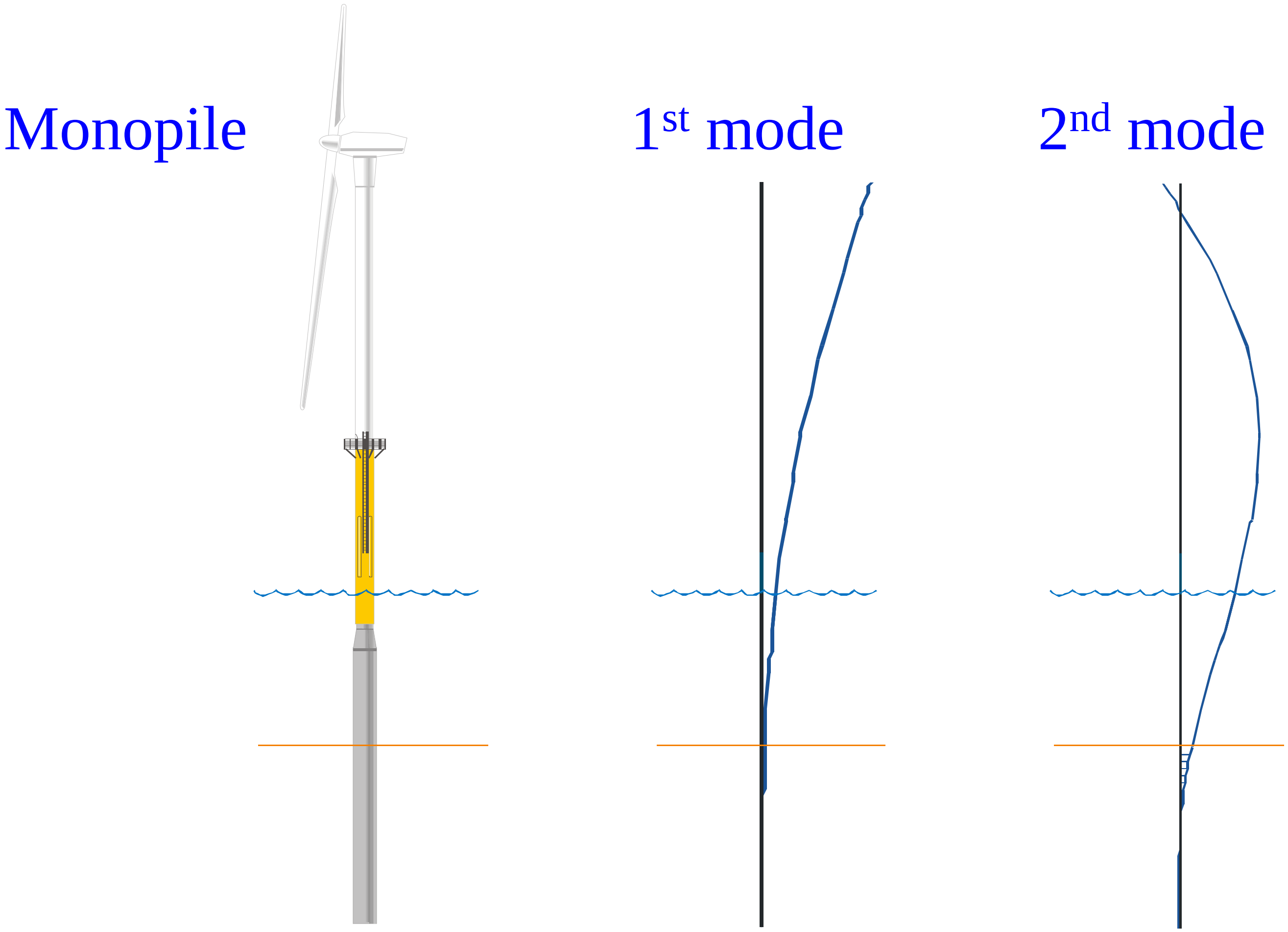
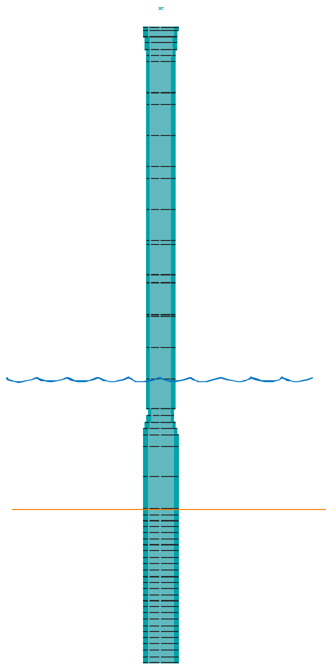
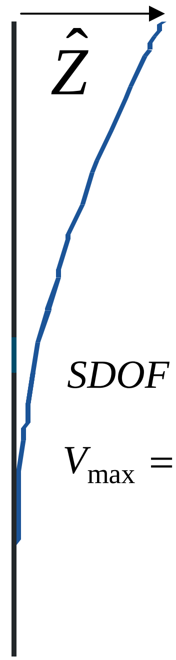
Modes of the support structure



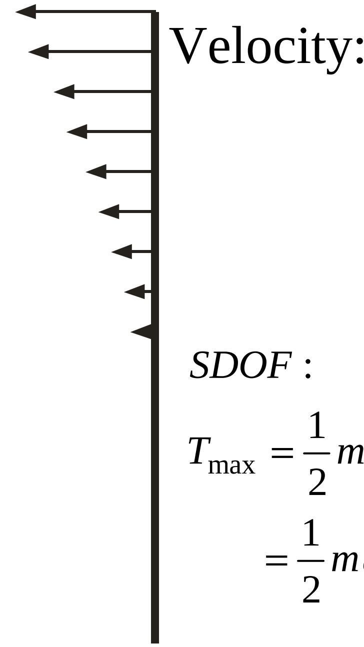
Rayleigh's method





$SDOF:$

$$V_{\max} = \frac{1}{2} k (\hat{x})^2$$



$SDOF:$

$$T_{\max} = \frac{1}{2} m \left((\dot{x})_0 \right)^2 = \frac{1}{2} m \omega^2 (\hat{x})^2$$

$$v(x,t) = \Psi(x) \cdot \hat{Z} \sin(\omega t)$$

Maximum strain energy $\sim \hat{Z}^2$ = Maximum kinetic energy $\sim \hat{Z}^2 \cdot \omega^2$

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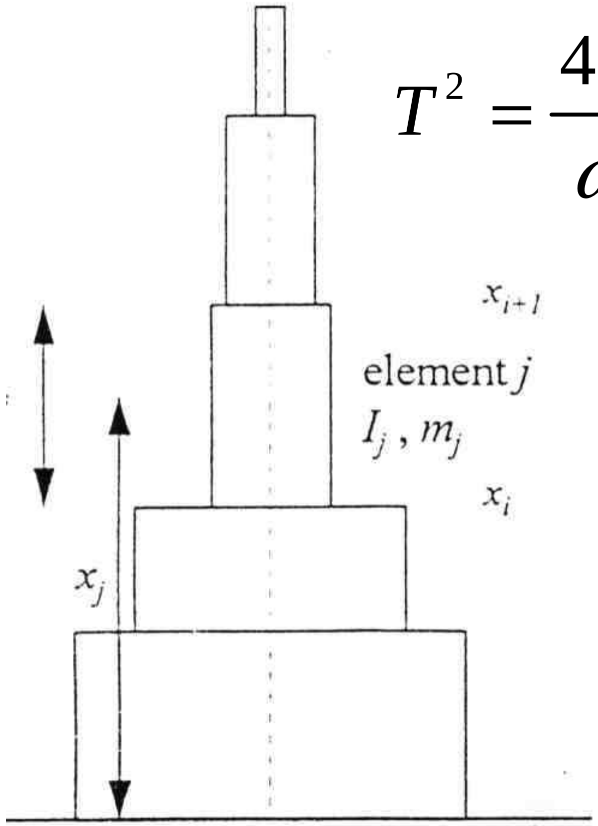
Rayleigh's method

- To estimate first natural frequency (lowest)
- Based on energy conservation in undamped, free vibration: Exchange of energy between motion and strain
- Mode shape must fit boundary conditions
- Best estimate of mode shape results in lowest estimate of natural frequency
- (Deflection under static top-load gives educated guess of mode shape)

Rayleigh's method for stepped tower



$$T^2 = \frac{4\pi^2}{\omega^2} \approx \frac{4\pi^2\left(m_{top} + m_{eq}L\right)L^3}{3EI_{eq}} \cdot \left(\frac{48}{\pi^4} + C_{found}\right)$$

See document on Blackboard for:

- Derivation of this equation
- Explanation of EI_{eq}, m_{eq}, C_{found}

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Free vibration of cylinder in water

$$f = C_M \cdot \rho \frac{\pi}{4} D^2 \cdot a_{w,\perp} - (C_M - 1) \cdot \rho \frac{\pi}{4} D^2 \cdot \ddot{x}_c + C_D \cdot \frac{1}{2} \rho D \cdot |v_{w,\perp} - \dot{x}_c| (v_{w,\perp} - \dot{x}_c)$$

Inertia force

Drag force

Inertia force due to moving cylinder

- Still water → remaining inertia term is called 'water added mass'
- With $C_M \approx 2$ → water added mass ≈ mass of replaced water

  But related to water surrounding the cylinder!
- Use water added mass in analysis of natural frequency and modes

Types of analysis and tools

Response analysis

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Types of response analysis

- Static analysis with dynamic response factors
- Time domain simulation
- Frequency domain analysis
- Mixtures

All approaches can also be divided in:

- Integrated combined loading
- Superposition of effect of load components (wind, wave, current, gravity)

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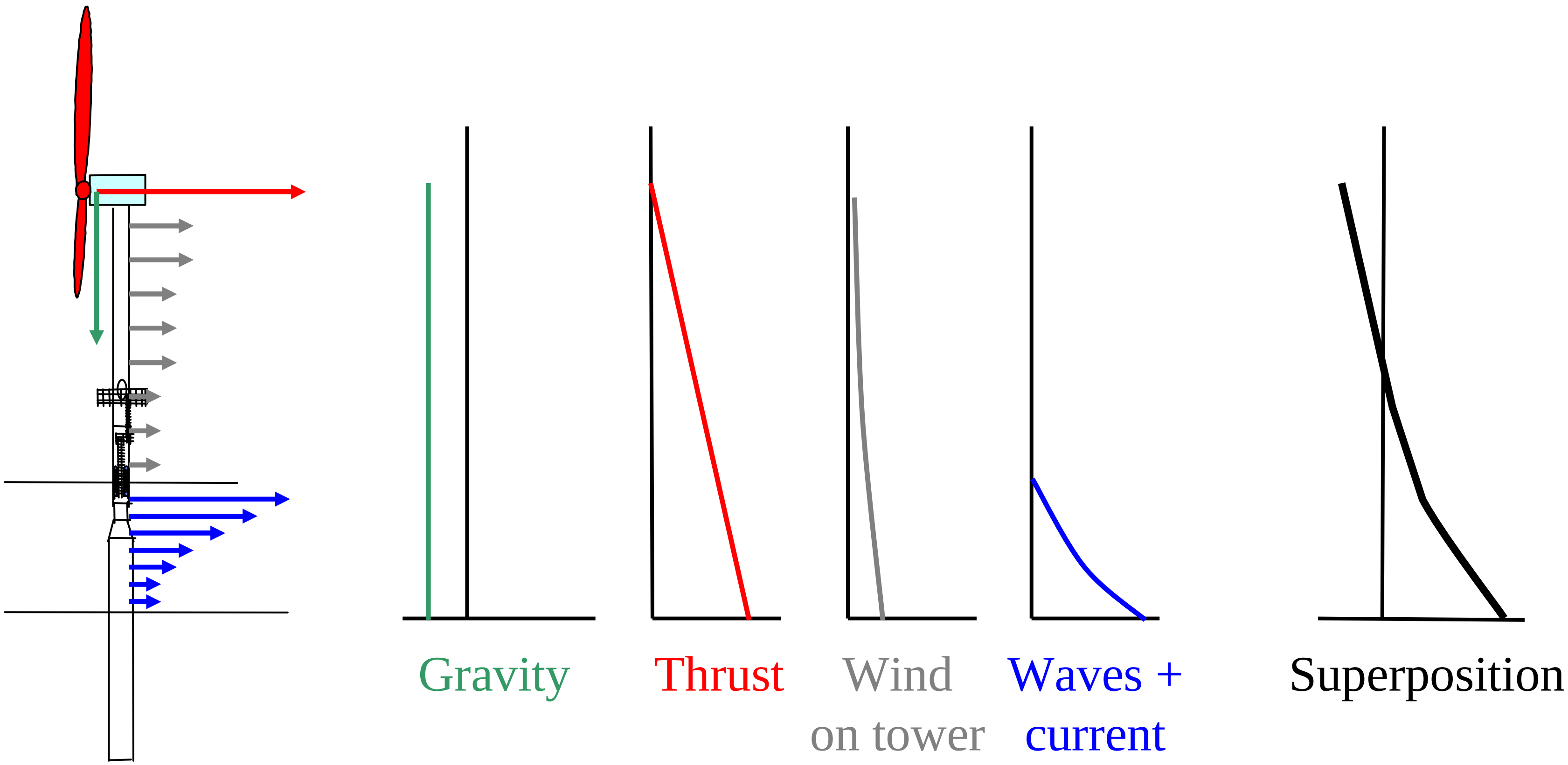
Static + dynamic response factors

- Calculate static response for several loading conditions (separate wind, wave, g)
- Estimate a dynamic response factor per condition (comparison of characteristic frequencies) Typical 1.2-1.5
- Superimpose results (including partial safety factors per loading type)

Superposition of forces



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Time domain simulation

- Generate realisations of external conditions
- Integrate equations of motion numerically
- Analyse response (extremes, probability distribution, fatigue, …)
- Repeat until statistically sound information is obtained

The tool used in the exercise to do this is ‘Bladed’.
See Blackboard item ‘Assignments’ for a tutorial and manuals.

Frequency domain analysis

Fourier transforms and linear systems

Time domain	Frequency domain
$x(t), y(t), h(t)$	$X(\omega), Y(\omega), H(\omega)$
$y(t) = \int x(\tau) \cdot h(t-\tau)\, d\tau = x(t) * h(t)$	$Y(\omega) = X(\omega) \cdot H(\omega)$
$a \cdot x_1(t) + b \cdot x_2(t) \rightarrow$ $a \cdot y_1(t) + b \cdot y_2(t)$	$a \cdot X_1(\omega) + b \cdot X_2(\omega) \rightarrow$ $a \cdot Y_1(\omega) + b \cdot Y_2(\omega)$

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Frequency domain analysis

- Determine transfer function per load source
  Linearise system or use small harmonic loads
- Multiply spectrum of load source with transfer function
- Superimpose response spectra of different sources

Due to non-linearity in the system, this procedure must be repeated for different average wind speeds

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Time domain - frequency domain

Time domain ⟷ Frequency domain

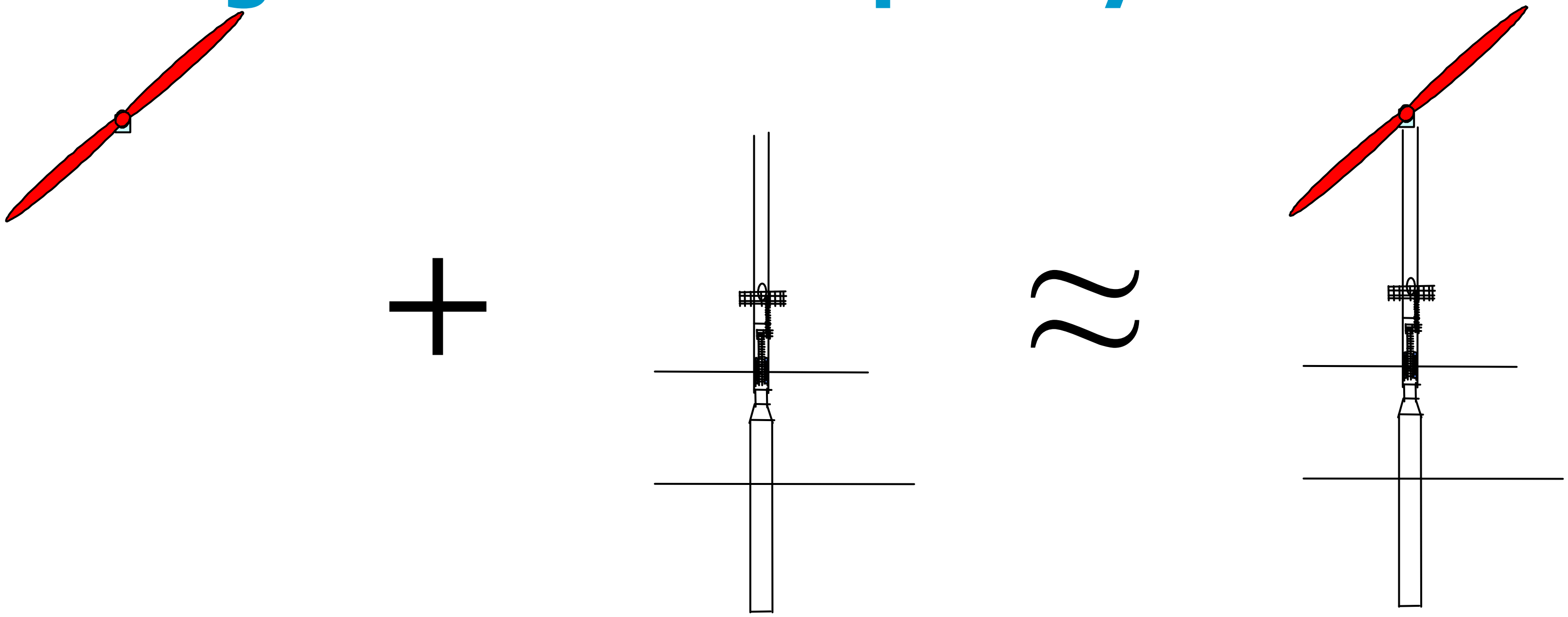
Time domain

- Comprehensive non-linear structural model
- Very time consuming
- Careful choice of time signal
- Able to model control system dynamics
- Established fatigue prediction tools

Frequency domain

- Simplified linear structural model
- Very rapid calculation
- Well documented wind turbulence spectra
- Able only to model linear control system
- Fatigue prediction tools relatively new

Mixing time- and frequency domain



TD simulation:
- Transfer function tower top loading (linearisation)
- Aerodynamic damping

FD analysis:
- Transfer function for wind loading
- Aerodynamic damping as extra structural damping
- Linear wave loading

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Aerodynamic damping

Tower for-aft motion

↓

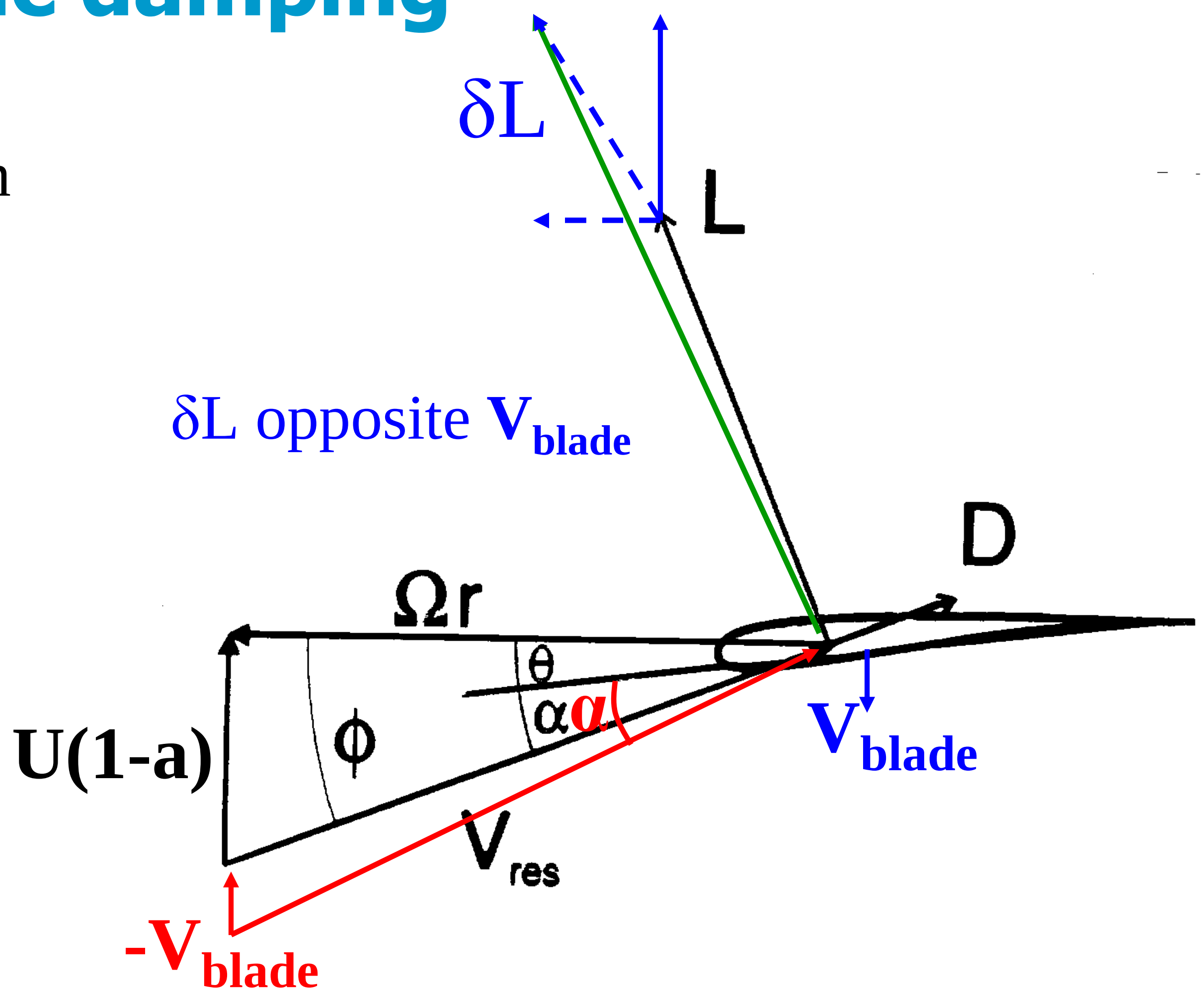
Blade motion

↓

Angle of attack decreases/increases

↓

Lift/thrust force diminishes/increases



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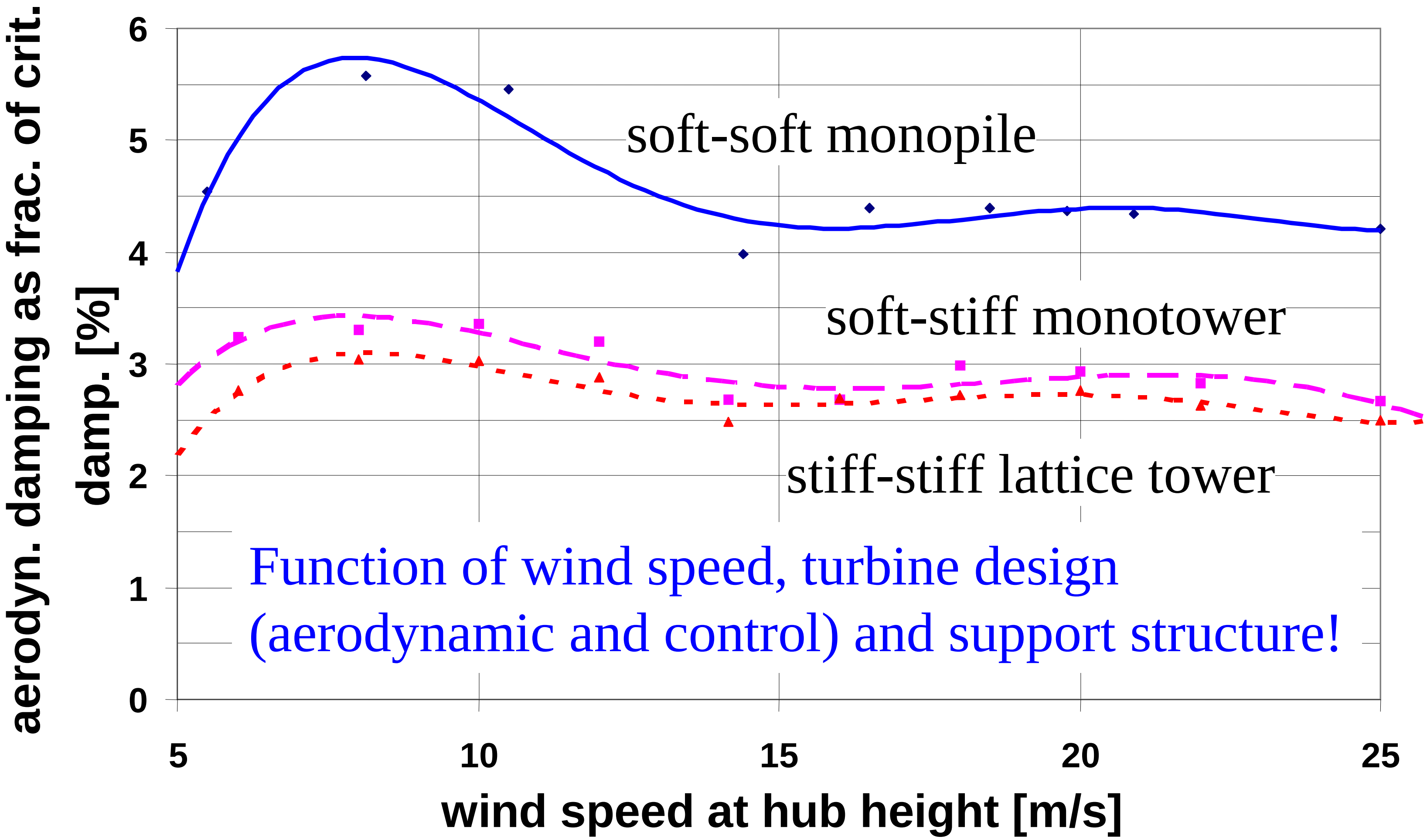
Aerodynamic damping



Some relevant analysis tools

	FEM	Time	Freq	Rotor	Offshore
ANSYS	X				
Sesam	X	X	X		X
Adams WT	X	X	X	X	
Phatas	X	X		X	X
Bladed	X	X		X	X
Flex	X	X		X	X
Turbu	X		X	X	X

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Loads and dynamics in design

Overview of the process

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Suggested steps

- Choose a limited set of load cases
- Make preliminary design based on static loads
- Check for resonance*
- Check extreme loads with time domain simulations*
- Check fatigue damage*

* Adjust design when necessary

Partial safety factor method

- Apply load and resistance factors to:
  - loads on the structure or load effects in the structure
  - resistance of the structure or strength of materials
- Fulfill design criterion: $\gamma_S \cdot S \leq \frac{R}{\gamma_R}$
- Combined loading with non-linear effects:
  - Apply one safety factor to combined load effect, determined from structural analysis of simultaneous loading

Values for safety factors

- Importance of structural component w.r.t. consequence of failure considered
- Typically between 0.7 and 1.35
- $\leq$ 1.0 for favourable loads!
- Load factor 1.0 for fatigue (safety in resistance)
- See e.g. Offshore standard DNV-OS-J101
  Design of offshore wind turbine structures

Loads and dynamics in design

Choose load cases

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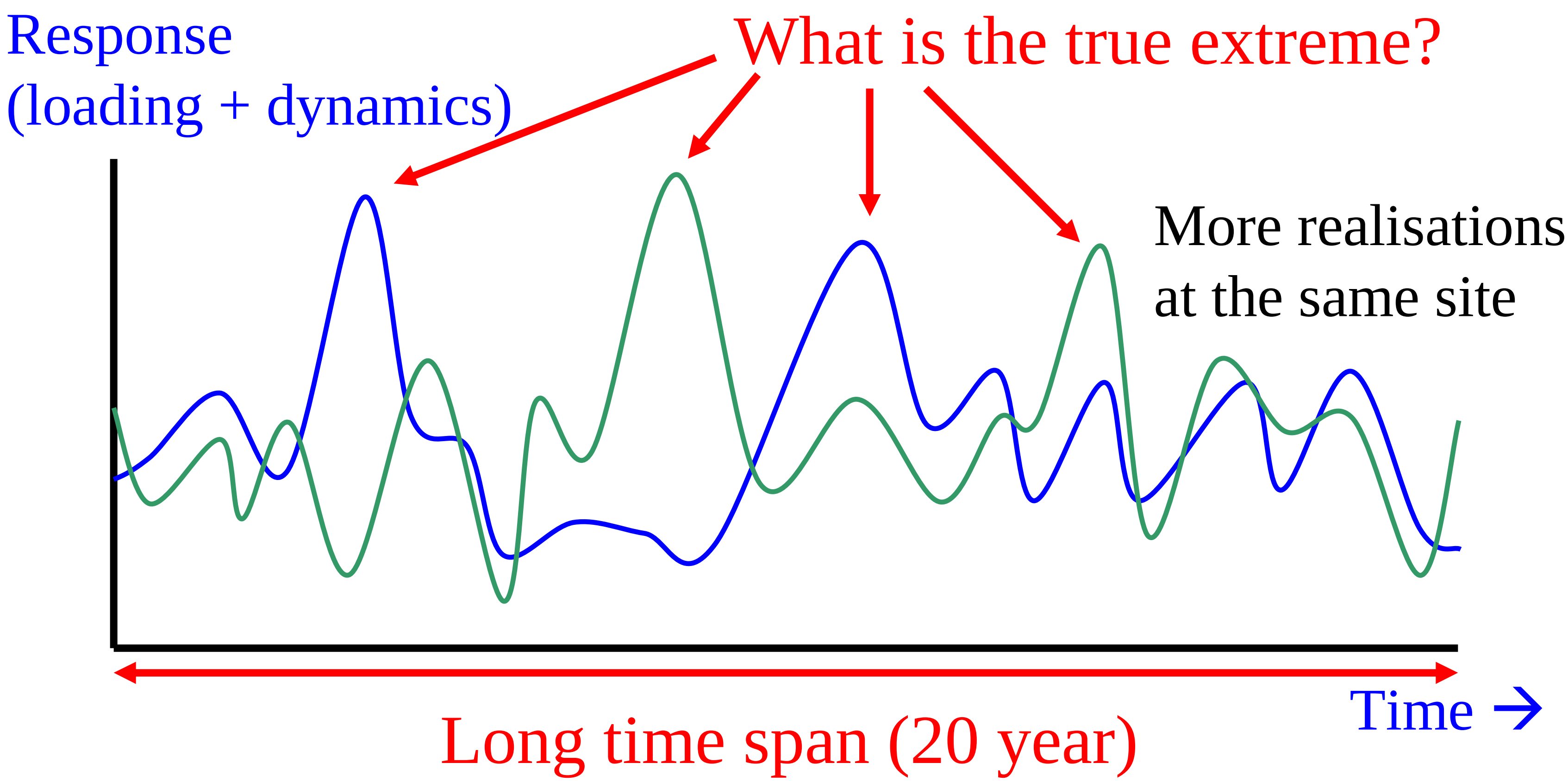
Fundamental problems in evaluation



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Load cases: Combine conditions

external conditions

- normal
- extreme

operational conditions

- normal conditions
  - stand-by
  - start-up
  - power production
  - normal shut-down
- fault conditions
- condition after occurrence of a fault
- erection

The number of combinations that is required in the standards is enormous!

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Reducing number of load cases (extremes)

Select a few independent extreme conditions that might be design driving, e.g.:

- Extreme loading during normal operation
- Extreme loading during failure
- Extreme wind loading above cut-out
- Extreme wave loading

And combine these with reduced conditions for the other aspects (wind, wave, current)

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Reducing number of load cases (fatigue)

Hs \\ Tz	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	total
5.5 - 6										0.0
5 - 5.5								0.08		0.1
4.5 - 5							0.04	0.3		0.3
4 - 4.5							0.3	0.08		0.4
3.5 - 4							0.7			0.7
3 - 3.5							0.7			0.7
2.5 - 3						0.6	0.04			0.7
2 - 2.5						0.2				0.2
1.5 - 2										0.0
1 - 1.5					3.4	0.4				3.8
0.5 - 1				19	58	0.7				77.7
0 - 0.5	0.68		1.0	65	12	0.1	0.11			79.0
total	0.7	0.0	1.0	84.2	73.4	2.0	1.9	0.5	0.0	164

Idling: $V_w > V_{cut\_out}$

lumped sea state

Normal operation: $V_{cut\_in} < V_w < V_{cut\_out}$

Idling: $V_w < V_{cut\_in}$

Lump states in 3D scatter diagram

Use normal operation and idling

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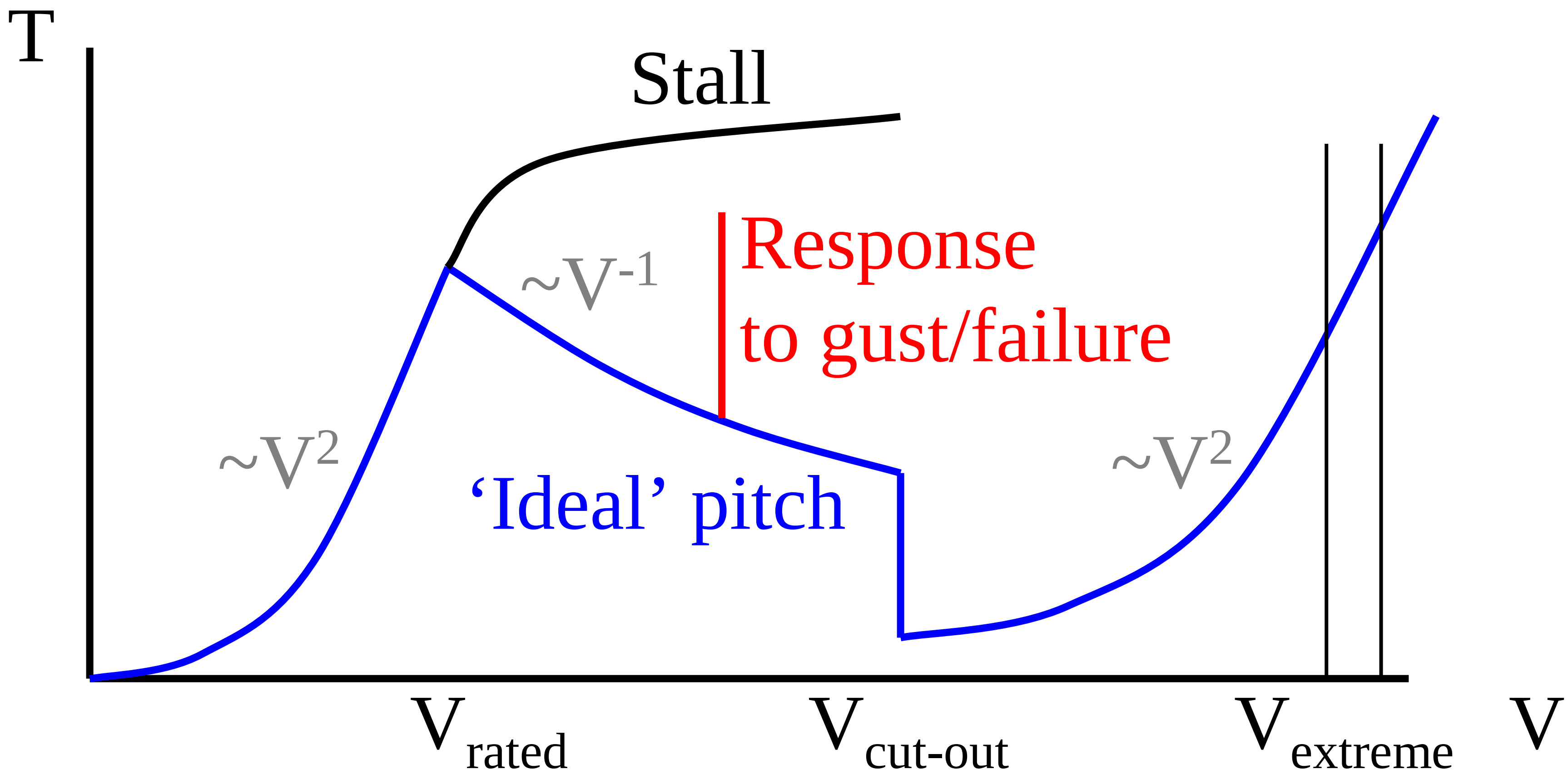
Knowledge about load case selection: Thrust curves



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Extreme and reduced conditions

- $H_{max} \approx 1.86 \cdot H_s$
- $H_{reduced} \approx 1.32 \cdot H_s$
- $V_{gust,max} \approx 1.2 \cdot V_{10\ min}$
- $V_{gust,reduced} \approx (1.2 / 1.1) \cdot V_{10\ min}$

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Loads and dynamics in design

Make preliminary design

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Preliminary support structure design

- Determine largest loads at several heights
  - Estimate wind, wave, current and gravity loads
    e.g. $C_{D,AX}$ = 8/9 (Betz) at V_{rated} & linear wave & DAF & safety
  - Superimpose and determine largest at each height
- Dimension tower (moments / section modulus)
- Rule of thump D/t
  - 200 tower section
  - ~60 driven foundation pile (see e.g. API on BB)
- Estimate pile size with Blum's method
  (See document on Blackboard!)

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Loads and dynamics in design

Check for resonance

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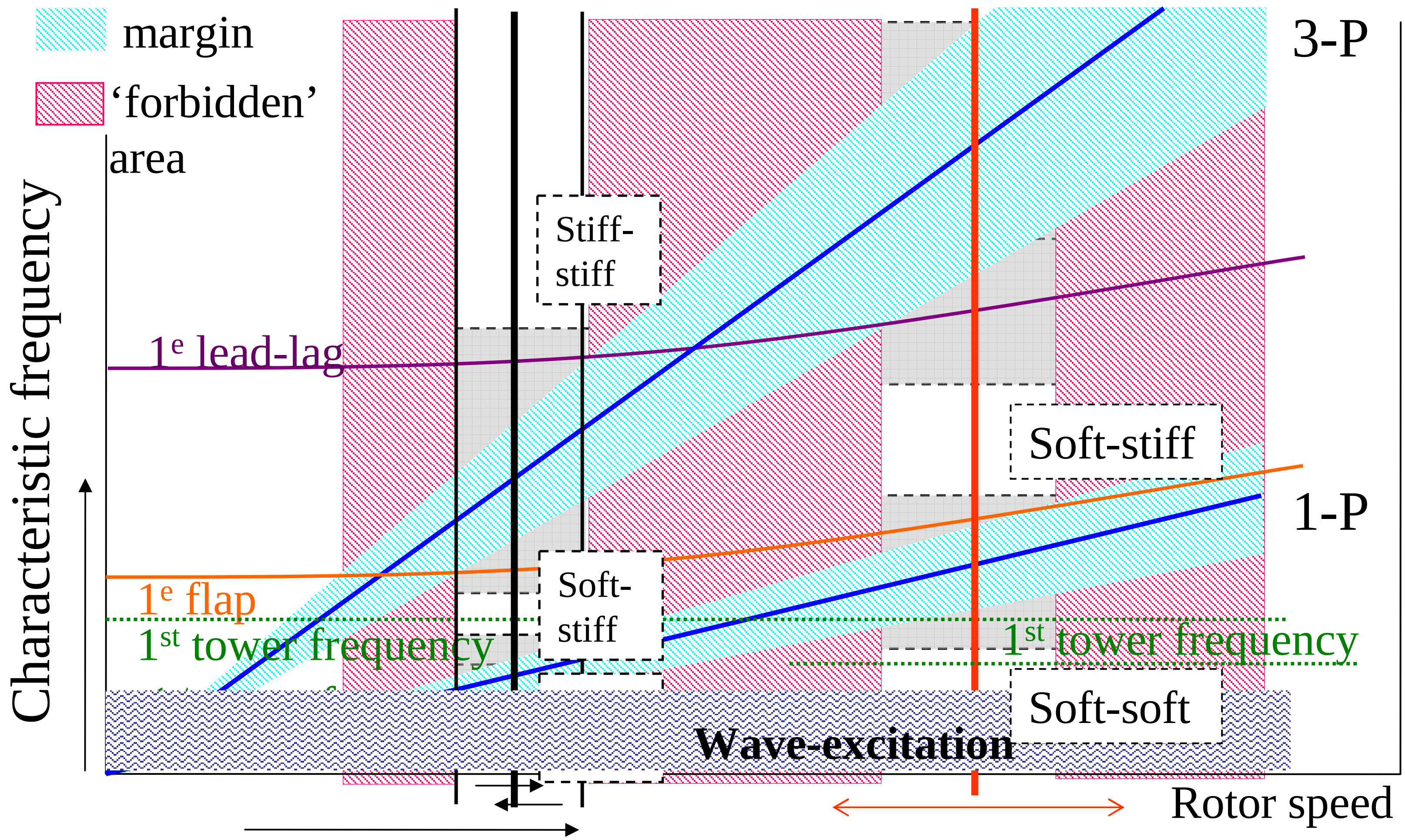
Campbell diagram



Design adaptations

- Change diameters and/or wall thicknesses
- Shift masses
  e.g. move transformer from nacelle to platform
- Adjust rotor speed control
  e.g. skip resonance in partial load region
- Change concept
  e.g. to braced tower / tripod

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Loads and dynamics in design

Check lifetime fatigue

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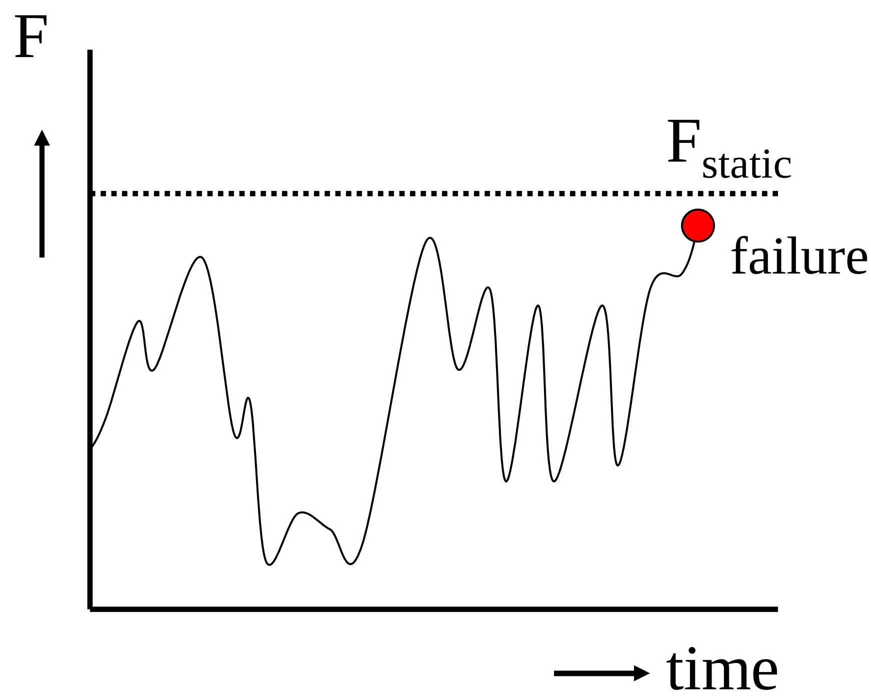
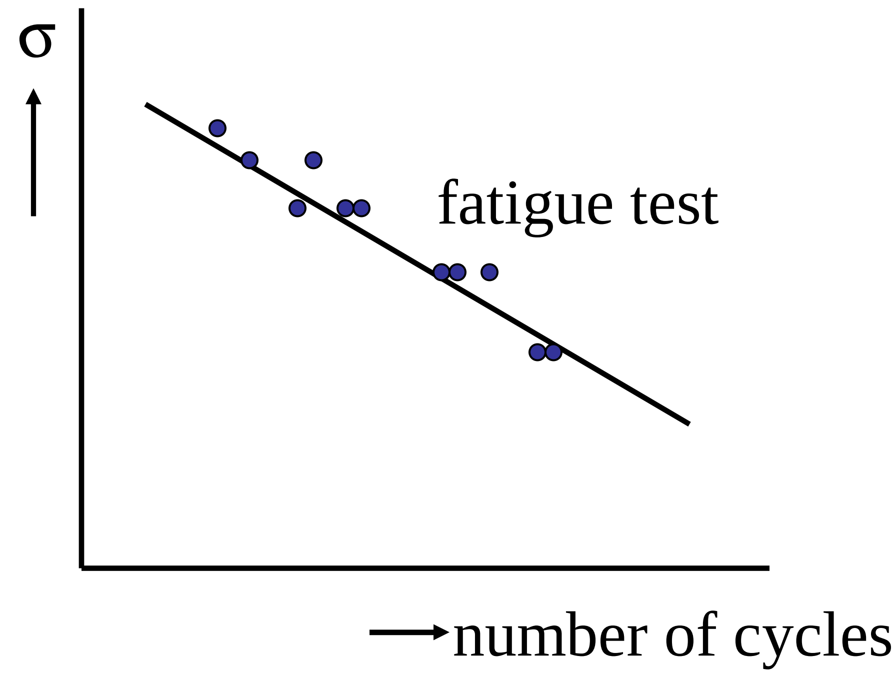
Fatigue

Fatigue: after a number of cycles of a varying load below static strength failure occurs.





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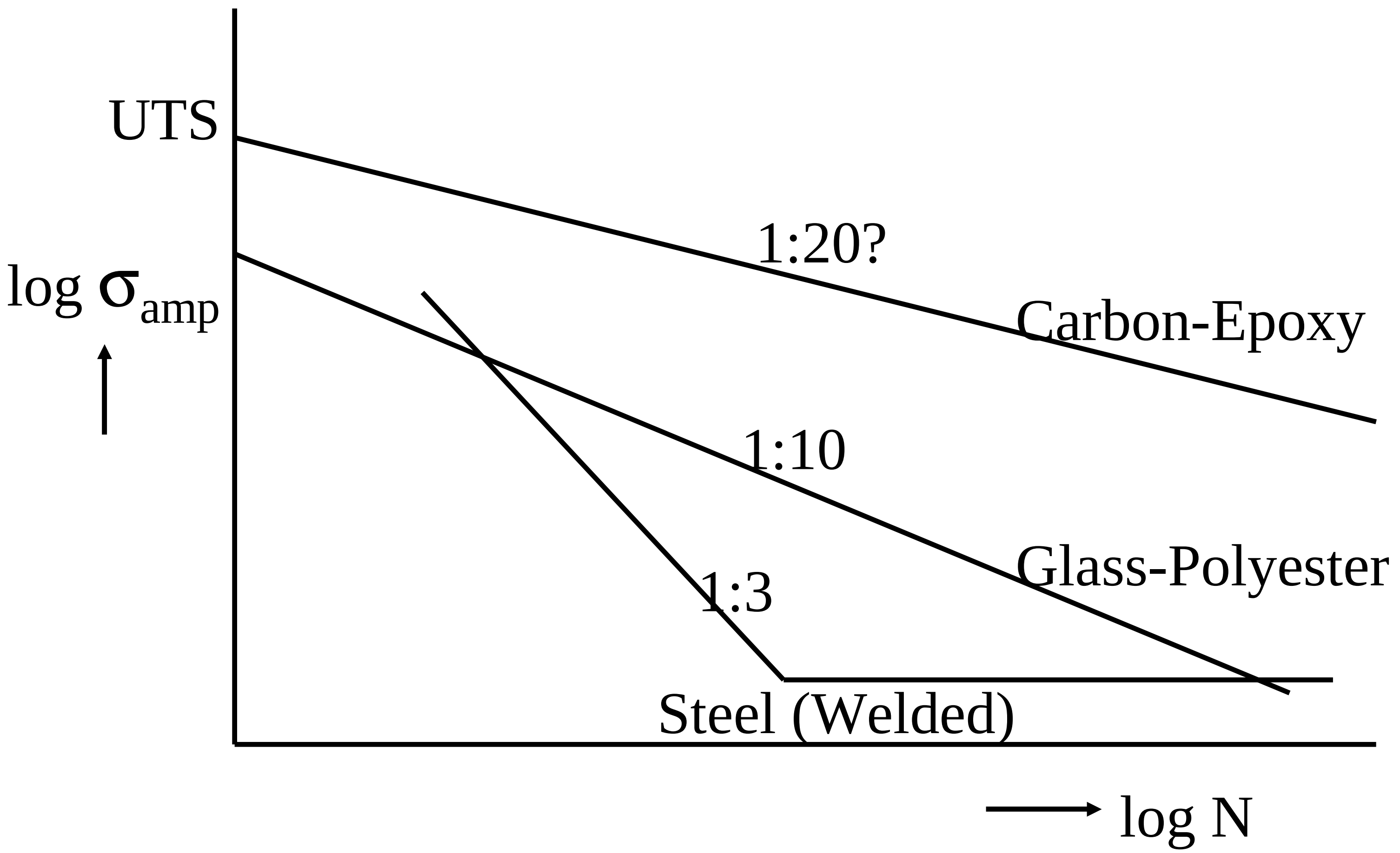
S-N curves



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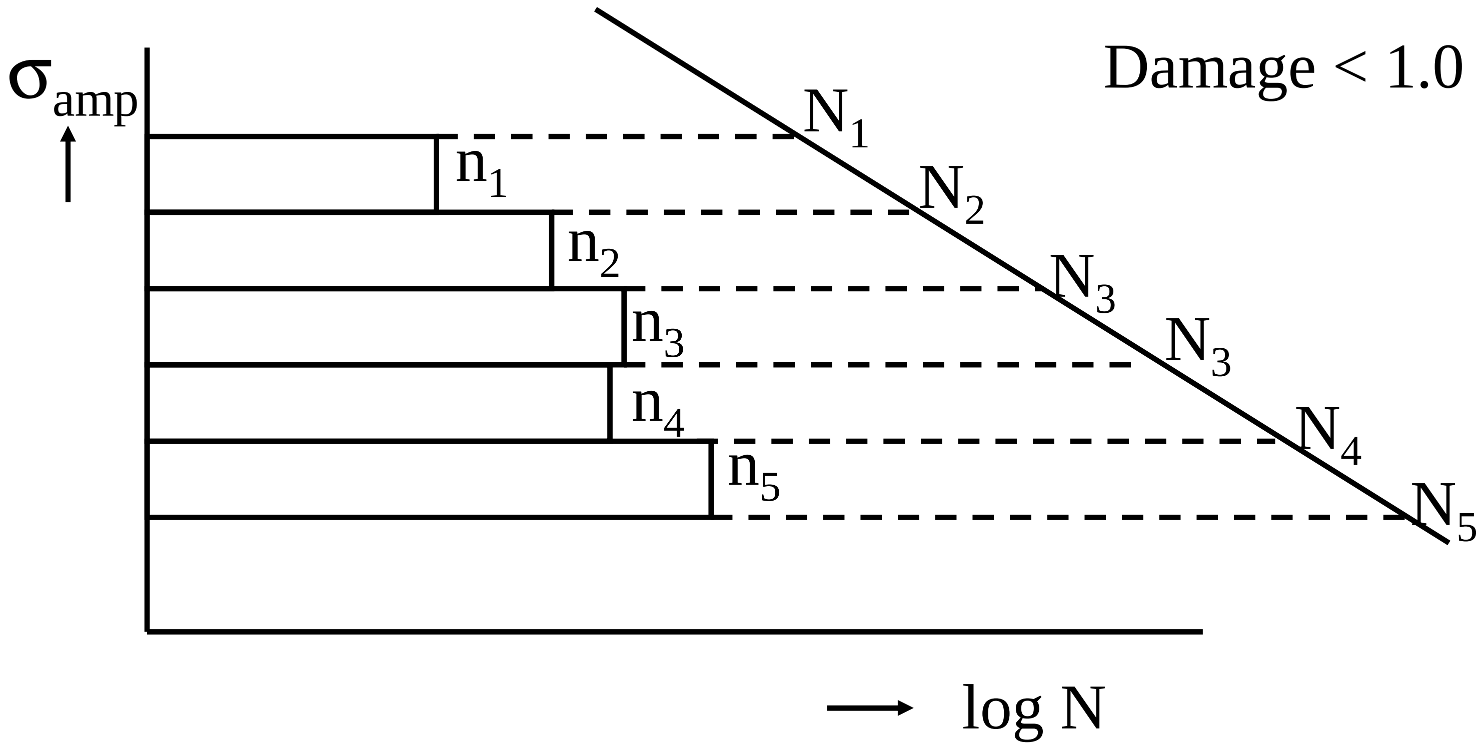
Variable amplitude loading

Miner's Damage Rule: $\sum \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \frac{n_4}{N_4} + \frac{n_5}{N_5}$



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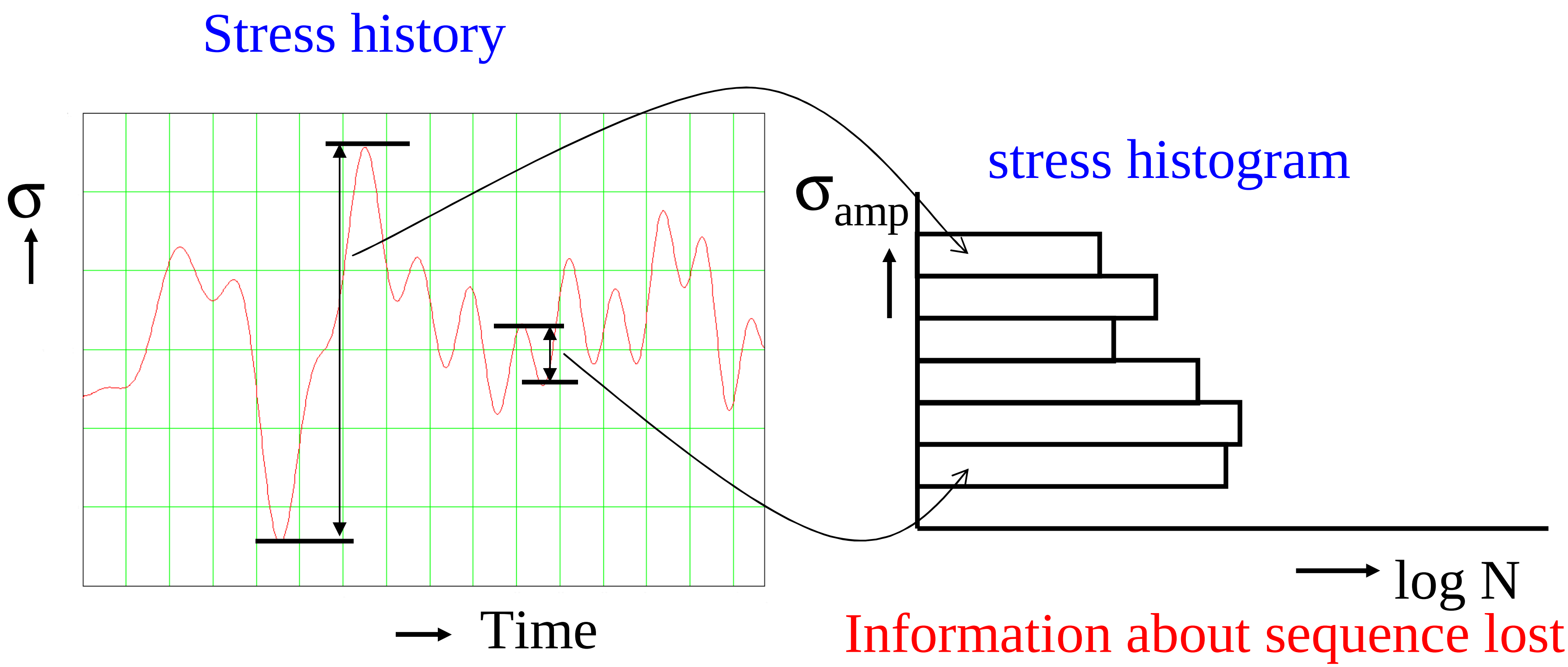
Stochastic loading

Stress history can be converted to blocks of constant amplitude loadings (using counting method)



Information about sequence lost

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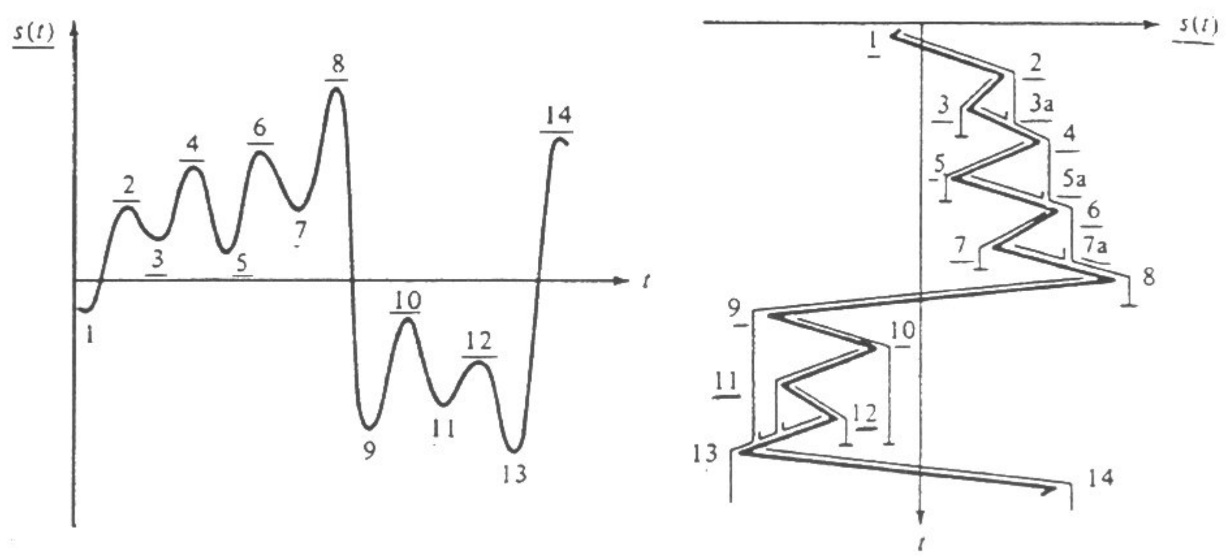
Rainflow counting

- Two parametric method: Range and mean
- Display series of extremes with vertical time axis
- Drip ‘rain’ from each extreme, stop at a larger extreme
- Start and stop combine to one stress cycle



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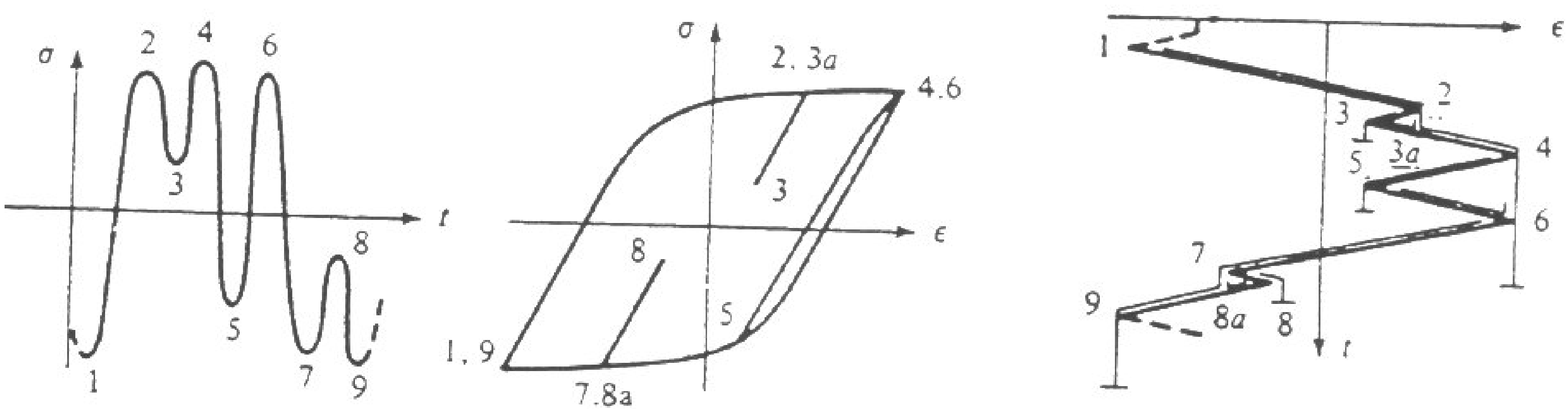
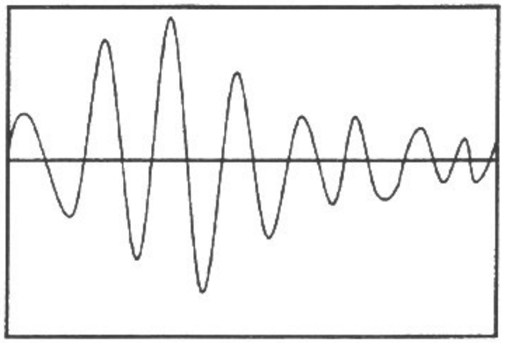
Rainflow counting

- Established method
- Several equivalent algorithms exist
  - Reservoir method
  - Intermediate extremes in groups of 4
- Principle based on stress-strain hysteresis loops:

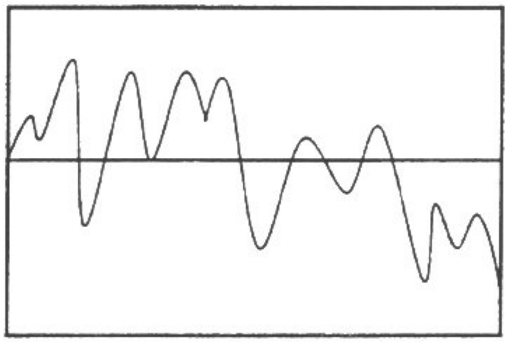


Frequency domain approach

Rayleigh: Theoretical, narrow band signals:



Dirlik: Empirical, wide band signals:



Used for spectra of random, Gaussian, stationary processes

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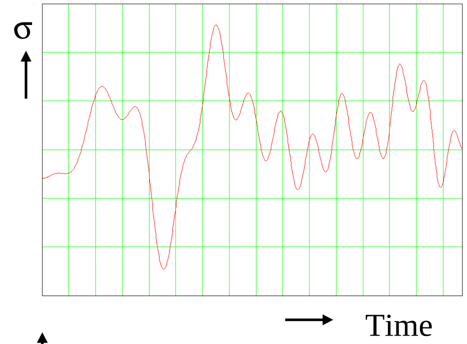
Lifetime fatigue analysis

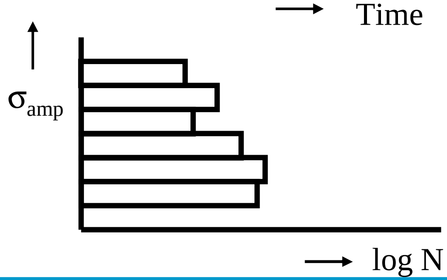
Do the following for all load cases (scatter diagram, operational and idle)

Hs\\Tz	0-1s	1-2s	2-3s	3-4s	4-5s	5-6s	6-7s	7-8s	8-9s	total
5.5-6m										0.0
5-5.5m								0.08		0.1
4.5-5m				idling high Vw>=Vcut_out			0.04	0.3		0.3
4-4.5m							0.3	0.08		0.4
3.5-4m		lumped seastate					0.7			0.7
3-3.5m							0.7			0.7
2.5-3m						0.6	0.04			0.7
2-2.5m						0.2				0.2
1.5-2m		idling low Vw<Vcut_in								0.0
1-1.5m					3.4	0.4				3.8
0.5-1m				19	58	0.7				77.7
0-0.5m	0.68		10	65	12	0.1	0.11			79.0
total	0.7	0.0	10	84.2	73.4	2.0	1.9	0.5	0.0	164

Determine stress time series or PSD
(PSD = Power Spectral Density)



Determine stress histogram
(Rainflow counting – Dirlik)



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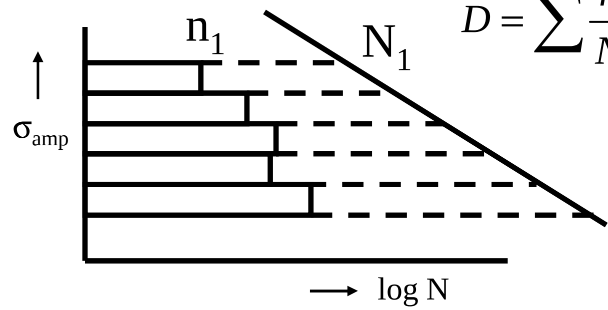
Lifetime fatigue analysis

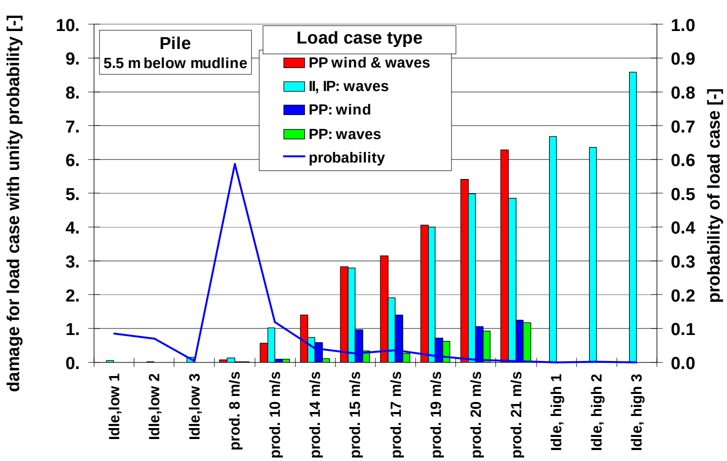
Apply Miner's rule to histogram
(damage per load case)

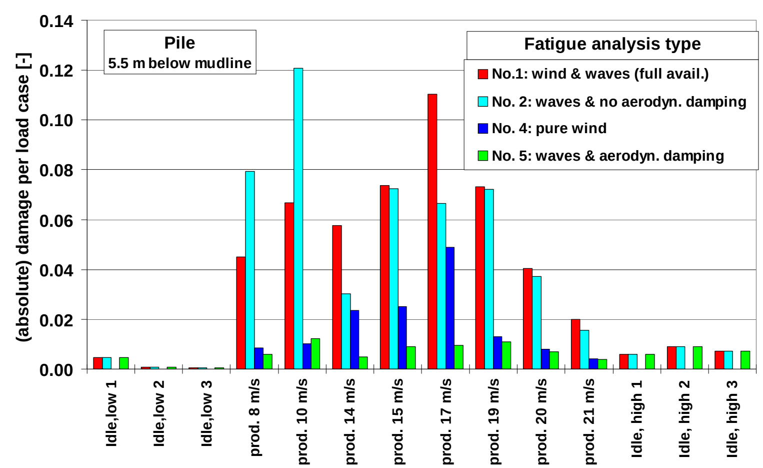
$$D = \sum \frac{n_i}{N_i}$$



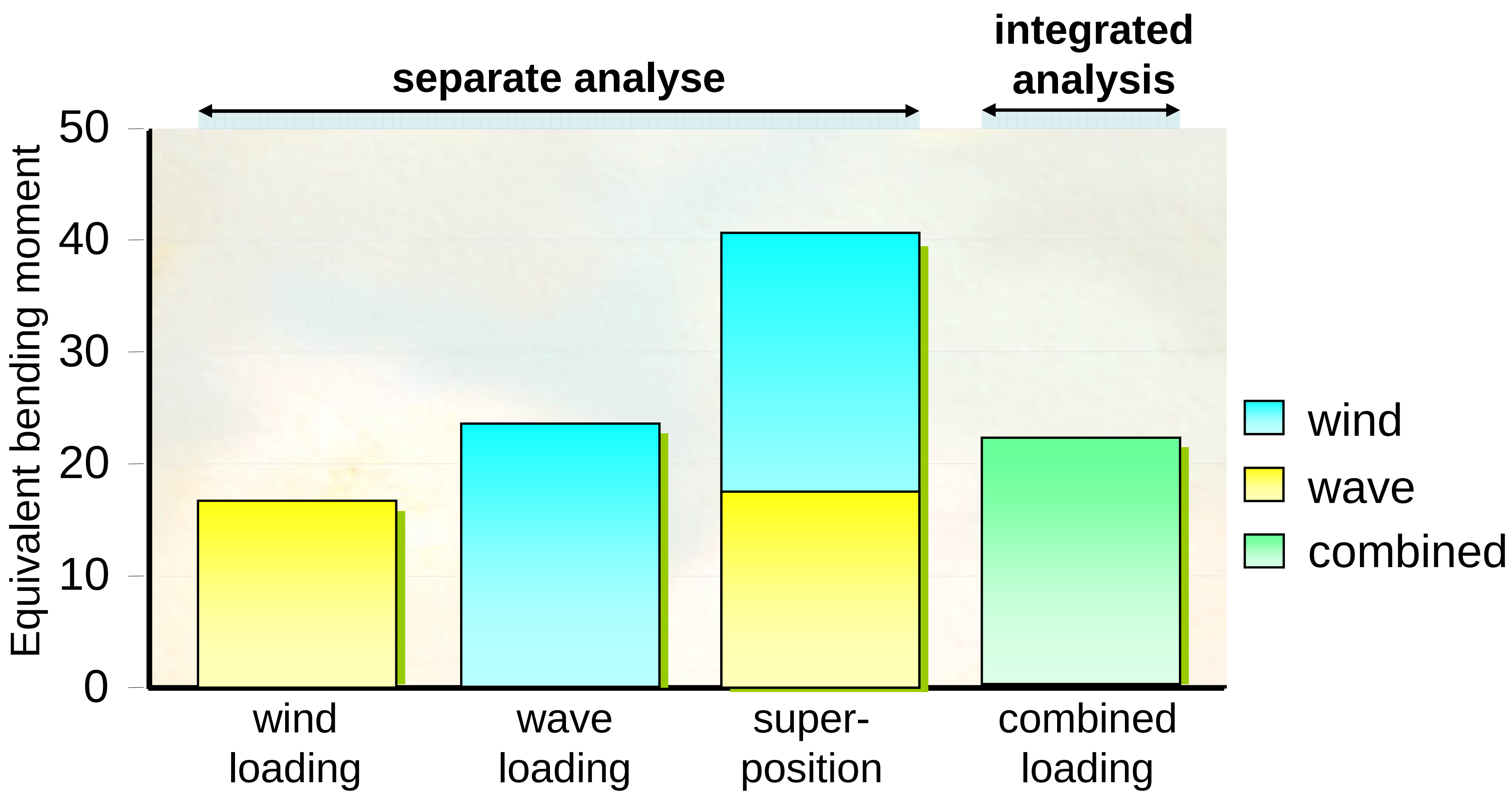
Apply Miner's to all load cases:

Damage of each load case (normalised to 1 unit of time) * Probability of load case * Total lifetime





Integrated system dynamics



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