Loads, dynamics and structural design

Offshore Wind Farm Design
Michiel Zaaijer
2007-2008

DUWIND
Overview

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

Loads, dynamics and structural design
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

27 RPM = 0.45 Hz
Non-harmonic periodic loading

\[ F(t) = a_0 + \sum_{k} a_k \hat{F} \sin(k \omega t + \varphi_k) \]

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

Loads, dynamics and structural design
The effect of dynamics

\[ k = 1 \, \text{[N/m]} \]

Force [N]

Response [m]

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The effect of dynamics

For $m = 0.0005 \text{ [kg]}$:

For $m = 0.1 \text{ [kg]}$:

(Static)
The effect of dynamics

System

\[ F_{intern} = k \cdot x \]

Internal forces ≠ external forces due to dynamics

Internal forces drive the design, not external forces!
Dynamic amplification factor

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

Note: the DAF is defined for harmonic excitation
Character of resonance

- Excitation frequency $\approx$ 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

DAF

1

Excitation

Response

soft-soft  soft-stiff  stiff-stiff

1P  3P  $f_0$
Soft-stiff example

$1P = 0.45 \text{ Hz}$

$f_{\text{natural}} = 0.55 \text{ Hz}$

$3P = 1.35 \text{ Hz}$
Reduced response to loading

Alleviation of (wind) loading by shedding loads through motion

Typical rotor loading frequencies

Typical wave loading frequencies

soft-soft structure

DAF
Increased response to loading

Quasi-static or amplified response to wave loading
Single degree of freedom system

\[ F = m \ddot{x} + k \cdot x + c \cdot \dot{x} \]
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:

\[ x(t) + x_0 \]

Non-linear system:

- No superposition possible
- Possible dependency on initial conditions
- Possible variation in output statistics for the same input (statistics)
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 (2nd order effects)
Introduction

Loads, dynamics and structural design
Lifelong response signal

Response (loading + dynamics)

Extreme events

Lifelong variations

Time
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
# Design drivers of wind turbines

<table>
<thead>
<tr>
<th>Component</th>
<th>Design drivers</th>
<th>Ultimate</th>
<th>Fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower top</td>
<td>top mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower</td>
<td></td>
<td></td>
<td>wind/wave</td>
</tr>
<tr>
<td>Submerged tower</td>
<td>wind/wave/current</td>
<td></td>
<td>wind/wave</td>
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<tr>
<td>Foundation</td>
<td>wind/wave/current</td>
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</table>
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

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
Flexibility of wind turbines

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

Offshore wind turbine

- Controllers
- Rotor
- Drive train
- Generator
- Support structure
- Grid
- Wind
- Wave
Rotor model

Aerodynamic properties

Distributed mass-stiffness

Beam theory
FEM

\[ C_l - \alpha \]

\[ C_d - \alpha \]

\[ \mu, EI_{x,y,p} \]
**Drive train model**

**Stiffness** torsion in transmission and main shaft; main shaft bending

**Damping** transmission suspension and generator torque control
Generator model

synchronous generator:

induction generator:

\[ T_{k,g} \]

\[ n_0 \]

\[ 2n_0 \]

\[ n \]

generator

motor

Slip
Tower model

Distributed mass-stiffness

Beam theory
FEM

\( \mu, EI_{x,y,p} \)

Modal representation

Deflection 1\textsuperscript{st} mode + Deflection 2\textsuperscript{nd} mode = “Total” deformation

Effective reduction of DOFs
Foundation model

\[
\begin{bmatrix}
H \\
M
\end{bmatrix} = 
\begin{bmatrix}
k_{xx} & k_{x\theta} \\
k_{x\theta} & k_{\theta\theta}
\end{bmatrix} \begin{bmatrix}
u \\
\theta
\end{bmatrix}
\]
Modelling of offshore wind turbines

Deriving parameters for foundation models
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

- External shaft friction (t-z curves)
- Internal shaft friction (t-z curves)
- Lateral resistance (p-y curves)
- Pile plug resistance (Q-z curves)
- Pile point resistance (Q-z curves)

Use:
Standards (API/DNV)
Existing software
(In exercise: ANSYS Macro’s)
Scour

- General scour depth
- Local scour depth
- Overburden reduction depth
- No scour condition
- General scour only
- Local scour condition

Typically 1-1.5 times pile diameter
Typically 6 times pile diameter
Effective fixity length

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Effective fixity length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiff clay</td>
<td>3.5 $D – 4.5 D$</td>
</tr>
<tr>
<td>Very soft silt</td>
<td>7 $D – 8 D$</td>
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<tr>
<td>General calculations</td>
<td>6 $D$</td>
</tr>
<tr>
<td>Experience with offshore turbines</td>
<td>3.3 $D – 3.7 D$</td>
</tr>
</tbody>
</table>

Seabed

Effective fixity length
Uncoupled springs

Forced displacement/rotation

Method A
Ignored M Ignored F

Method B
Ignored θ Ignored u

In exercise: Use ANSYS Macro’s and method B for a monopile
Stiffness matrix

Run two load cases with FEM model with py-curves
(See next slide)

\[
\begin{bmatrix}
H \\
M
\end{bmatrix} =
\begin{bmatrix}
k_{xx} & k_{x\theta} \\
k_{\theta x} & k_{\theta\theta}
\end{bmatrix}
\begin{bmatrix}
u \\
\theta
\end{bmatrix}
\]
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)

   \[ F_2 = k_{xx} \cdot u_2 + k_{x\theta} \cdot \theta_2 \]
   \[ M_2 = k_{\theta x} \cdot u_2 + k_{\theta \theta} \cdot \theta_2 \]

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
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)
### Documented GBS model parameters

<table>
<thead>
<tr>
<th>GBS</th>
<th>Spring stiffness</th>
<th>Viscous damping</th>
<th>Inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocking</td>
<td>( \frac{G \cdot D^3}{3 \cdot (1-\nu)} )</td>
<td>( 0.65 \cdot \frac{D^4 \cdot \sqrt{\rho \cdot G}}{32 \cdot (1-\nu)} )</td>
<td>( 0.64 \cdot \frac{\rho \cdot D^5}{32 \cdot (1-\nu)} )</td>
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<tr>
<td>Horizontal</td>
<td>( \frac{16G \cdot D \cdot (1-\nu)}{7-8\nu} )</td>
<td>( 4.6 \cdot \frac{D^2 \cdot \sqrt{\rho \cdot G}}{4 \cdot (2-\nu)} )</td>
<td>( 0.76 \cdot \frac{\rho \cdot D^3}{8 \cdot (2-\nu)} )</td>
</tr>
<tr>
<td>Vertical</td>
<td>( \frac{2G \cdot D}{1-\nu} )</td>
<td>( 3.4 \cdot \frac{D^2 \cdot \sqrt{\rho \cdot G}}{4 \cdot (1-\nu)} )</td>
<td>( 1.08 \cdot \frac{\rho \cdot D^3}{8 \cdot (1-\nu)} )</td>
</tr>
</tbody>
</table>

**Lumped springs and dashpots for:**
- Horizontal
- Vertical
- Rocking
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
Natural frequencies

- Monopile
- Monopod
- Tripod
- Truss
Modes of the support structure

Monopile

1\textsuperscript{st} mode

2\textsuperscript{nd} mode
Rayleigh's method

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

Velocity:

- Maximum strain energy: \( \sim \hat{Z}^2 \)
- Maximum kinetic energy: \( \sim \hat{Z}^2 \cdot \omega^2 \)

**SDOF:**

- Maximum strain energy: \( V_{\text{max}} = \frac{1}{2} k(\hat{x})^2 \)
- Maximum kinetic energy: \( T_{\text{max}} = \frac{1}{2} m(\dot{x})_0^2 = \frac{1}{2} m \omega^2 (\hat{x})^2 \)
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

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

See document on Blackboard for:
• Derivation of this equation
• Explanation of \( EI_{\text{eq}}, m_{\text{eq}}, C_{\text{found}} \)
Free vibration of cylinder in water

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

- Inertia force
- Drag force

Inertia force due to moving cylinder

- Still water \( \rightarrow \) remaining inertia term is called ‘water added mass’

- With \( C_M \approx 2 \rightarrow \) water added mass \( \approx \) 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
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)
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

Gravity
Thrust
Wind on tower
Waves + current
Superposition
**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**

\[ y(t) = \int x(\tau) \cdot h(t - \tau) \, d\tau = x(t) \ast h(t) \]

\[ a \cdot x_1(t) + b \cdot x_2(t) \rightarrow a \cdot y_1(t) + b \cdot y_2(t) \]

**Frequency domain**

\[ X(\omega), Y(\omega), H(\omega) \]

\[ Y(\omega) = X(\omega) \cdot H(\omega) \]

\[ a \cdot X_1(\omega) + b \cdot X_2(\omega) \rightarrow a \cdot Y_1(\omega) + b \cdot Y_2(\omega) \]
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
Time domain - frequency domain

**Time domain** → **Frequency domain**

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

- 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
Aerodynamic damping

Tower for-aft motion
  ↓
  Blade motion
  ↓
  Angle of attack decreases/increases
  ↓
  Lift/thrust force diminishes/increases

\[ \delta L \text{ opposite } V_{\text{blade}} \]

\[ V_{\text{blade}} \]

\[ \phi \]

\[ \alpha \]

\[ \theta \]

\[ \Omega r \]

\[ U(1-a) \]

\[ V_{\text{res}} \]
Aerodynamic damping

Function of wind speed, turbine design (aerodynamic and control) and support structure!
## Some relevant analysis tools

<table>
<thead>
<tr>
<th></th>
<th>FEM</th>
<th>Time</th>
<th>Freq</th>
<th>Rotor</th>
<th>Offshore</th>
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<td>ANSYS</td>
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<td>Turbu</td>
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<td>X</td>
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</table>

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Loads and dynamics in design

Overview of the process
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
Fundamental problems in evaluation

Response (loading + dynamics)

What is the true extreme?

More realisations at the same site

Long time span (20 year)

Time →
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!
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)
### Reducing number of load cases (fatigue)

<table>
<thead>
<tr>
<th>Hs</th>
<th>Tz</th>
<th>0 - 1</th>
<th>1 - 2</th>
<th>2 - 3</th>
<th>3 - 4</th>
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<td>5 - 5.5</td>
<td>Idling: $V_w &gt; V_{\text{cut_out}}$</td>
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<tr>
<td>3 - 3.5</td>
<td>Normal operation: $V_{\text{cut_in}} &lt; V_w &lt; V_{\text{cut_out}}$</td>
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<td>2 - 2.5</td>
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<td>0 - 0.5</td>
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<td>1.9</td>
<td>0.5</td>
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<td>164</td>
</tr>
</tbody>
</table>

Lump states in 3D scatter diagram

Use normal operation and idling

Idling: $V_w > V_{\text{cut\_out}}$
Idling: $V_w < V_{\text{cut\_in}}$
Normal operation: $V_{\text{cut\_in}} < V_w < V_{\text{cut\_out}}$
Knowledge about load case selection: Thrust curves

- Stall
- ‘Ideal’ pitch
- Response to gust/failure

- $V_{\text{rated}}$
- $V_{\text{cut-out}}$
- $V_{\text{extreme}}$
- $T$
- $V$

$T \sim V^{-1}$
$T \sim V^2$

$V_{\text{rated}}$
$V_{\text{cut-out}}$
$V_{\text{extreme}}$
Extreme and reduced conditions

- \( H_{\text{max}} \approx 1.86 \cdot H_s \)
- \( H_{\text{reduced}} \approx 1.32 \cdot H_s \)
- \( V_{\text{gust, max}} \approx 1.2 \cdot V_{10 \text{ min}} \)
- \( V_{\text{gust, reduced}} \approx \frac{1.2}{1.1} \cdot V_{10 \text{ min}} \)
Loads and dynamics in design

Make preliminary design
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 $V_{\text{rated}}$ & 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!)
Loads and dynamics in design

Check for resonance
Campbell diagram

Characteristic frequency

- Margin
- ‘forbidden’ area

1\textsuperscript{st} lead-lag

1\textsuperscript{st} flap

1\textsuperscript{st} tower frequency

Soft-stiff

Stiff-stiff

Soft-soft

Wave-excitation

Rotor speed

3-P

1-P
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
Loads and dynamics in design

Check lifetime fatigue
Fatigue: after a number of cycles of a varying load below static strength failure occurs.
S-N curves

UTS

log $\sigma_{\text{amp}}$

Carbon-Epoxy

1:10

1:20?

Glass-Polyester

1:3

Steel (Welded)

$\rightarrow$ log N
Variable amplitude loading

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

Damage < 1.0
Stochastic loading

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

Stress history

![Stress history diagram with stress histogram and information about sequence lost]
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
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
Lifetime fatigue analysis

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

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

Determine stress histogram (Rainflow counting – Dirlik)
Lifetime fatigue analysis

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

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

- Separate analyse
- Integrated analysis

Equivalent bending moment

- Wind loading
- Wave loading
- Super-position
- Combined loading

Legend:
- Blue: wind
- Yellow: wave
- Green: combined