NOWITECH
Norwegian Research Centre for Offshore Wind Technology

NTNU – Trondheim
Norwegian University of Science and Technology

The full-height lattice tower concept

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Offshore wind turbine technology
Marine Civil Engineering
Department of Civil and Transport Engineering

OG Dahlhaug *et al.*

Overview

1. Previous experience with lattice towers
2. Comparison with monopiles / hybrid support structures
3. Optimization of full-height lattice towers

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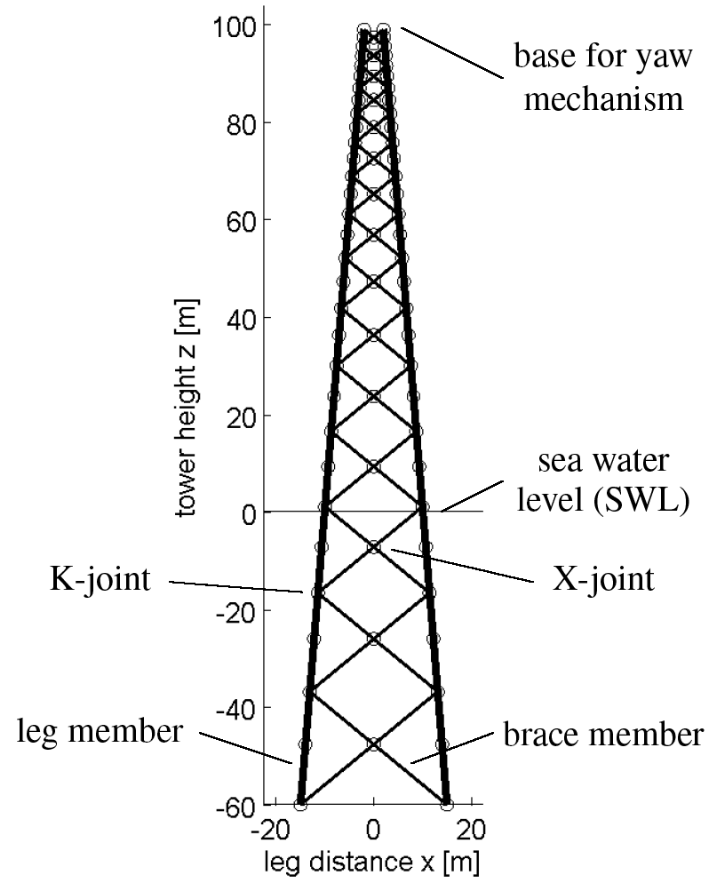
The full-height lattice tower concept

- Developed by our group
  (for offshore wind turbines)
  - Prof. Geir Moe
  - Haiyan Long
  - Daniel Zwick
  - and others….
- First published in Moe *et al.* (2007)

- Main goal:
  - cost reduction by weight minimization

- This design will be further developed and optimized in the course of the
  NOWITECH 10 MW project



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Part 1: Previous experience with lattice towers

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Previous experience with lattice towers 1/3

Figure 16.15. Wind park Qingdao in China with Nordex N62 wind turbines (Nordex)

Onshore:

- Predominant type of wind turbine support structure until late 80s
- Up to 750 kW (Zond Z750) in the US, 55m tall tower
- Difference of 5 percent of total cost compared to monopile (from 20-25 to 15 percent)

Figure 18.14. Assembly of a Vestas V-66 on a 117-m-high lattice tower, using a top crane extension

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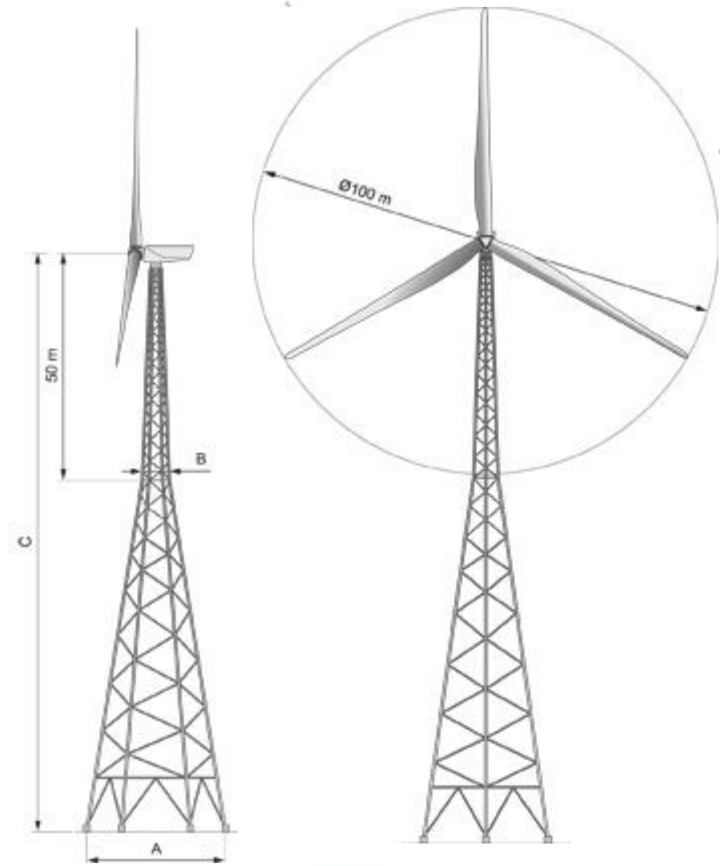
Previous experience with lattice towers 2/3

- Ruukki onshore wind towers
- Hexagonal tower concept
- Bolted joints
- Stepped design
- around since 2010



Typical dimensions of the Ruukki wind tower with a 2.5 MW turbine

C: Hub height (m)	100			120			140			160		
B: Waist diam. (m)	4	6	8	4	6	8	4	6	8	4	6	8
A: Root circle diam. (m)	19	20.01	21.2	25	25.8	26.5	31	31.4	31.8	37	37	37
Mass (w/o foundation) (tons)	196	184	177	241	227	219	291	277	270	350	336	328

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Previous experience with lattice towers 3/3

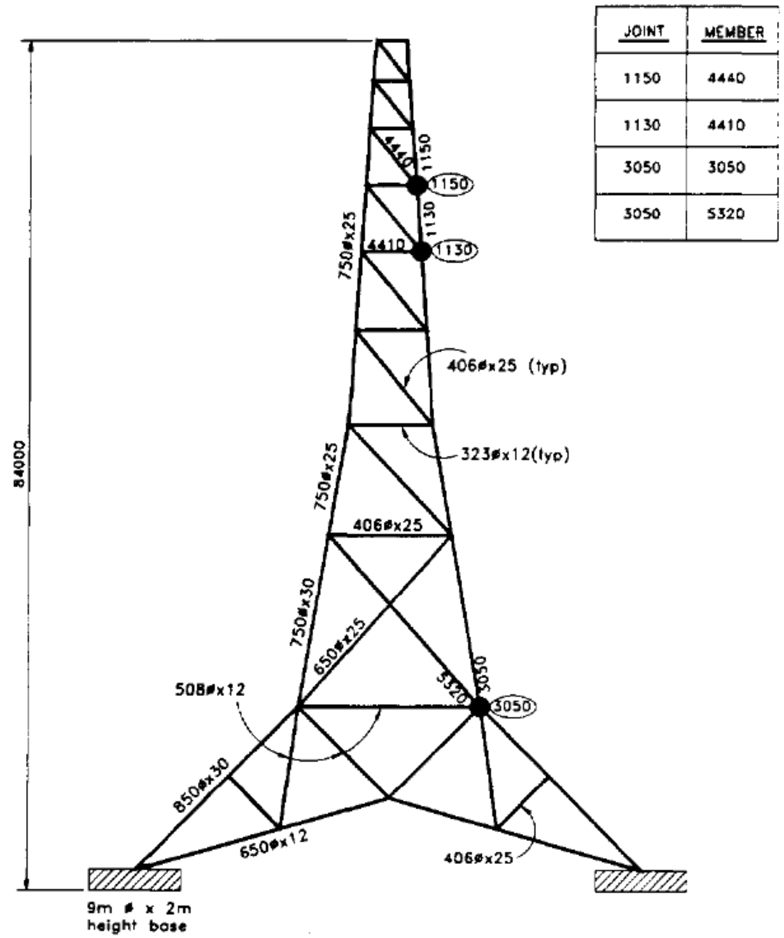
The Opti-OWECS support structures:

Gravity lattice tower
(Kühn 2001)

Developed for NL-5 site

- Wind V_{ave} = 10.1 m/s
- Mean sea level 25 m
- Sea state
  H_{max} = 15.4 m, T_p = 12.5 s
- Stiff design: ≈0.7 Hz first eigenfrequency

height	triangle edge length
- 23 m (MSL)	50 m
- 7 m (MSL)	18 m
21 m (MSL)	8.32 m
59 m (MSL)	3 m
total ballast 1000 t	



LATTICE TOWER

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Part 2: Comparison with monopiles and hybrid towers

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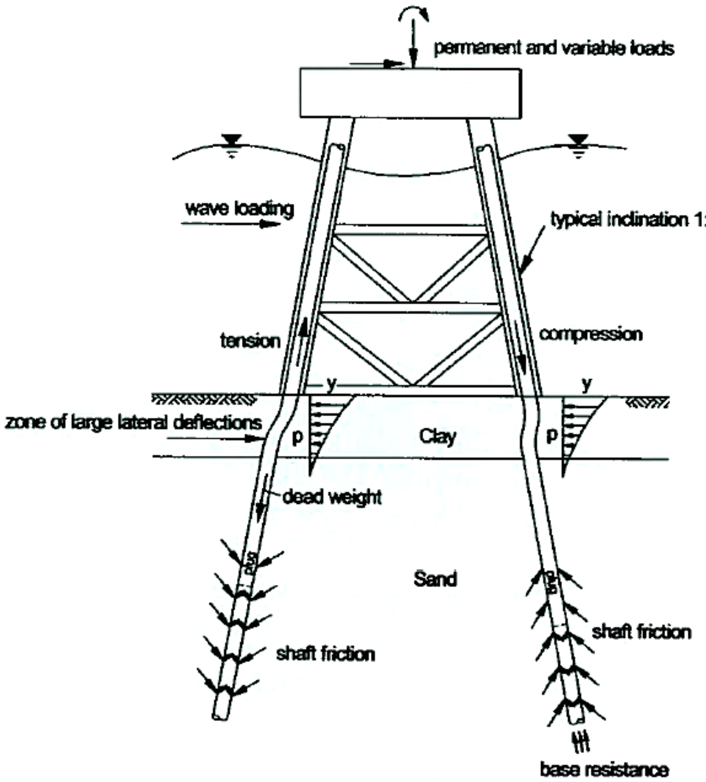
Differences between monopiles and jackets

- Properties of lattice towers
  - Thrust force results mostly in axial forces in legs
  - Bending stiffness depends quadratically on leg bottom distance
  - Needs to be weighted against lengthening of the legs



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Differences between monopiles and jackets (for design purposes)

adapted from Marc Seidel (EWEA Offshore 2011)

Monopiles

- Excitation of *global vibration* by waves in fundamental mode
- *Misaligned waves* cause large fatigue loads
- Significant impact of *secondary structures* (e.g., boat landing)
- *Soil data* most important parameter
- Fatigue loads often *higher for idling turbine*:
  Reduced availability must be considered

Jackets

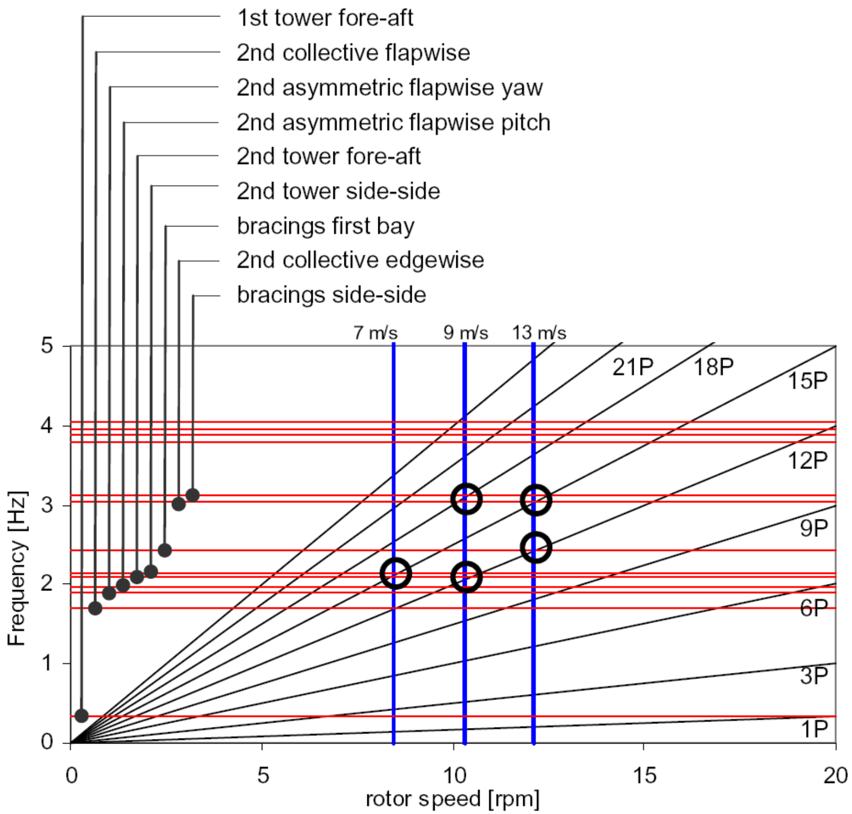
- Stiff jacket structure prevents global vibrations
- Misalignment effects negligible?
- Soil has no significant influence?
- 100 percent availability is conservative

Jackets are easy to design?

Challenges for design optimization of lattice support structures

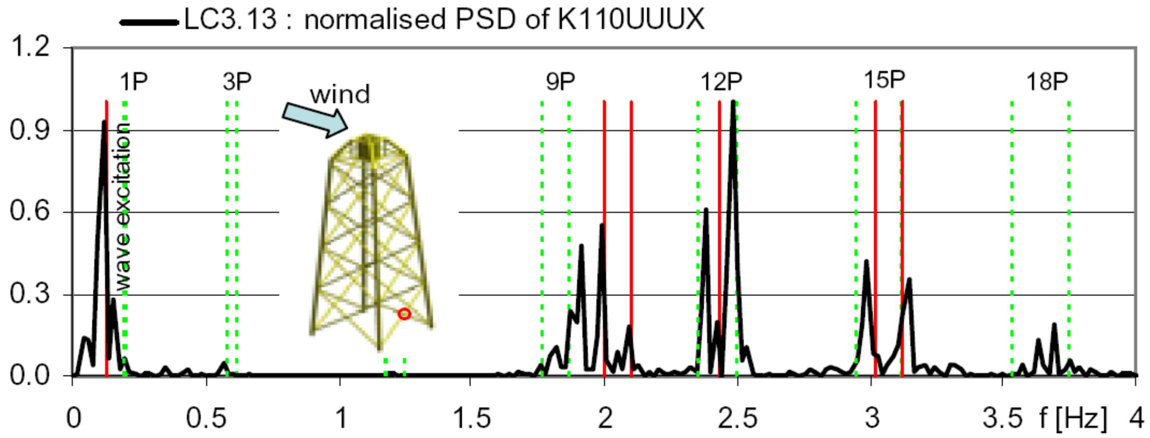
- Irregular and transient loads
- Uncertainty about soil conditions (scour)
- Fatigue-driven
- Importance of local vibrations (Böker 2009)

  Excitable from higher-order rotor modes

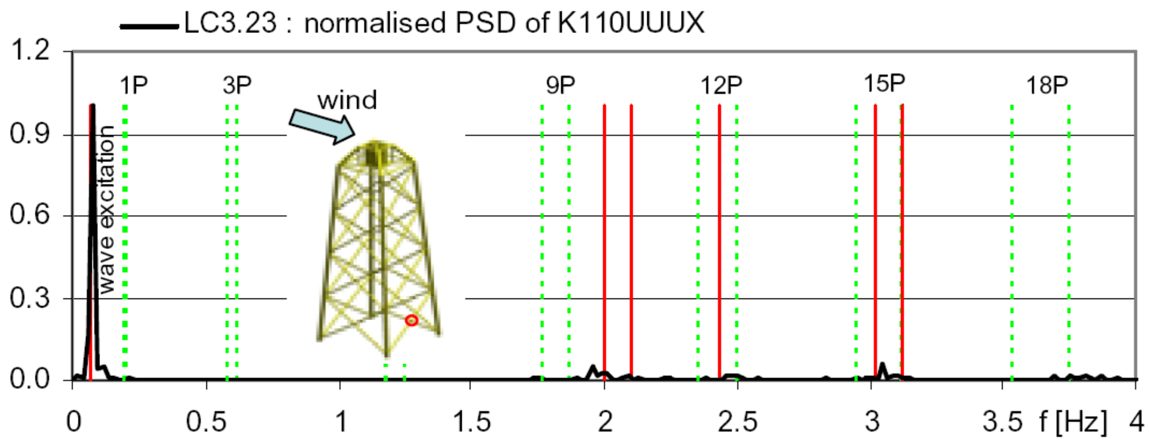


Part 2: Comparison with other concepts

Local vibrations



Irregular sea state
$H_s = 1.5$m
$T_p = 5.5$ s



Irregular sea state
$H_s = 5.6$m
$T_p = 10.6$ s

More severe sea state
Local vibrations less important

NB: normalized PSDs

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Summary

Monopiles

- Large diameter in deeper water: Problems for fabrication and pile-driving
- Problems with grouted connection
- Excitation of *global vibrations*
- *Soil uncertainty* critical design factor
- Secondary structure and wind-wave misalignment complicate the design
- Expensive transition piece
- Relatively large weight
- Protected space for access and maintenance (also: security, cold climates)

Jackets (half-height and full-height)

- Larger structures (esp. full-height tower): Problems for fabrication and installation
- Grouted connection unproblematic?
- *Local vibrations* of braces a potential problem
- Soil influence negligible (conservative)?
- Secondary structure negligible?

- More economical transition to yaw bearing
- Much lighter structure
- Access and maintenance not as straightforward and economical
- Many members and welds increase production time and cost
- Optimization of structures (different sites) not straightforward

> "if the combined cost of piling and access systems for the full-height lattice tower is significantly lower than the cost of the monopile foundation and transition piece, the full-height lattice tower is an interesting alternative"

Part 2: Comparison with other concepts

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Part 3: Optimization of full-height lattice towers

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Assessment of fatigue damage

- For design optimization it is important
  - to obtain good approximations of lifetime fatigue damage
  - in a quick and efficient way (for many points in design space)
  - more or less **UNSOLVED PROBLEM**
- Available approaches
  - Short-term assessment of fatigue
    - Simplified fatigue assessment
    - Spectral assessment
    - Time-domain simulation (most accurate; expensive)
  - Long-term assessment of fatigue
    - Statistical lumping of load cases
    - Parametric load models?
  - (also see: API 2A WSD)

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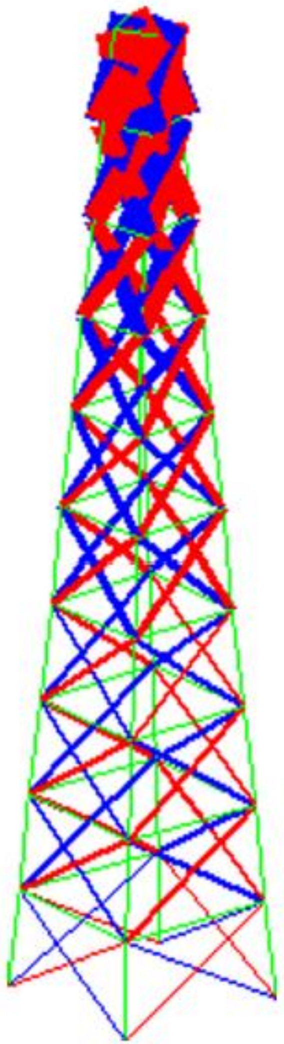
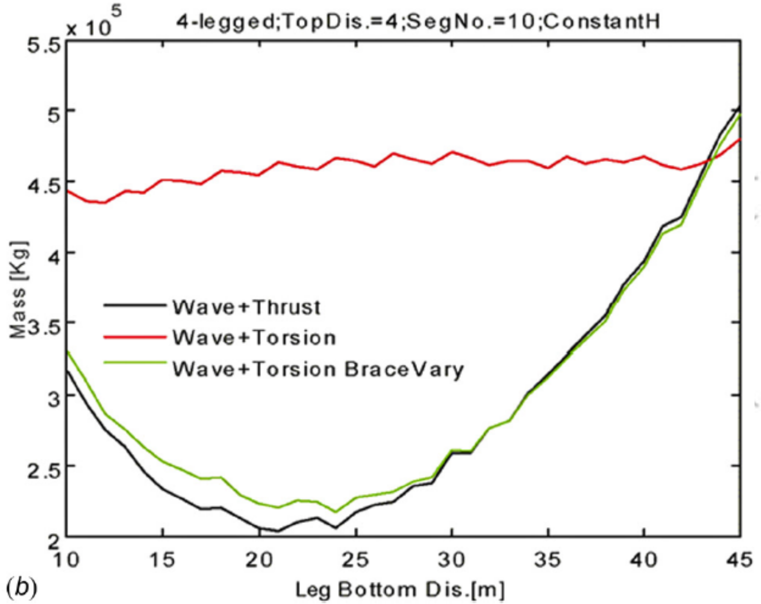
Baseline design for a full-height lattice tower

- Work of Haiyan Long
- Optimized for ULS with constant global sections (Long *et al*. 2012)
  - Designed for NREL 5 MW turbine and 35 m MSL
  - Total height around 88 m
  - One leg diameter and thickness
  - One brace diameter and thickness
  - Fixed tower top spacing
  - Variable bottom leg spacing
  - Just 5 parameters
  - Buckling analysis (column and shear buckling)
  - Joint checks
- Results
  - Torsion at top governs brace dimensions
  - Results in heavy towers (≈ 400 t) : comparable to monopiles



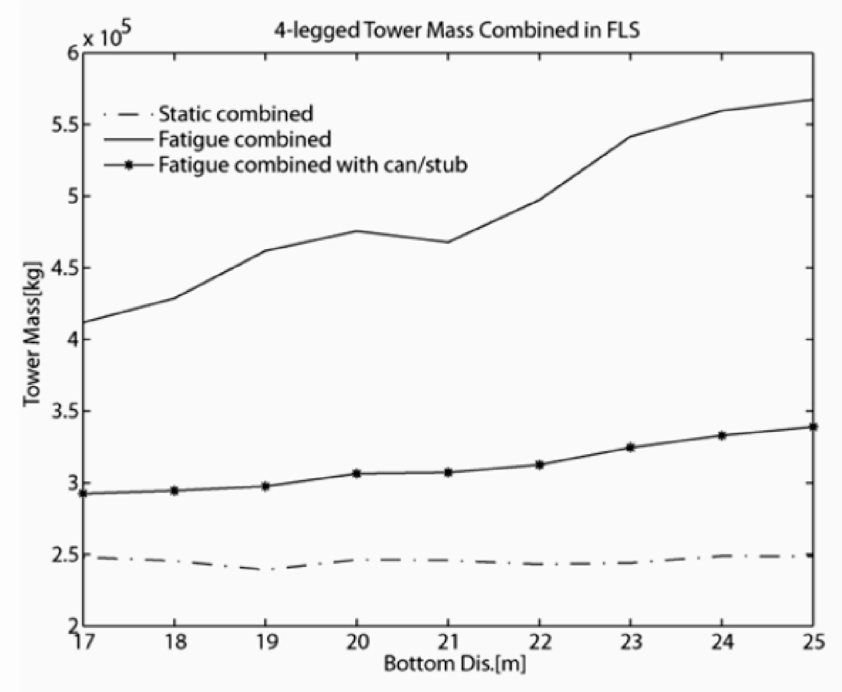
Further optimization of full-height lattice tower 1/2

- Optimized for ULS
  (Long *et al.* 2012)
  - Lattice structures weak in torsion
  - Study local variation of brace diameters
  - Simple algorithm ("local optimization"): Cross-sectional area increased by the value of its *utilization*
- Results
  - Significant weight reduction (≈ 225 t) of *about 50 percent*



Further optimization of full-height lattice tower 2/2

- Optimized for FLS
  (Long & Moe, in press)
  - Increase in wall thickness where necessary
  - Simplified fatigue assessment
  - Adding of response spectra
  - Dirlik method
  - Hot spot stress analysis (SCFs)
  - 19 lumped wind speeds + sea states
  - Two separate classes of loadcases
    - Torsion only loading:
      most critical close to the top
    - Thrust / wave loading:
      most critical close to sea surface
  - Effect of joint cans / stubs studied (NORSOK)



- Results
  - Final design (≈ 300 t) saves 25 percent of weight compared with monopile (under joint detailing)

Combined local optimization (ULS + FLS)

- Work of Daniel Zwick (POSTER PRESENTATION)
- Tower adapted to 10 MW NOWITECH turbine: 93.5 m + 60 m
- Detailed flexible multibody model in FEDEM Windpower
  - Flexible blades
  - Distributed soil model (p-y method; stiff sand)
- Time-domain simulations:
  - 10 min @ 1 hour simulation time
  - Time series of forces / moments in joints
- Simplification
  - Only one loadcase: power production at 12 m/s wind
- Automatic evaluation of fatigue damage
  - Stress concentration factors
  - Extrapolated to lifetime
  - Normalized with respect to design goals (20 year lifetime)

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First results

(Zwick et al., submitted)

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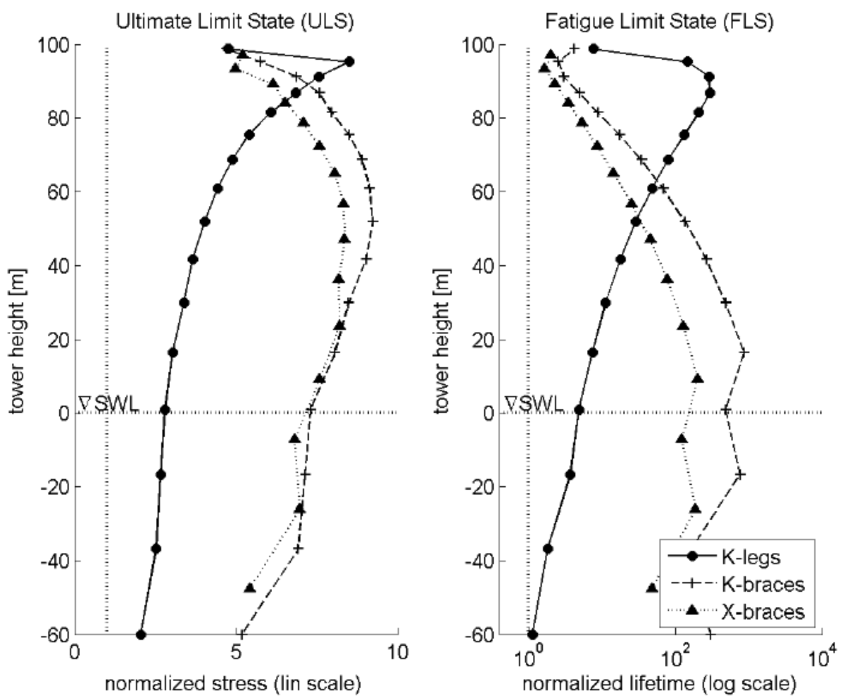
submitted for publication

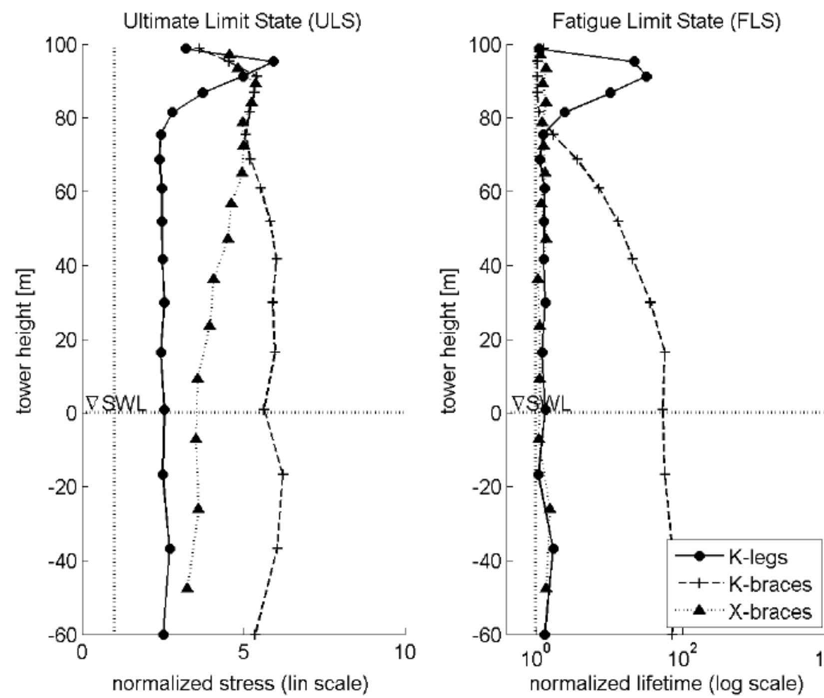
Baseline design

(constant member dimensions)



Optimized design

(variable thickness; constant diameter)



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Part 3: Optimization of full-height lattice towers

Optimal member thicknesses

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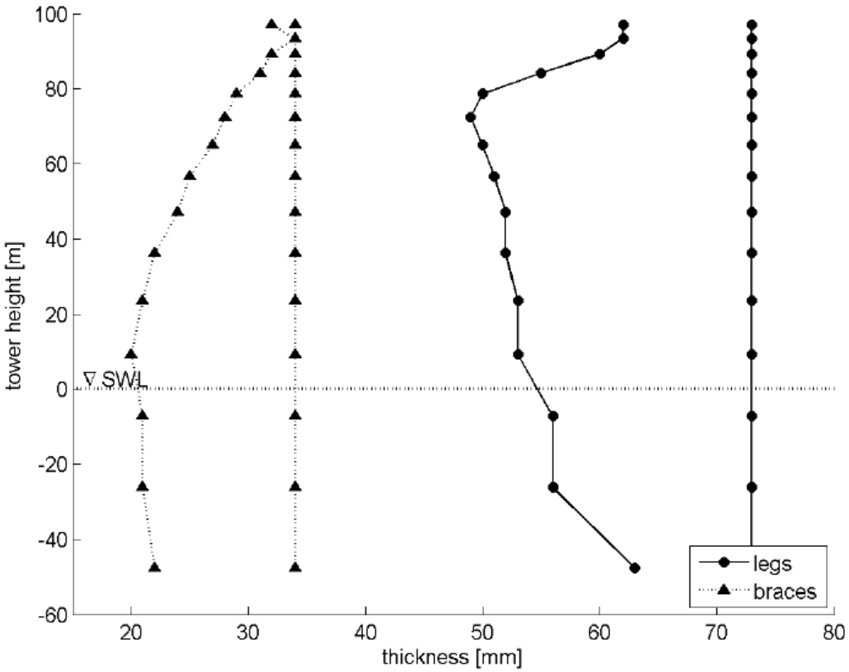
submitted for publication

- Significant reduction in weight (25 percent) compared to baseline truss tower (with constant members)
- Time-domain optimization possible
- Local optimization is reasonable approach

- Compare with Enercon E126 Onshore turbine
  14.5 m base diameter, 450 mm
  2800 t tower
  135 m instead of 158 m



	Constant member dimensions (Section 3.1)	Optimized design (Section 3.2)
tower height [m]	158.70	158.70
leg/brace diameter [m]	1.6/0.8	1.6/0.8
leg/brace thickness [mm]	73/34	49..63/20..34
number of sections	15	15
tower weight [t]	3082	2283

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Summary

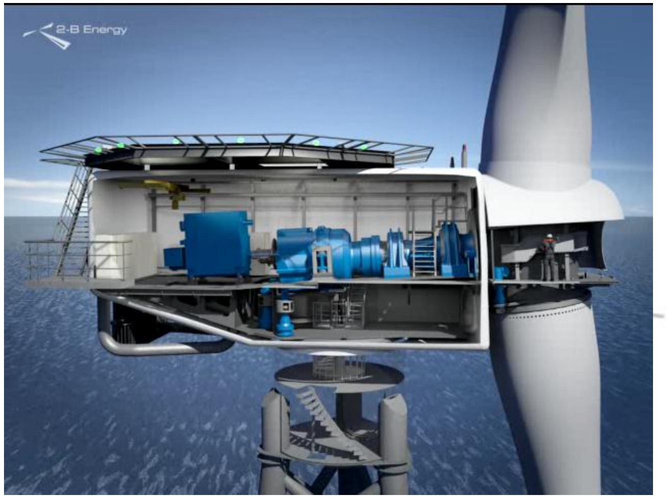
"The future, in fact, will be full of optimization algorithms. They are becoming part of almost everything. They are moving up the complexity chain to make entire companies more efficient. They also are moving down the chain as computers spread."

(USA Today, 31 Dec 1997)

Optimization of support structures

- Difficult problem
  - Large design space (many parameters)
  - Fatigue-driven designs in stochastic environment: expensive evaluation
- Need fast multibody/FEM solver
- Need simplified fatigue analysis methods
- Need efficient optimization method
  1. Local optimization
  2. Simultaneous perturbation
  3. Response-surface method
  4. *Specialized software for integrated support structure optimization?*

Outlook



- Full-height lattice tower concept
  - Pro: Lighter structure, no expensive transition piece
  - Con: More difficult fabrication and installation, more difficult design (local vibrations), more difficult access
- Intermediate water depth (35 m)
  - Tower weight comparable to (shorter) monopile – or joint detailing needed
  - NB: Transition piece and foundation costs not included
- Deep water (60 m)
  - Lighter by at least 20 percent than (shorter) monopile
- First commercial concepts?
  - http://www.2-benergy.com/

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Additional slides

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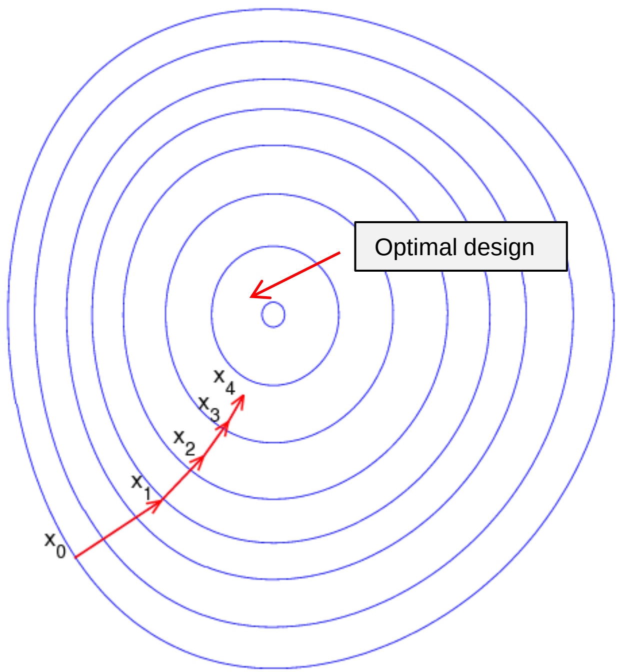
Structural optimization: Direct search methods

- Gradient search
  - Improve design step-wise by following direction of steepest improvement
  - Θ_k: k-th parameter vector
  - a_k: gain sequence
  - g_k: estimate of the gradient
- Issues with gradient search
  - Can be slow close to optimum
  - Only finds local optima
    - Depends on initial point in design space
    - Restart optimization with different starting points
  - How to obtain gradient information?

$$\hat{\theta}_{k+1} = \hat{\theta}_k - a_k \hat{g}_k(\hat{\theta}_k)$$



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How to obtain gradient information?

- Sensitivity analysis
  (Haftka & Adelman, 1989)
  - Analytical methods (for static loads)
    - Accurate and efficient
    - Needs special software capabilities
  - Central difference approximation
    - Necessary to evaluate 2N designs for N parameters
    - Choice of interval (finite difference) can be problematic
      - Too large: bad approximation
      - Too small: unstable (numerical noise)
  - Simultaneous perturbation
    (Spall 1992)
    - Needs only 2 evaluations for N parameters
    - Not a true gradient, but behaves similarly

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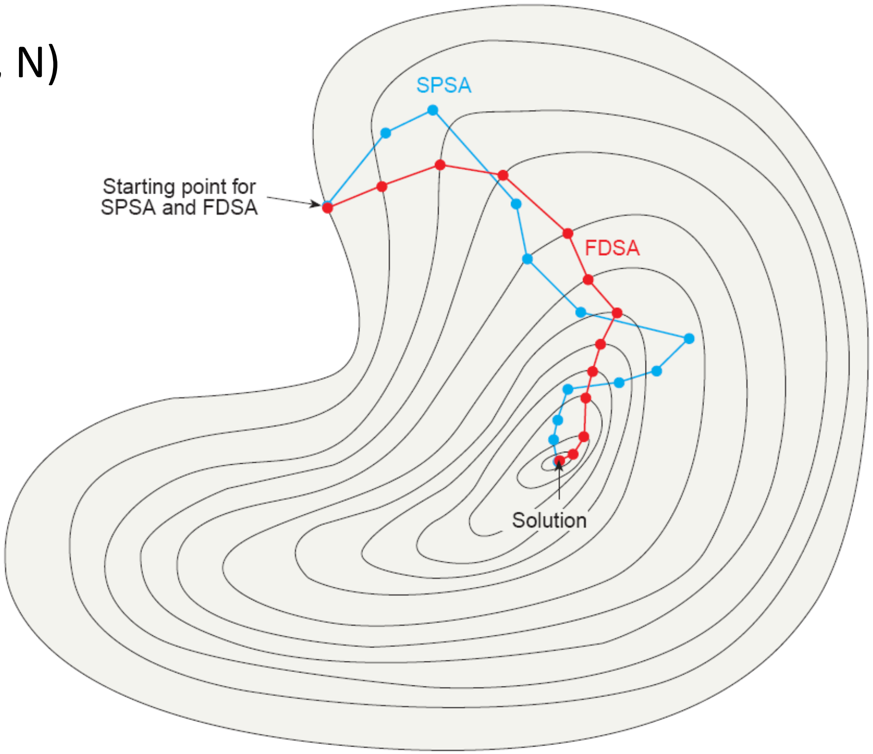
Spall's simultaneous perturbation method

- Two-sided finite-difference approximation (FDSA) (for comparison)
  Results in i-th component of g_k
  Needs N function evaluations (i=1, 2, …, N)

$$\hat{g}_{ki}(\hat{\theta}_k) = \frac{y(\hat{\theta}_k + c_k e_i) - y(\hat{\theta}_k - c_k e_i)}{2c_k}$$

- Two-sided *simultaneous* approximation (SPSA)
  Results in i-th component of g_k
  Needs only 2 function evaluations
  Perturbation Δ_k chosen randomly

$$\hat{g}_{ki}(\hat{\theta}_k) = \frac{y(\hat{\theta}_k + c_k \Delta_k) - y(\hat{\theta}_k - c_k \Delta_k)}{2c_k \Delta_{ki}}$$



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Alternative: Metamodels

- Classical response-surface method
  (Khuri & Cornell 1996; Myers *et al.* 2009)
  - Use a linear (statistical) model for the objective function in terms of *parameters* and their *interactions*
  - Fitted by least-squares: very efficient
  - Works well with randomness (numerical noise)
  - Use response surface for direct search
- Kriging metamodels
  (Sacks *et al.* 1989; Simpson *et al.* 2001)
  - Use spatial correlation between function values
  - Developed for geoscientific applications (reservoir characterization)
- Variations and other approximations
  (Barthelemy & Haftka 1993)

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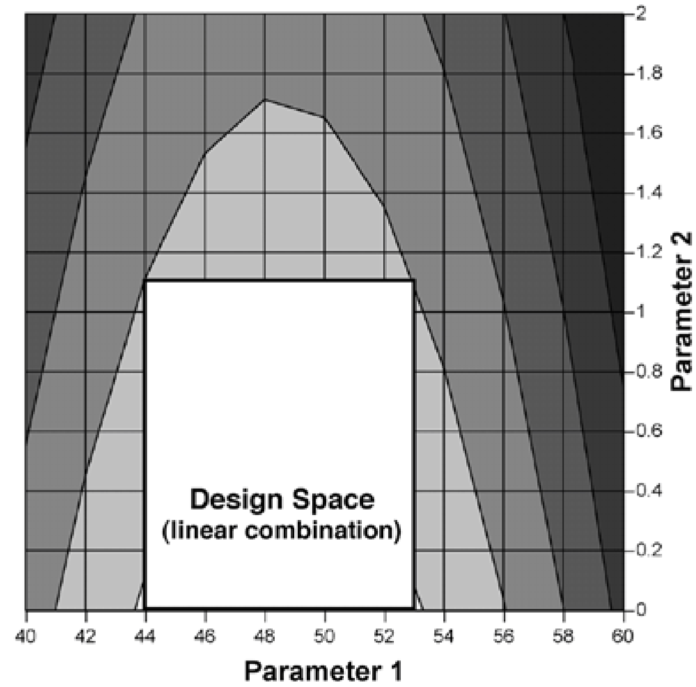
Response-surface method



- Linear regression model (ANOVA)
  - Constructed as an *approximation* of the true behavior of the objective function
  - Fitted by least-squares regression
  - Ideally suited for expensive *black-box simulation optimization*: uses knowledge from function evaluations optimally
- First-order response surface

$$y_u = \beta_0 + \beta_1 x_{1u} + \beta_2 x_{2u} + \ldots + \beta_v x_{vu} + e_u$$

- Second-order response surface

$$y_u = \beta_0 + \sum_{i=1}^{v} \beta_i x_{iu} + \sum_{i=1}^{v} \beta_{ii} x_{iu}^2 + \sum_{i=1}^{v-1} \sum_{i'=i+1}^{v} \beta_{ii'} x_{iu} x_{i'u} + e_u$$

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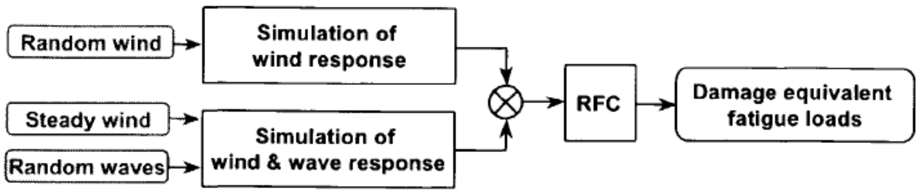
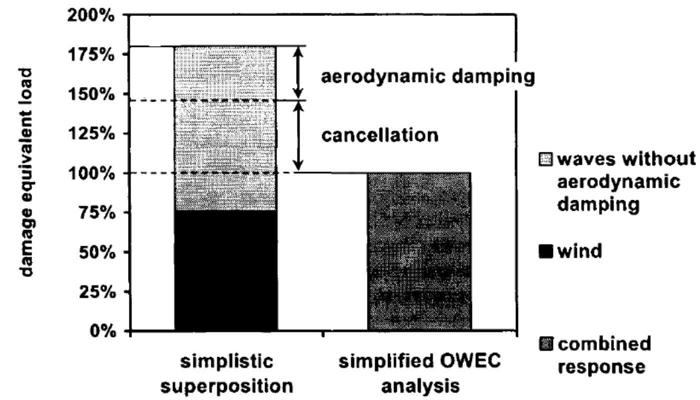
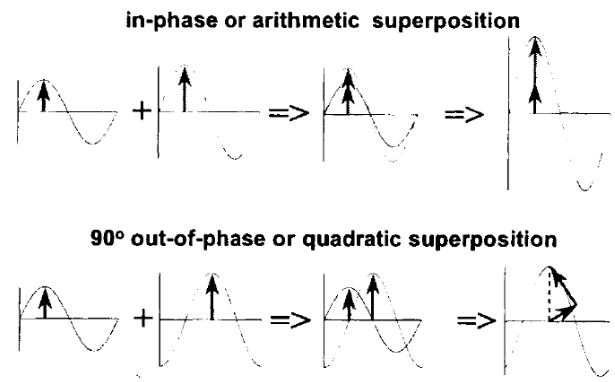
Simplified fatigue assessment 1/2

- Separation of simultaneous response under wind and wave loading
  (Kühn 2001)



  - *Approximate aerodynamic damping* by structural damping
  - Superposition of damage-equivalent loads
    - *In-phase superposition*
      Too conservative
      Overestimates fatigue damage
    - *Out-of-phase superposition*
      Axial and bending loads *largely independent*
      90 degree phase angle (geometric average)
      No empirical or theoretical basis?





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Simplified fatigue assessment 2/2

- Frequency-domain considerations
  - Both aerodynamic and simultaneous response not narrow-banded
  - Usually *Dirlik's method* best for fatigue in frequency domain
  - Easier, although less accurate empirical correction (Hancock & Gall, 1985)
- Weighted quadratic superposition of equivalent stress ranges
  - Given in terms of spectral moments m_n

$$\Delta\sigma_{eq,ah} = \sqrt{\sqrt[\mu]{\frac{m_{2,a}+m_{2,h}}{m_{0,a}+m_{0,h}}}\left(\Delta\sigma_{eq,a}^{2}\sqrt[\mu]{\frac{m_{0,a}}{m_{2,a}}}+\Delta\sigma_{eq,h}^{2}\sqrt[\mu]{\frac{m_{0,h}}{m_{2,h}}}\right)}$$

- Further simplification:
  - Direct quadratic superposition of equivalent fatigue loads

$$\Delta\sigma_{eq,ah} \approx \sqrt{\Delta\sigma_{eq,a}^{2} + \Delta\sigma_{eq,h}^{2}} \qquad \text{for } T_{z,a} \approx T_{z,h}$$

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