Investigation of Structural Uncertainty of Wind Turbine Rotor Blades

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Outline

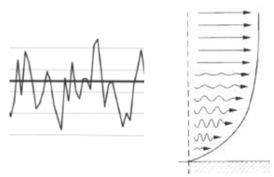
1. **Introduction**
2. **Modelling Structural Uncertainty**
3. **Simulation Process**
4. **Results**
5. **Conclusions and Outlook**

Motivation

For long and slender rotor blades, the consideration of uncertainties and aeroelastic phenomena becomes increasingly important.

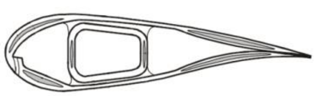
Main sources of uncertainties in WT design

Complex flow environment

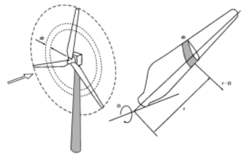


Geometry deviations

Structural imperfections



(Simple) Simulation tools



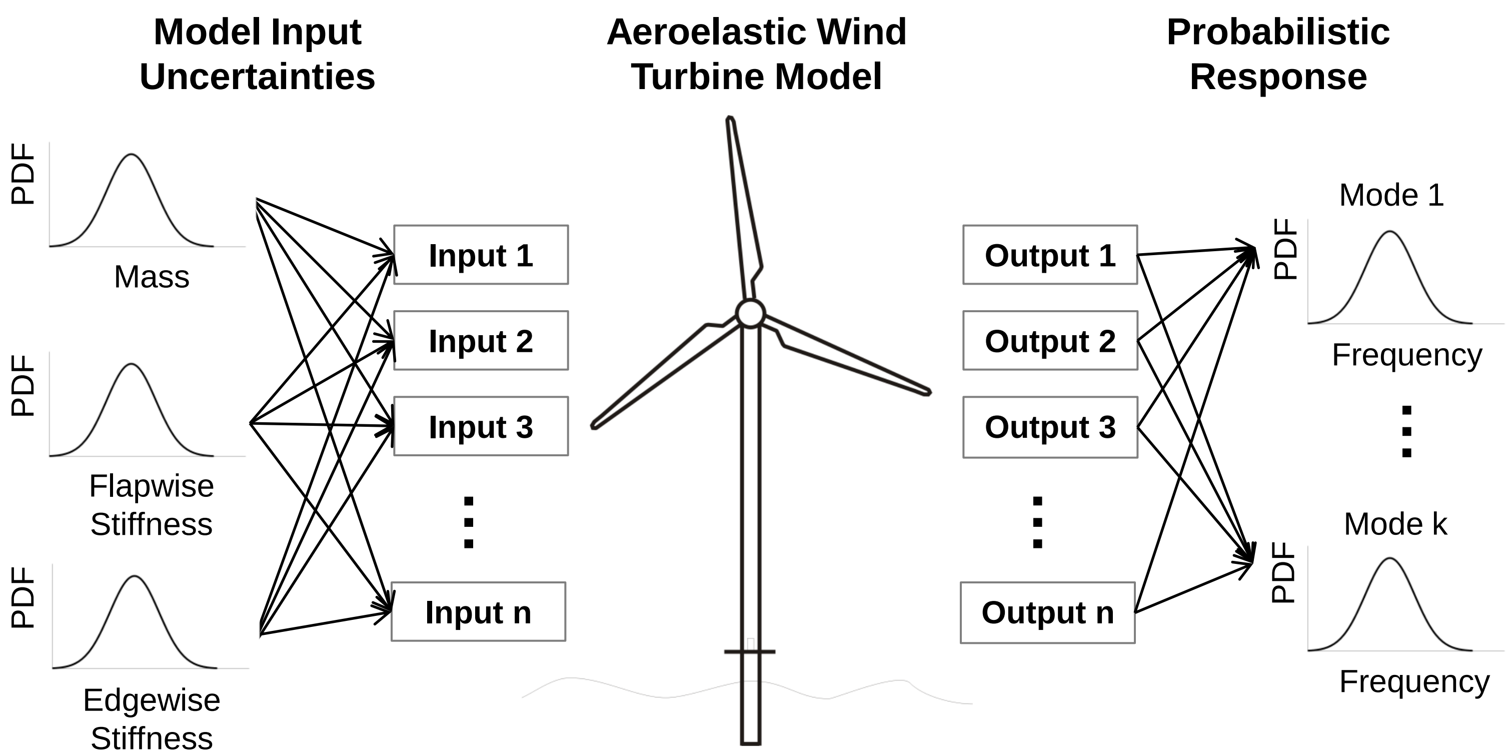
- Imperfections of composite materials due to the variability of
  - the fiber and matrix material properties,
  - fiber volume ratio,
  - …
- Manufacturing tolerances due to non-automated processes

Pictures: Gasch and Twele (2011); Sørensen et al. (2004); Burton et al. (2011)

Approach

Using spatial random fields and Latin hypercube sampling to investigate the effect of structural uncertainty of rotor blades on…

1) the full system mode shapes and
2) the system natural frequencies of an offshore wind turbine (OWT).



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Aeroealstic Wind Turbine Model

The aeroelastic model of the NREL 5MW reference wind turbine is used with 15 degrees of freedom (DOF).

- Pitch-controlled variable-speed wind turbine
- Based on available information of the REpower 5M and the DOWEC design study

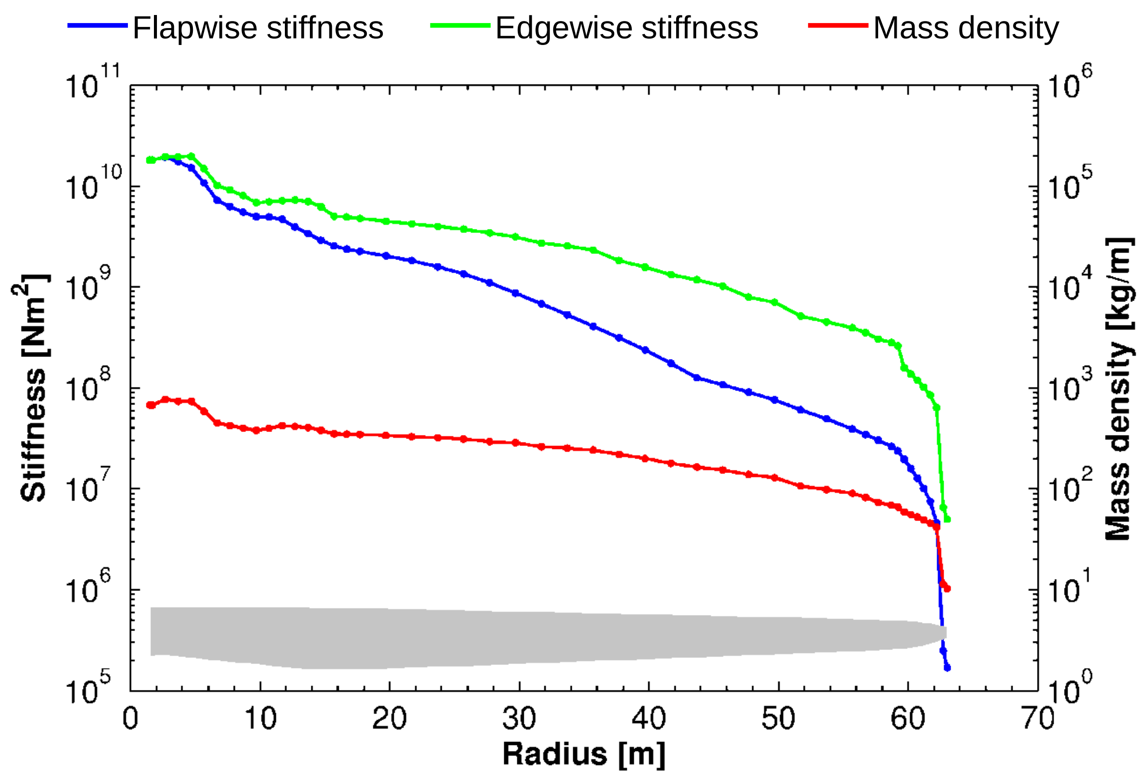
Rated power	5000 kW
Rotor diameter	126 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3, 11.4, 25 m/s
Cut-in, rated rotor speed	6.9, 12.1 rpm

- Known data of:
  - blade structural and aerodynamic properties
  - nacelle and hub
  - drivetrain
  - tower
  - control system

Source: REpower

Jonkman J., Buttereld S., Musial W., and Scott G. (2009): *Defnition of a 5-MW Reference Wind Turbine for Offshore System Development.* NREL/TP-500-38060. Golden, Colorado, USA: National Renewable Energy Laboratory

Modeling Structural Uncertainty of Rotor Blades



- Structural blade parameters are varied with respect to the corresponding baseline parameters.
- Variations are normally distributed (μ = 0%, σ = 10%).
- Spatial variations of the structural parameters along the blade are…
  - uniform,
  - independent, or
  - correlated.

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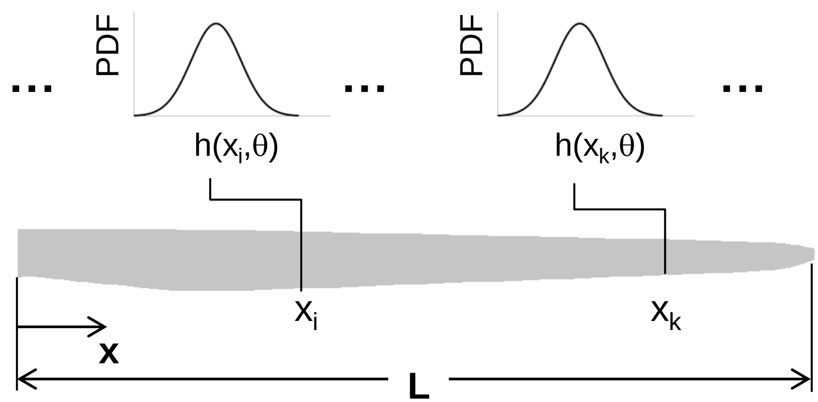
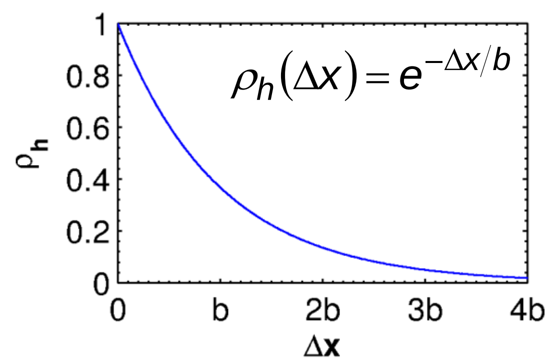
Homogeneous, Isotropic, Gaussian Random Field

Variations of structural properties, which are spatially correlated, can be described by a random field $h(x,\theta)$.



$i,k = 1,\ldots,n$

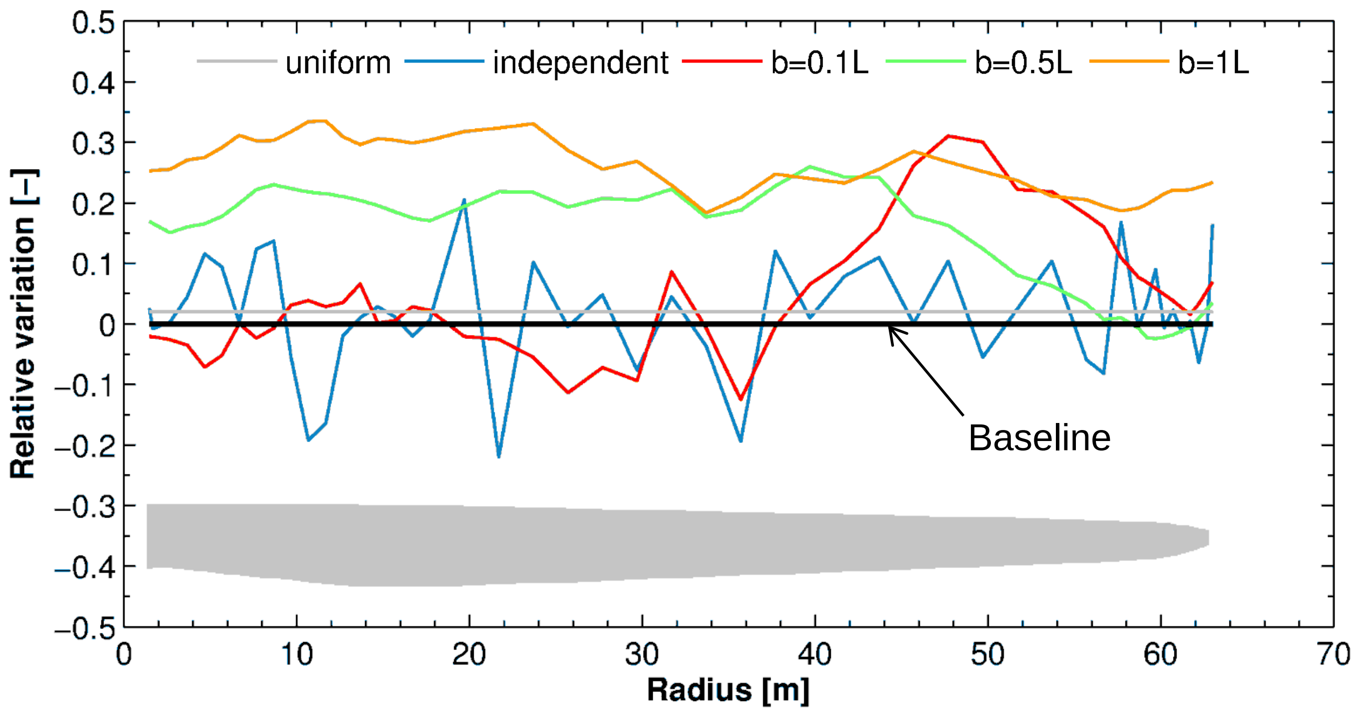
$$C_{hh} = \sigma^2 \cdot \begin{bmatrix} \rho_h(x_1,x_1) & \rho_h(x_1,x_2) & \cdots & \rho_h(x_1,x_n) \\ \rho_h(x_2,x_1) & & & \vdots \\ \vdots & & \ddots & \\ \rho_h(x_n,x_1) & \cdots & & \rho_h(x_n,x_n) \end{bmatrix}$$



- Spatial distribution is fully characterized by its mean and its covariance.
- Inverse-exponential correlation with b=0.1L, 0.5L, and 1L is assumed.
- *Karhunen-Loève* expansion is used to create random fields.

Spatial Parameter Variations

The rotor blade is divided into 50 equally spaced elements/cross sections and 1000 samples are created for each type of spatial variation.



- Spatial independent variations can cause local extreme fluctuations.
- The correlation increases with an increasing correlation length *b*.
  - ➔ Variations along the blade become smoother.

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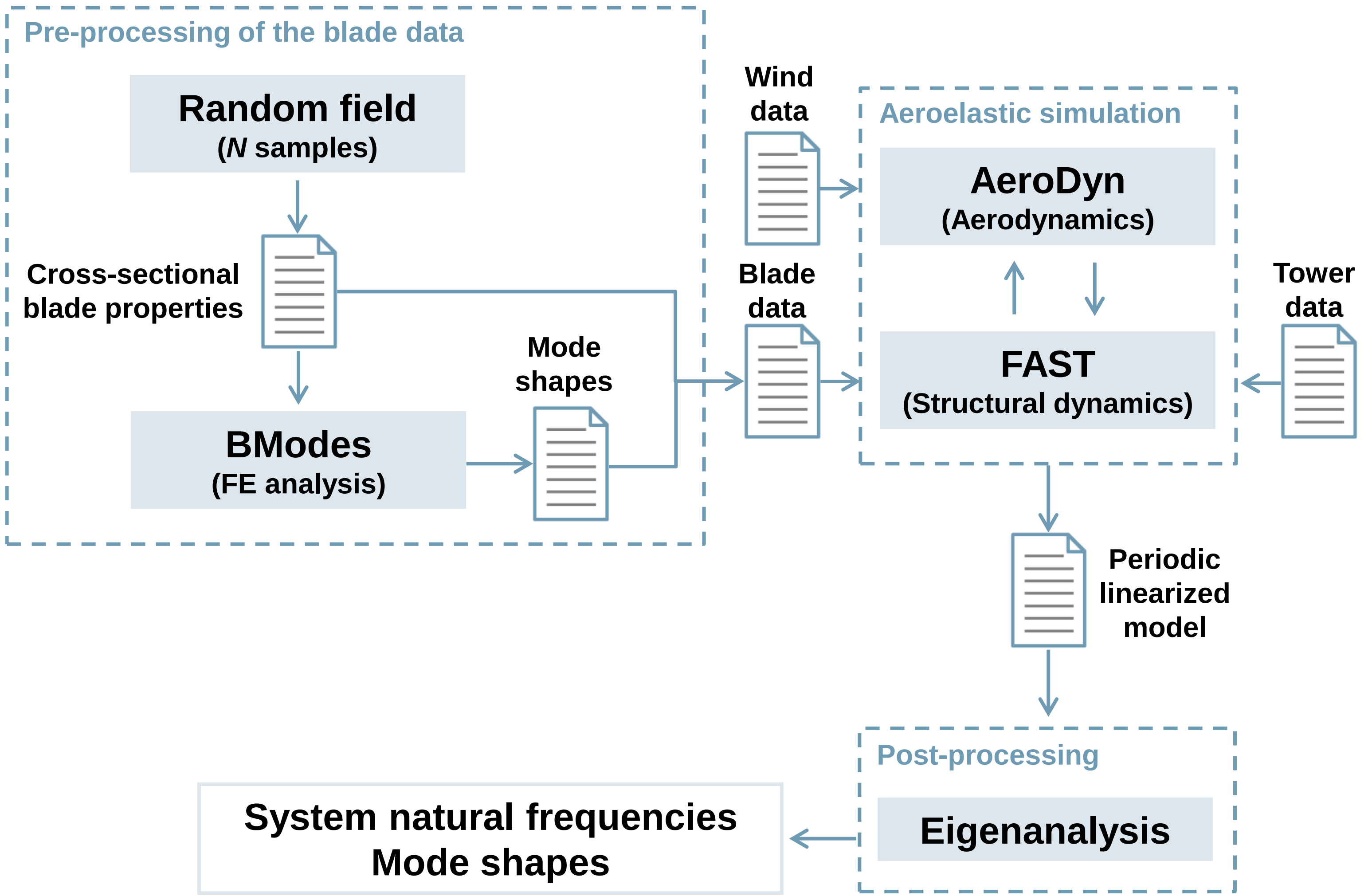
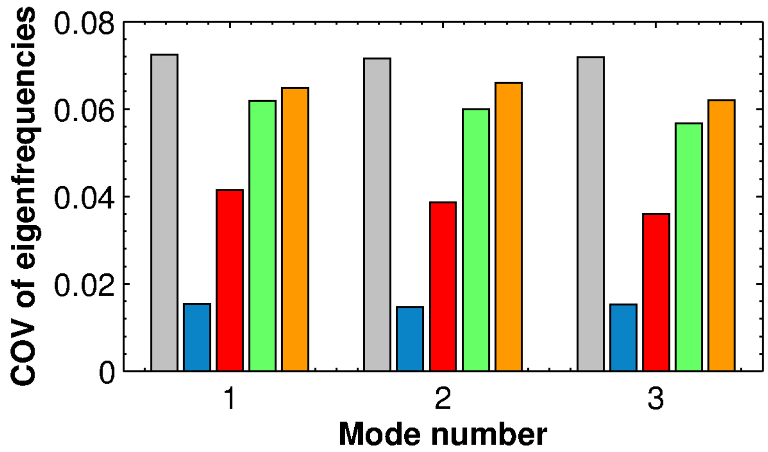
Simulation Process



FAST: Jonkman J. M. and Buhl Jr. M. J. (2005): *FAST User's Guide.* NREL/TP-500-38230. Golden, Colorado, USA: National Renewable Energy Laboratory

BModes: Bir G. S. (2005): *User ́s Guide to BModes (Software for Computing Rotating Beam Coupled Modes).* NREL/TP-500-39133. Golden, Colorado, USA: National Renewable Energy Laboratory

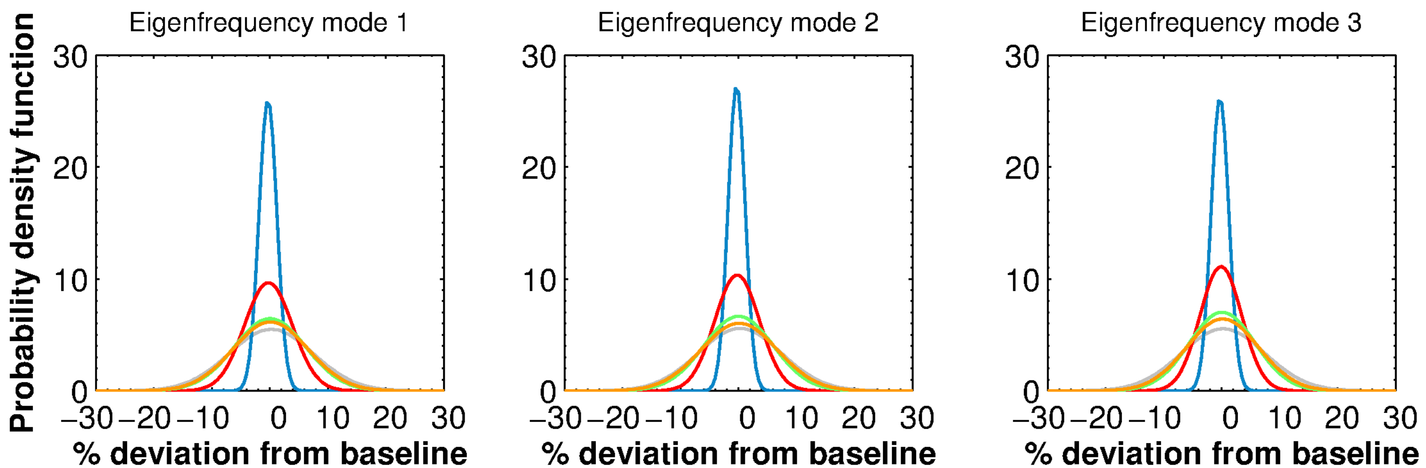
Blade Eigenfrequencies at Standstill (BModes)



Coefficient of variation:

$$COV = \frac{\sigma_\omega}{\overline{\omega}}$$

uniform
independent
b=0.1L
b=0.5L
b=1L



- ➔ Scatter of blade eigenfrequencies are almost identical
- ➔ Increase in scatter with increasing correlation length
- ➔ Relative deviations seem to be normally distributed

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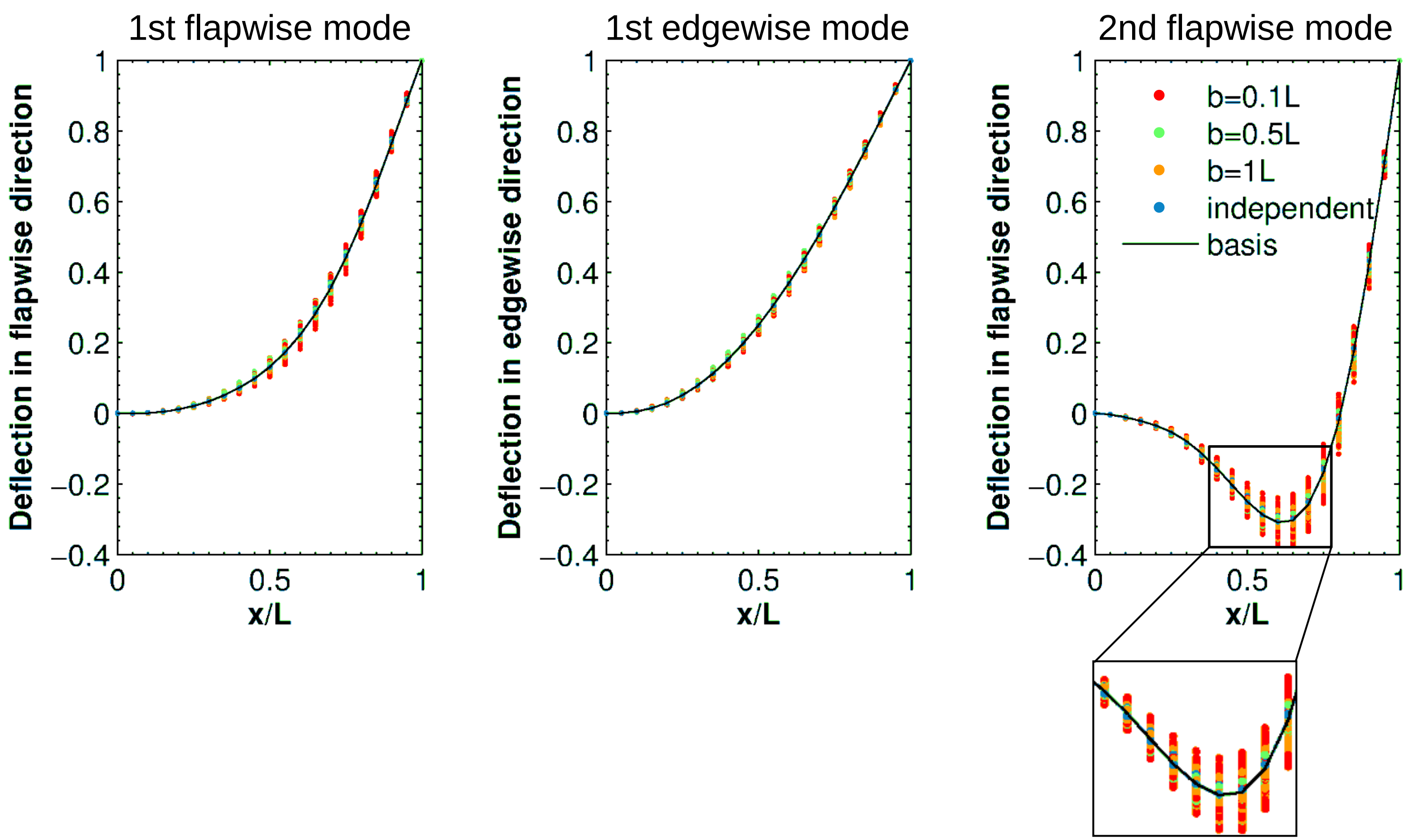
Variations of Blade Mode Shapes at Standstill (BModes)

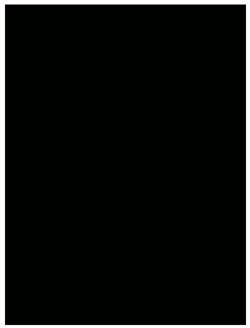


- ➔ No scatter of the mode shapes for spatially uniform variations
- ➔ Increase in scatter of the mode shapes with decreasing correlation length

First 5 Rotor Modes at Standstill

The drivetrain and the tower-nacelle subsystem feel combined effects of all rotor blades.

1st collective flapwise



1st flapwise yaw

1st flapwise pitch

1st edgewise yaw

1st edgewise pitch

Videos: standstill mode shapes of a 600 kW turbine (Hansen 2011)

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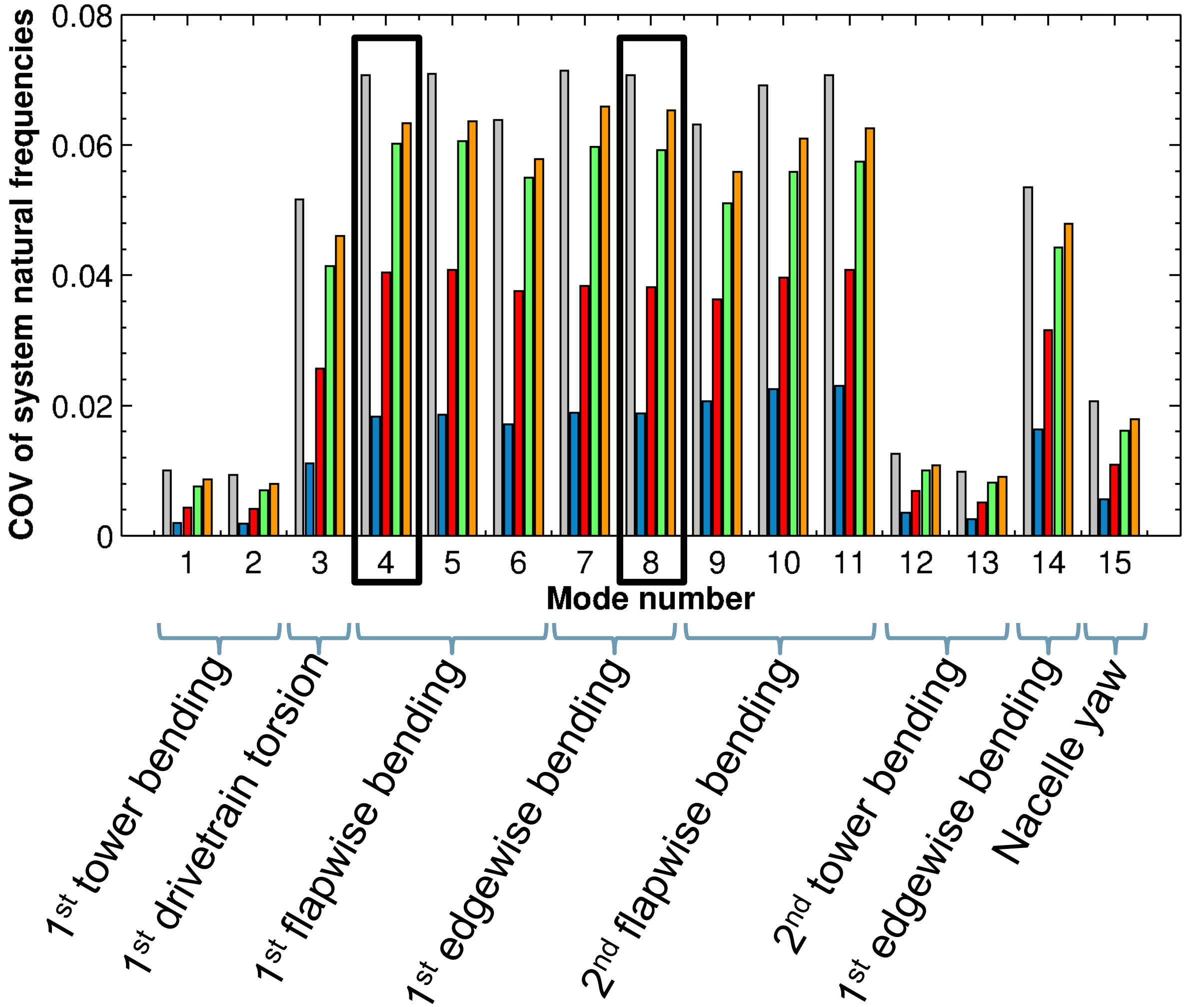
System Natural Frequencies at Standstill (FAST)



Coefficient of variation:

$$COV = \frac{\sigma_\omega}{\overline{\omega}}$$

- ➔ High frequency scatter for the rotor modes
- ➔ Significant impact on the drivetrain
- ➔ Almost no effect on the tower modes
- ➔ Correlation length *b*=0.1*L* seems to be a reasonable assumption

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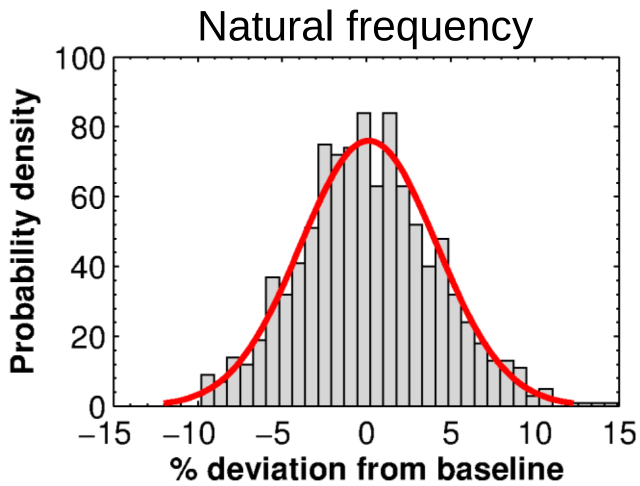
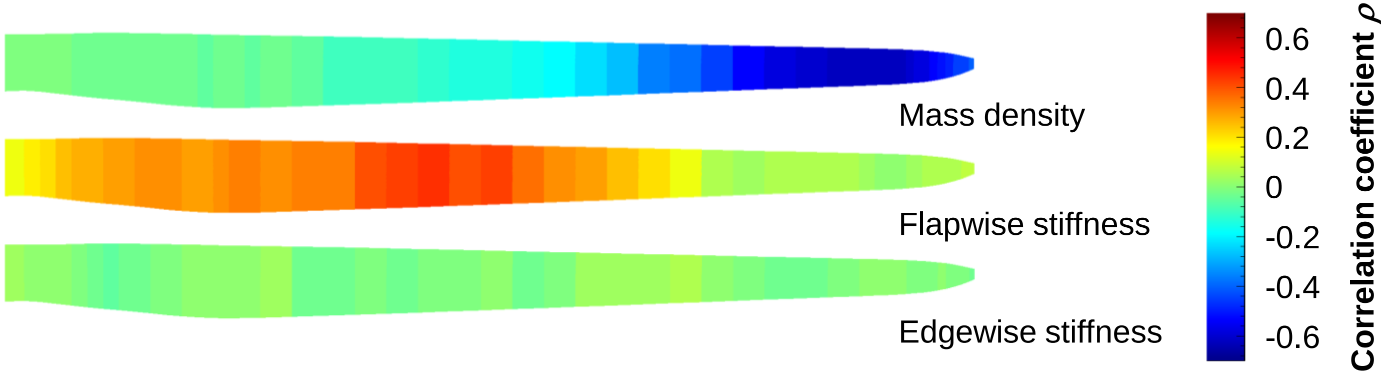
Natural Frequency of the 1st Flapwise Yaw Mode (b=0.1L)



Hansen (2011)

<u>Correlation between the structural parameters and the frequency</u>



- ➔ Relative deviations follow a normal distribution
- ➔ Negative dependency between blade mass density and frequency
- ➔ Positive dependency between flapwise stiffness and frequency

Natural Frequency of the 1st Edgewise Yaw Mode (b=0.1L)

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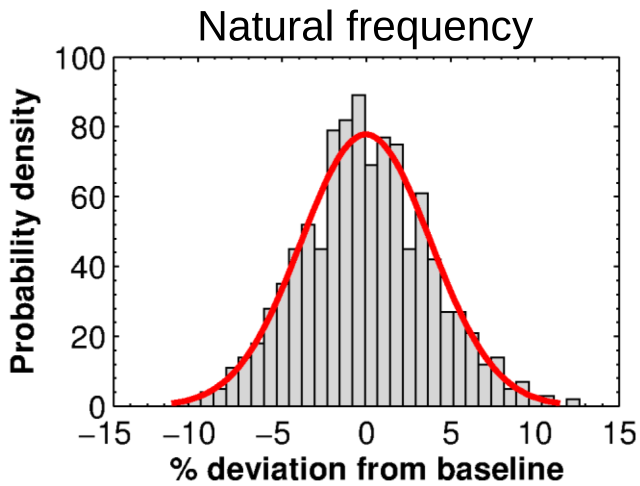
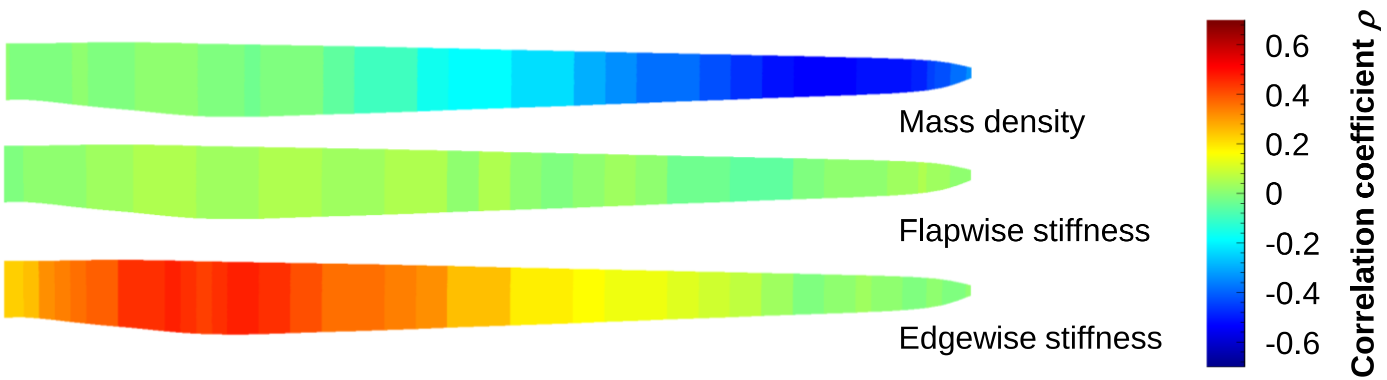


Hansen (2011)

Correlation between the structural parameters and the frequency



- ➔ Relative deviations follow a normal distribution
- ➔ Negative dependency between blade mass density and frequency
- ➔ Positive dependency between edgewise stiffness and frequency

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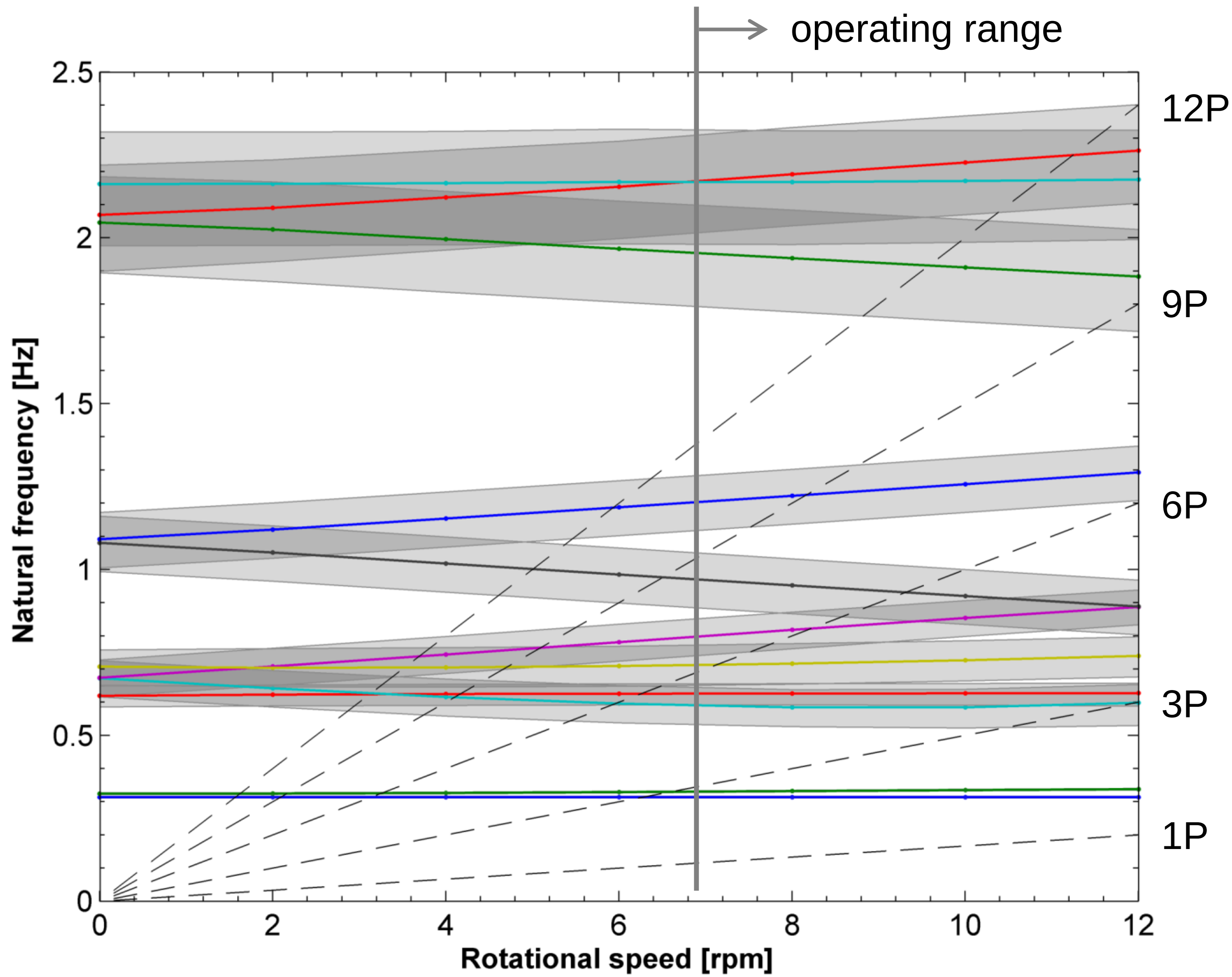
Campbell Diagram (*b*=0.1*L*)



- ➔ High frequency scatter of the rotor modes in the operating range
- ➔ Increased risk for resonances, e.g. drivetrain torsion and 3P frequency

Error bars: inter-quantile range $IQR = Q_{0.975} - Q_{0.025}$

Conclusions and Outlook

Conclusions

- Spatial uncertainty of structural blade parameters is modeled with a random field approach:
  - Increasing correlation length leads to a larger frequency scatter.
  - Correlation length b=0.1L seems to be a reasonable assumption.
- Variations of blade structural parameters cause
  - a significant effect on blade eigenfrequencies and mode shapes.
  - a significant effect on system natural frequencies of the rotor modes.
  - an increased risk for resonances.
- Scatter of the frequencies follows a normal distribution.

Outlook

- Investigation of modal frequencies at different wind speeds
- Combined analysis of structural and geometric uncertainties
- Investigation of the effect on the loads

Thank you for your attention!

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