Structural health monitoring in the wind energy sectors

A. **Nuber,** H. **Friedmann**, Wölfel Engineering GmbH + Co. KG

E-LASS / MariLight.NET - Seminar on Structural Health Monitoring
Bremen, 29.01.2020

OUTLINE

- Wölfel Engineering GmbH + Co. KG
- Why monitoring?
- Structural Health Monitoring or Condition Monitoring?
- Sensors are the nerves of the monitoring system
- Instrumentation of the foundation in the construction phase
  - Sensor technology for the grouted joint
- Instrumentation of tower, nacelle and rotor
  - Pile and tower
  - Load monitoring and service life
  - Rotor blades
  - Population monitoring in addition to ice detection

WELCOME TO THE WORLD OF VIBRATIONS, STRUCTURAL MECHANICS AND ACOUSTICS

We are experts in this world. It is our home.

Vibrations and noise are almost always unwanted. Their reduction provides safety, prevents damage and avoids unnecessary costs.

We support our customers with engineering services and products for the analysis, prognosis and solution of tasks in the fields of vibrations and noise.

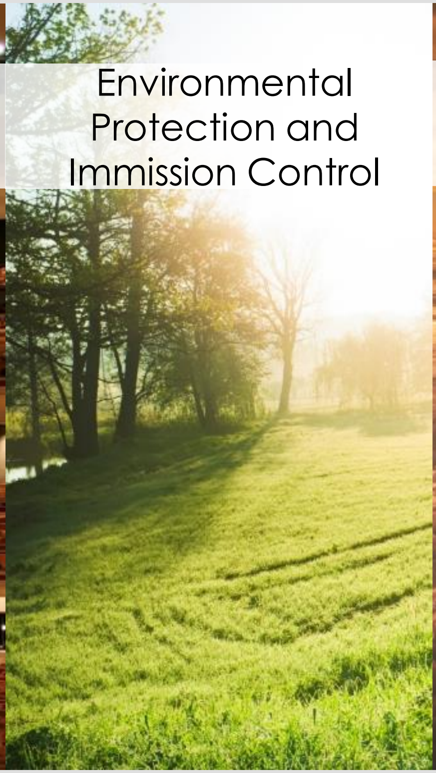
ARE VIBRATIONS REALLY EVERYWHERE?

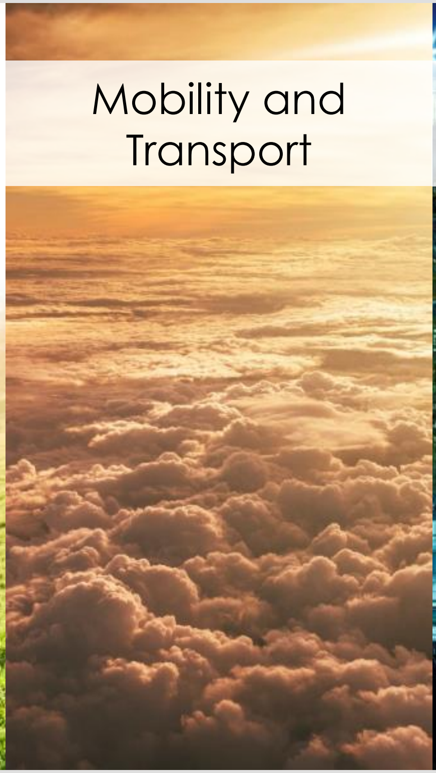
YES! THAT IS WHY WE OFFER A WIDE VARIETY OF SOLUTIONS!

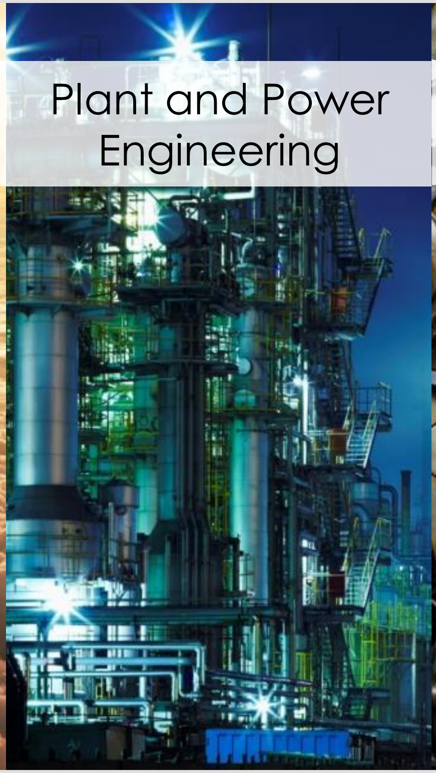
Vibrations are always the initiator for us to take action.

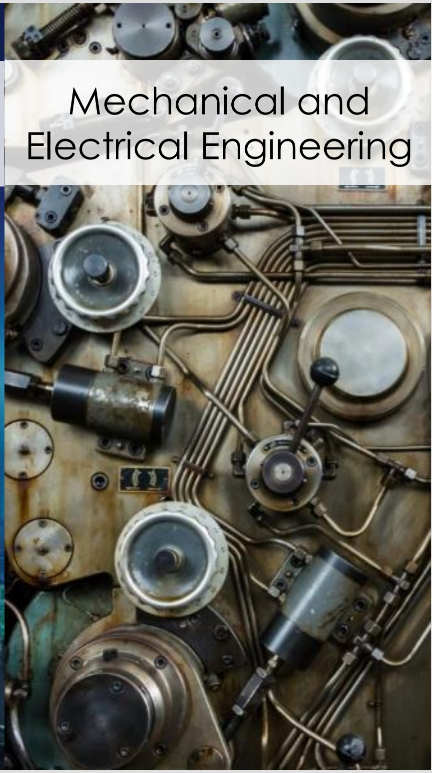
That is why Wölfel offers a manifold of general as well as specific solutions in the form of engineering services, systems or software for practically all industries worldwide.

IN WHICH INDUSTRIES ARE WE CURRENTLY ACTIVE?









HOW DID WE BECOME WHAT WE ARE TODAY?

HOW DID WE BECOME WHAT WE ARE TODAY?

1971

Foundation of Wölfel Beratende Ingenieure

1986

Foundation of Wölfel Meßsysteme · Software
Appointment of Prof. Wölfel to the Institute of Structural Dynamics of Darmstadt University of Technology

2000

Construction of new headquarters: HiTech Center Höchberg

2009

Participation in Micromega Dynamics SA

2014

Foundation of Wölfel Wind Systems GmbH
Foundation of VICODA GmbH (joint venture with LISEGA SE, Zeven)

2016

45 years of Wölfel Beratende Ingenieure / name change to Wölfel Engineering
30 years of Wölfel Meßsysteme · Software / name change to Wölfel Monitoring Systems

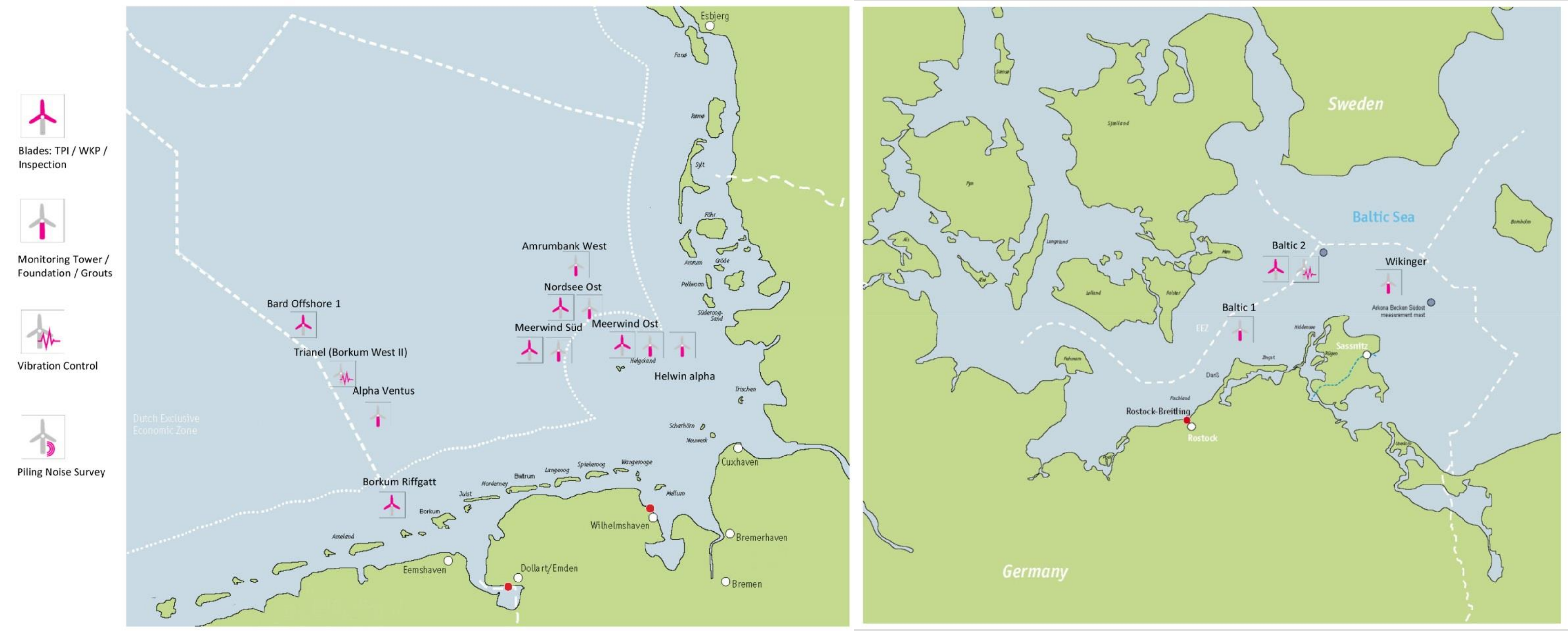
2018

Foundation of Wölfel Holding GmbH

2019

More than 100 employees are working as qualified partners of medium-sized businesses and industry.

REFERENCE PROJECTS OFFSHORE WIND



WHY MONITORING?

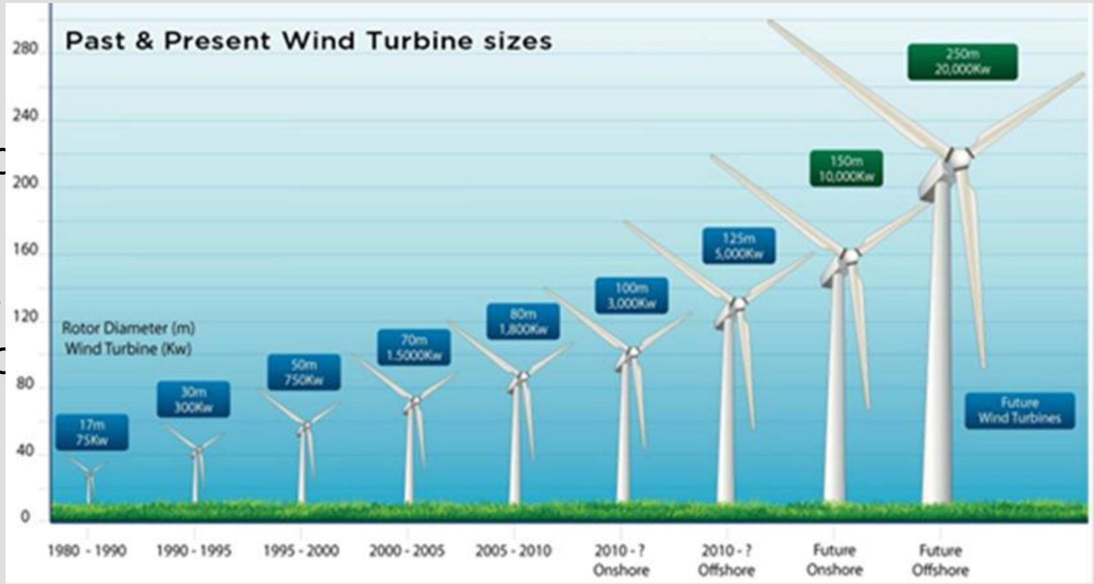
The special position of offshore buildings and structures is due, among other th
to:

- High investment costs
- Extreme stresses from salt water, corrosion, wind, swell, tidal current, hydrostatic pressure, vegetation, ...
- Limited accessibility due to extreme weather conditions, swell, travel times
- Logistics planning with long lead times
- Limited availability of highly specialized ships
- Cost-intensive requirements regarding periodic inspections
- Rapidly growing number of monitoring objects (offshore wind)
- Risks of diving operations
- …

WHY MONITORING?

Why do wind turbines have to be monitored?

- The growth in the size of wind turbines is unbroken for reasons of economic efficiency; rotor blades today ho a length of 60 to 80 m!
- Wind turbines are subject to extremely high loads due complex superposition of cyclical and stochastic dyna loads from wind, waves and operation.
- With a service life of 20 to 25 years, rotor blades experience approx. 2×10^8 load cycles, making them one of the most heavily stressed technical components of all.

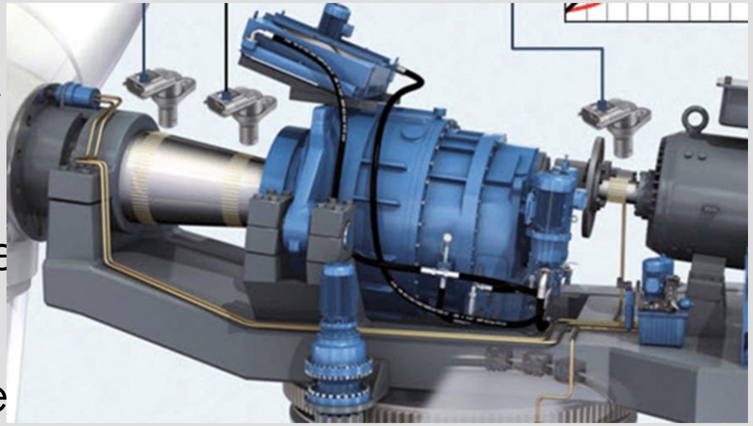


- Due to the largely manual production, imperfections (ondulation, delamination, bonding) are to be expected. In interaction with dynamic loads, they are often crystallization points for damage.

→ Wind turbines must be monitored!

WHAT DOES CONDITION MONITORING MEAN?

Monitoring objects of **Condition Monitoring** are



- standardized, precisely manufactured, movable, frequently rotati machine parts such as bearings
- the mass distribution and the stiffness of the monitored objects are known and are the same from component to component
- natural and rollover frequencies and other modal parameters are
- certain damage patterns are very closely linked to the geometric and kinematic boundary conditions of the monitored objects. These can be, for example, rollover or tooth engagement frequencies in the case of bearing damage. This enables data-driven identification and often also localization.
- most industrially available CM applications are based on the analysis of temperatures, oil quality, torsional loads and other parameters for which there are limit values, and especially on the above mentioned frequencies associated with kinematics
- the aim of monitoring is to **check the functionality of a machine**.

WHAT DOES STRUCTURAL HEALTH MONITORING MEAN?

Objects of **structural health monitoring** are

- Load-bearing structures that are often manufactured manu The accuracy of the manufacturing process is more in the decimetre than in the millimetre range, the load is mostly sto
- The masses of these structures and their stiffness vary in the percentage range. For example, on a 40 m rotor blade weig about 7 t, deviations in mass in the order of 50 to 100 kg are within the usual range.
- The goal of SHM is to **monitor the load-bearing capacity and stability of a structure**
- In most cases the ultimate load capacity or the maximum load is not known
- The remaining service life of a supporting structure is a very important information
- It is often not known where what kind of damage is to be expected? Therefore SHM often means novelty and change detection

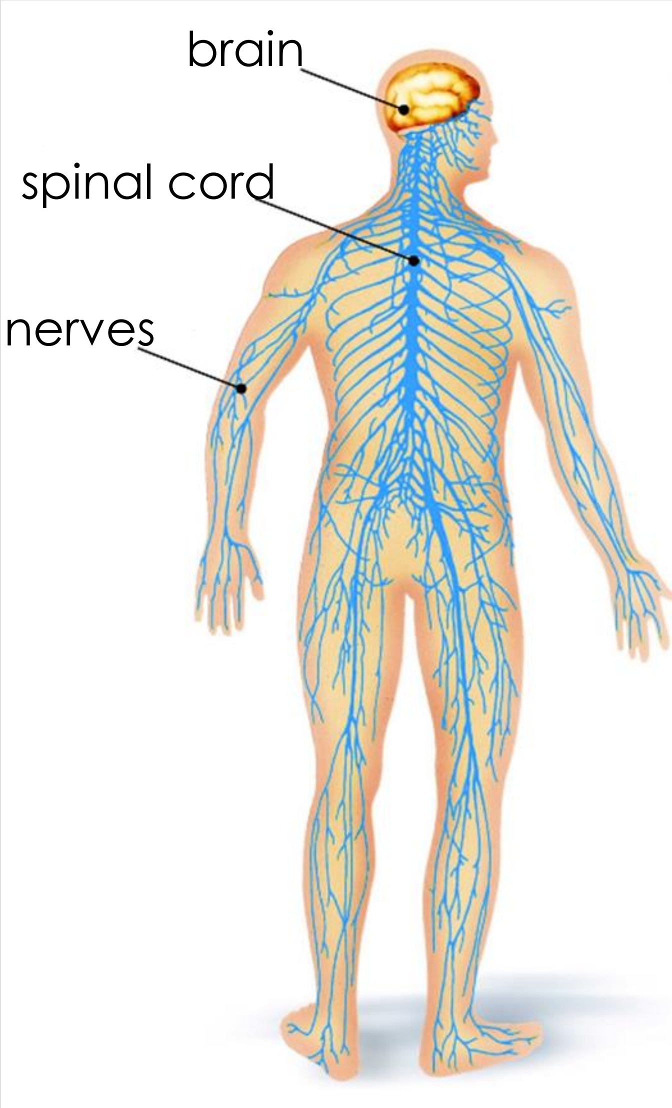
SENSORS ARE THE NERVES OF THE MONITORING SYSTEM

The functioning of an SHM system can be compared to the human nervous system and brain in terms of tasks and functionality.

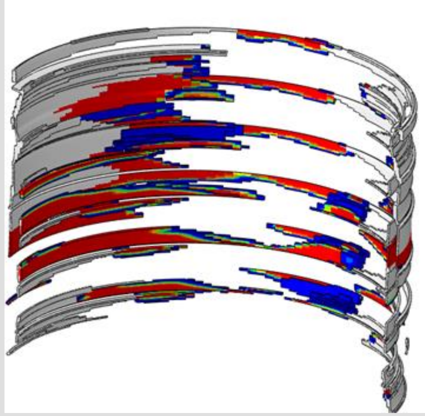
Example Fire → Sensing heat and pain prevent burns

Example Toothache → "repair" before incurable damage or loss of teeth

An SHM system should detect changes at an early stage with the help of a **sensor network** and ongoing **signal analysis**. A **classification** of the detected changes distinguishes between **"benign" changes**, e.g. wind speed, and **"malignant" damage**, which must be warned of.



SENSORS, SIGNAL ANALYSIS, HARDWARE AND FEM MODEL

Sensors	**Hardware** DAQ	DPU	DTU	Web-Interface	FEM-Model
ACC Temp Strain Inclin. Humid others	Data Acquisition Unit with data manage-ment, circular buffer etc.	Data processing Unit • Reference values • Operational modal analysis • Characteristic diagram based on FEM results • Thresholds • EOCs, moving loads • Damage indicatorts • Pattern recognition • Self organizing maps • Decission making • …	Data transfer Unit Transmission of raw or pre-processed data and status alerts	Web-Interface Graded access rights to the data Graphically prepared raw and processed data, status messages and warnings	FEM model to digital twin, coupling with monitoring 

Causes of damage:

- Overload
- Vibrations, fatigue
- Corrosion
- Manufacturing defects
- …

Damage can occur anywhere, monitoring the hot spots alone is not enough!

Sensors:

- Strain measurement e.g. with DMS, FBG: local method, only suitable for monitoring highly stressed parts of the structure or known damage locations
- Structural vibrations (accelerations, vibration velocities) are integral measurement variables that cover the entire structure
- Load measurement or reconstruction from vibration data is possible
- Further parameters such as temperatures, humidity etc.

Signal analysis:

Dynamics, but: Increase of mass → Natural frequency decreases

Loss of stiffness → Natural frequency decreases

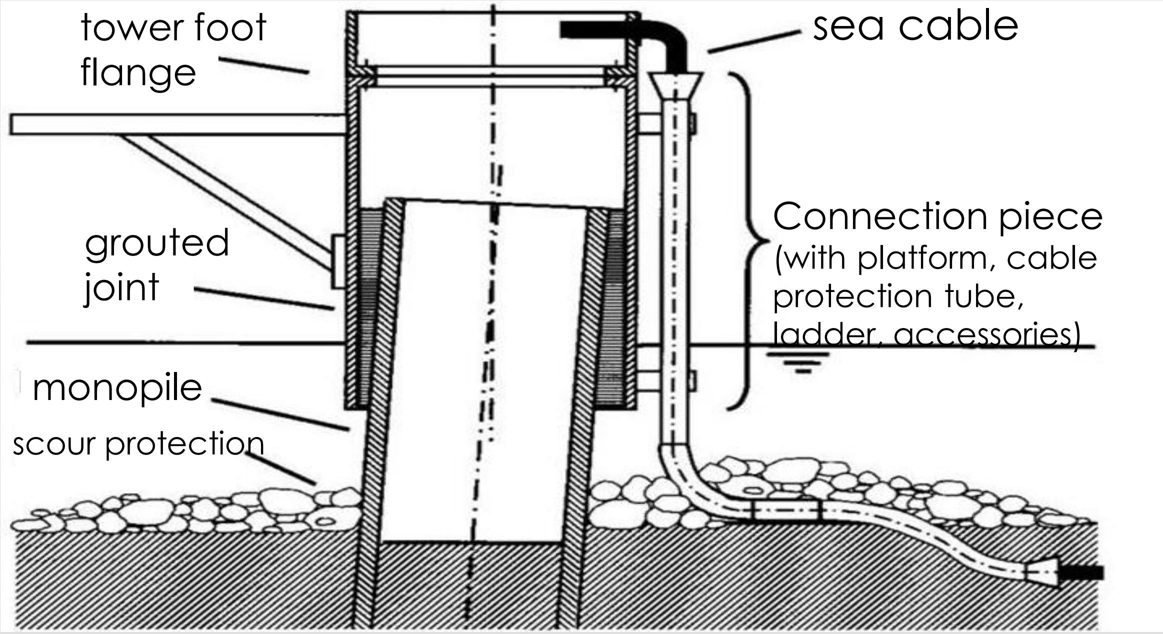
How do we distinguish operational changes that change the natural frequency from damage that also changes the natural frequency? → Compensation of EOCs (operational and environmental conditions)

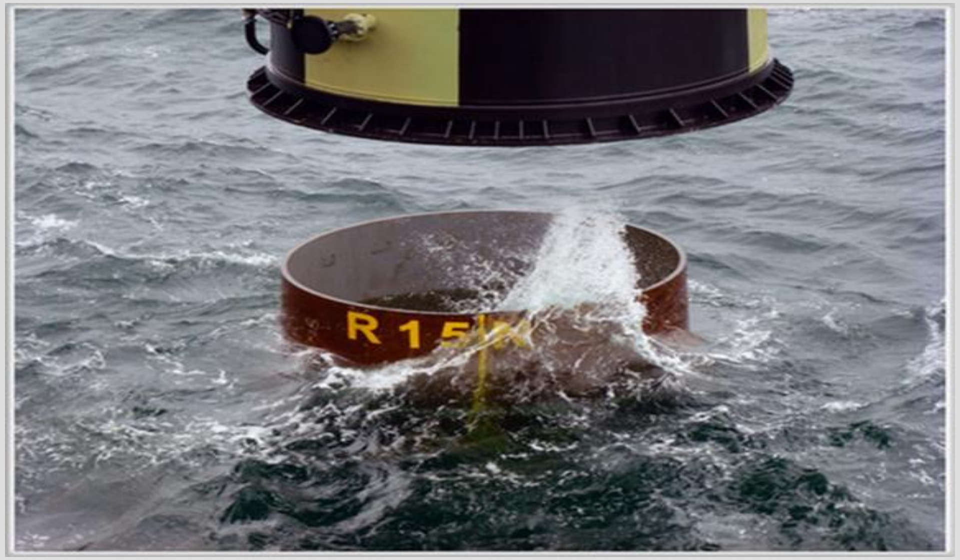
Very high demands on signal analysis, which must take all modal values into account

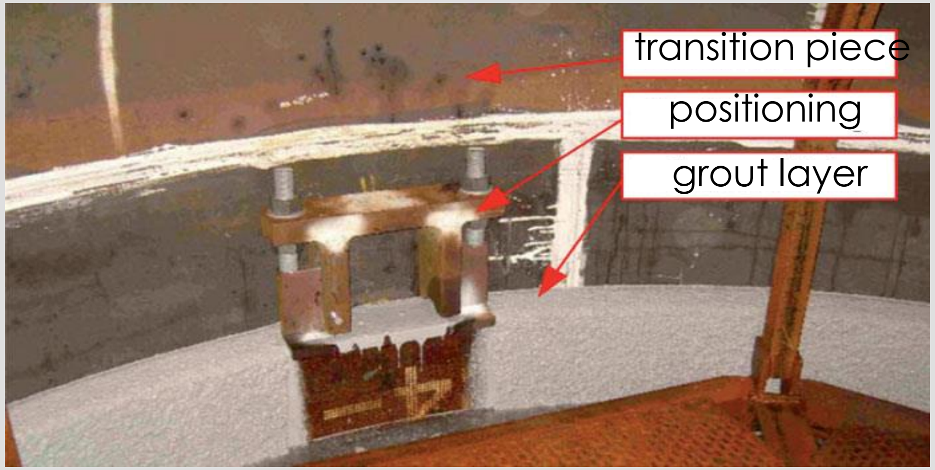
Procedure:
- operational modal analysis, OMA, system identification
- Statistics, pattern recognition, self-organizing maps etc.
- Differently sensitive condition parameters and damage indicators

SENSOR FOR THE GROUTED JOINT

- Steel (pile) - concrete - steel (sleeve) - connection
- Use of high strength concrete
- Concrete reinforcement with silicate particles

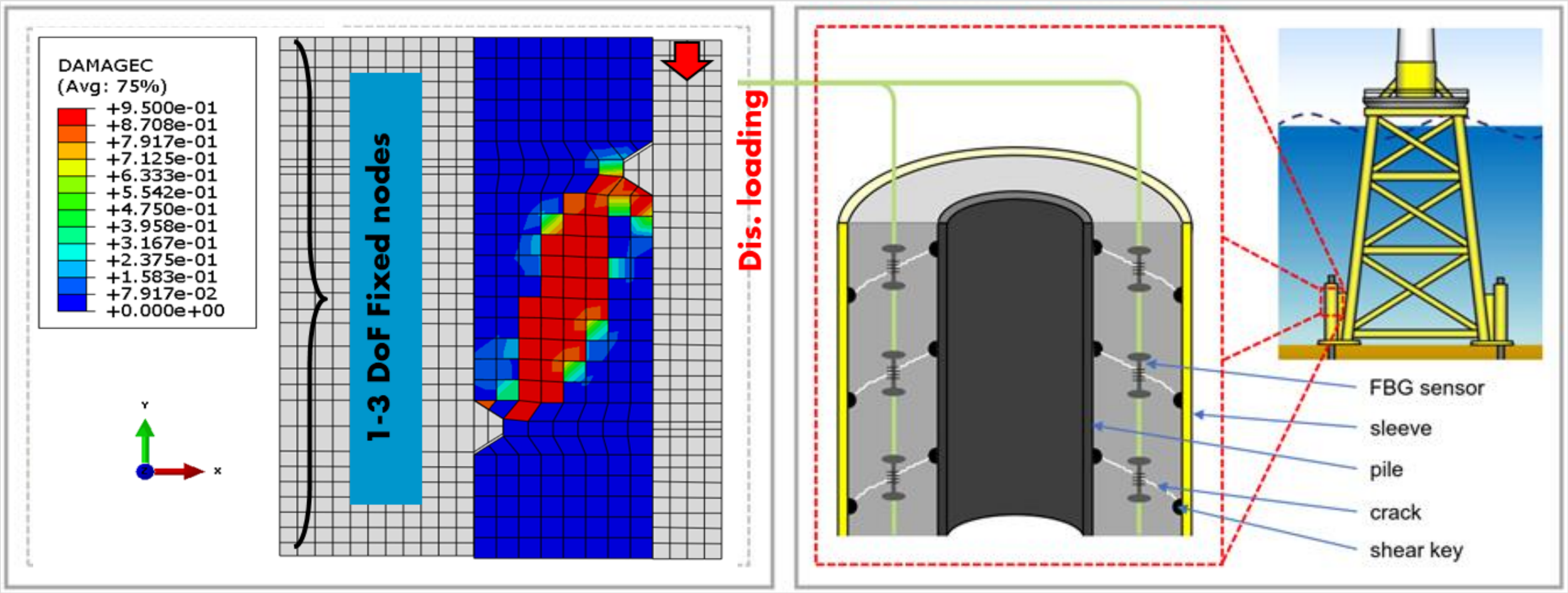






INSTRUMENTATION FOR GROUT MONITORING WITH STRAIN SENSORS

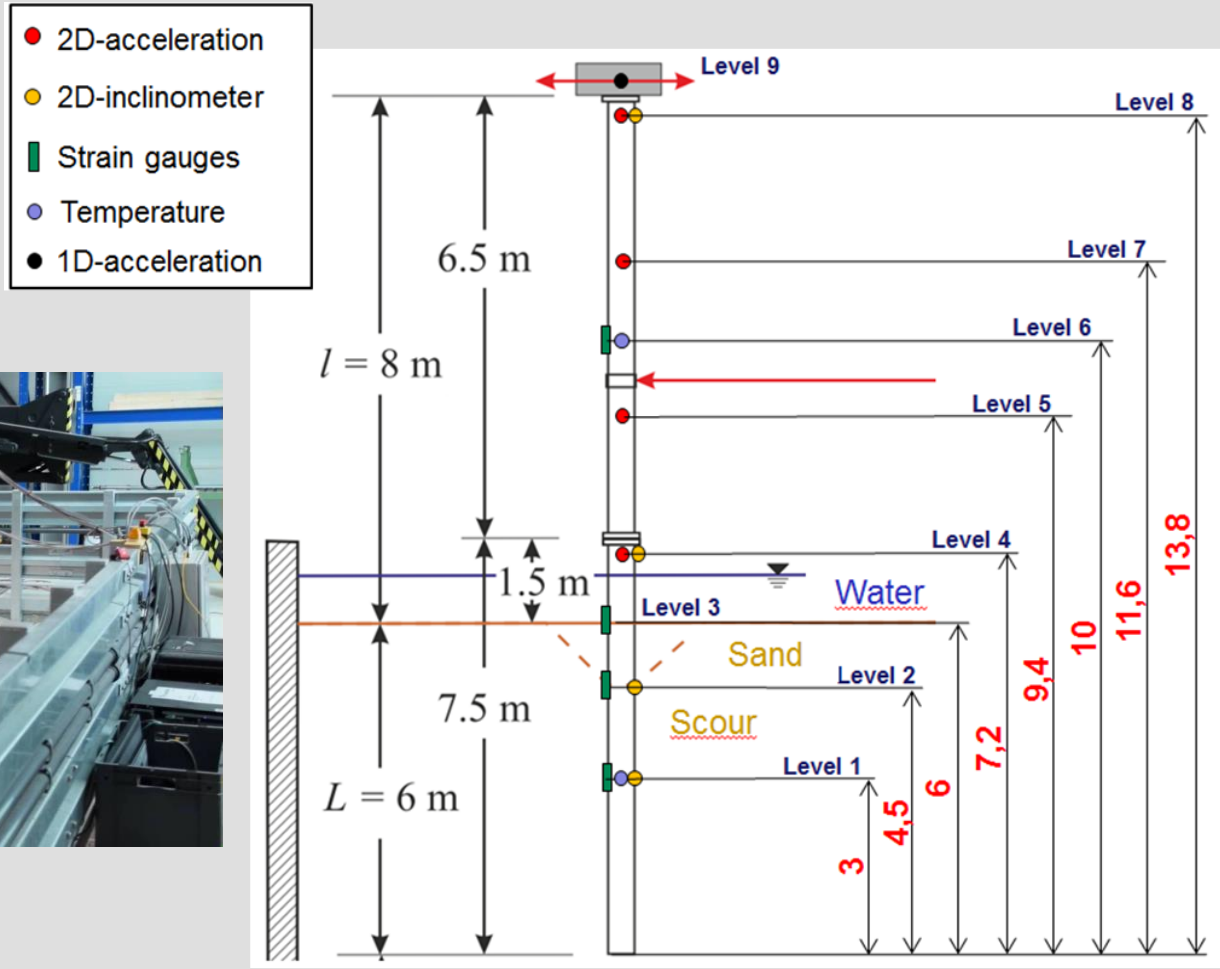
- Strain sensors in the grouted joint
- Transfer of the strain information into an FEM model
- Reverse engineering for the three-dimensional representation of damage
- Assessment of the load-bearing capacity



Quelle: IfB Uni Hannover, Wölfel, F+E-Projekt Grout-WATCH

INSTRUMENTATION FOR GROUT MONITORING WITH ACCELERATION SENSORS

SHM of offshore foundations
Large scale test in TTH



INSTRUMENTATION FOR GROUT MONITORING WITH ACCELERATION SENSORS

Large-scale test in QS-M Grout at TTH

Foundation test pit

Span field: 10/25 kN

Foundation test pit

Span field: 50/70 kN

Foundation test pit

Span field: 90 kN/100 kN

Before, between and after the loads from the hydraulic cylinder in the span field, the structure was excited by the shaker. Therefore the cylinder was removed.

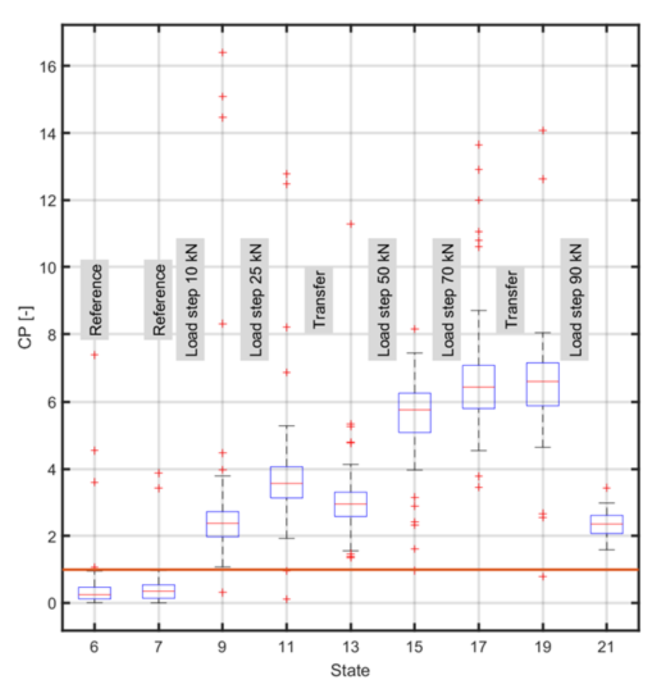


Diagramm 4 TP 2 Spannfeld

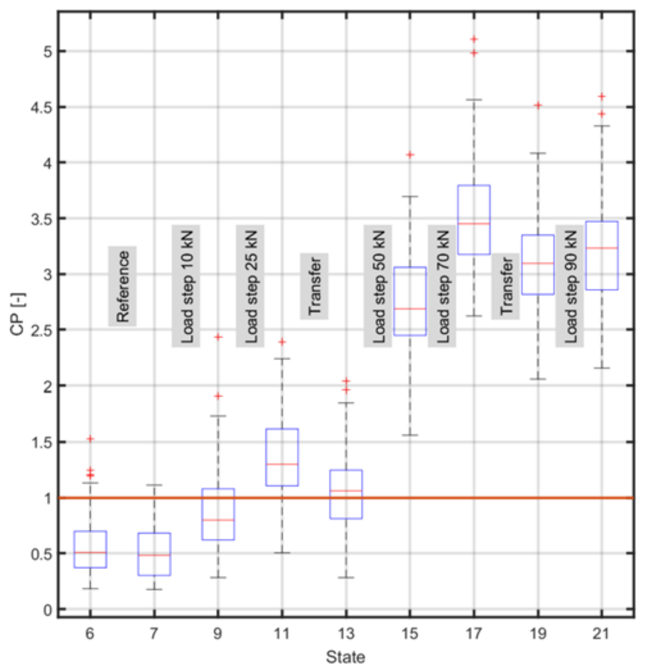


Diagramm 4 TP 2 Spannfeld

Two different types of damage indicators show the change in stiffness; left SSI COV (covariance driven stochastic subspace identification, right AE accumulated energy)

LOSS OF STIFFNESS OF THE PILE

Reproducible structural damage

flange (20 screws) between pile and tower

Loosening of 2, 4 and 6 screws,

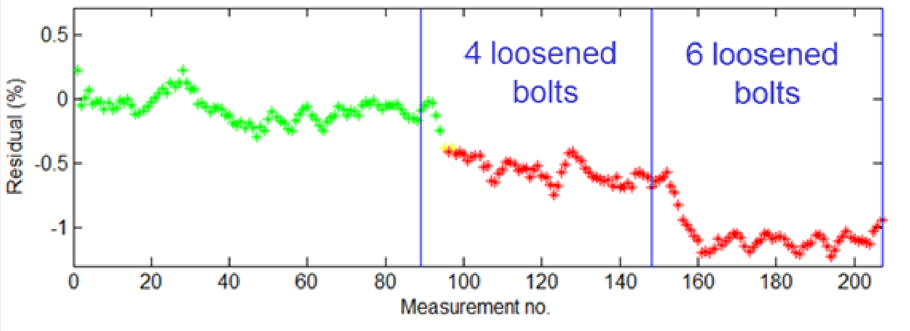
Locknuts

small residual stress

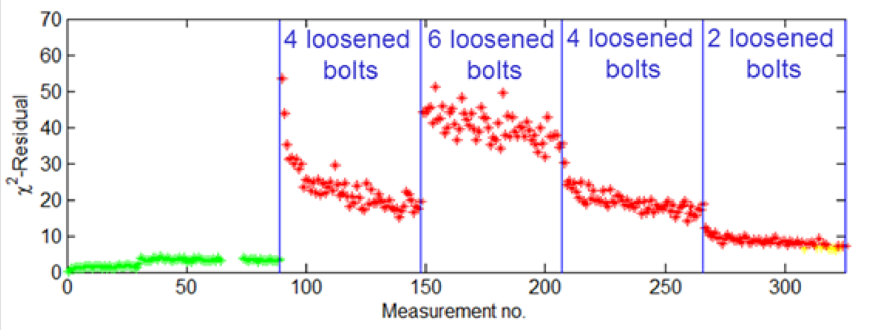
SSI-COV is based on changes in 4 natural frequencies reliably detects 4 and 6 loosened screws

NSFD clearly identifies all three damage states

SSI-COV based indicators

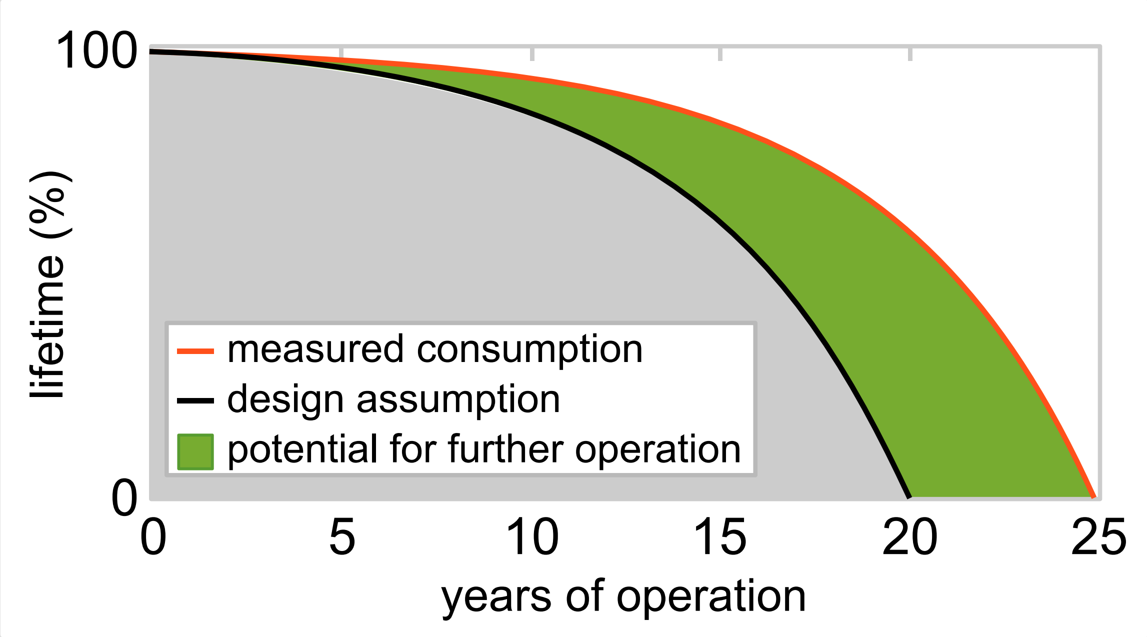


NSFD based indicators



Onshore WTGs are designed for a service life of 20 yea

- Stress according to WTG classes
    - I → 10 m/sec
    - II → 8.5 m/sec
    - III → 7.5 m/sec
- Basis for design and type certificate
- Often unlimited BImSchG permit



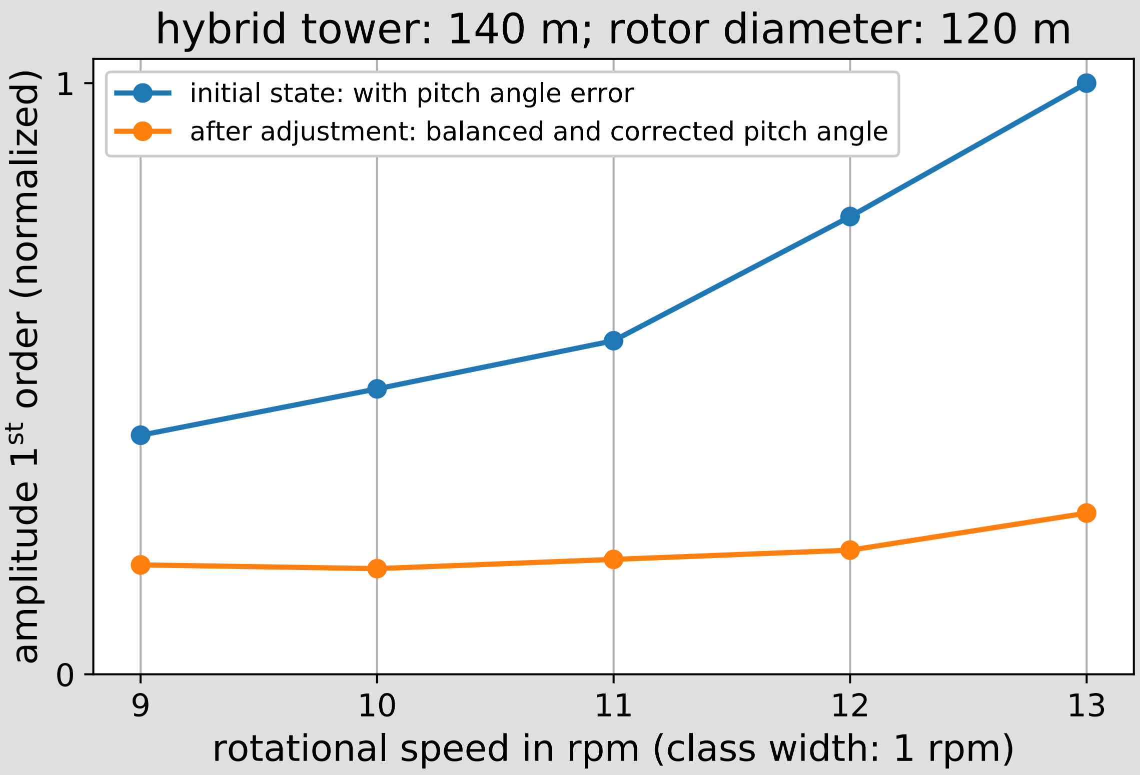
Low wind area → Has a WTG experienced the design loads or is further operation possible?

Up to now, extension of the operating permit on the basis of proxidates, e.g. wind speeds.

But: Operation of a WTG has a great influence on fatigue! → Monitoring

Increase of the damage as a function of the vibration amplitude

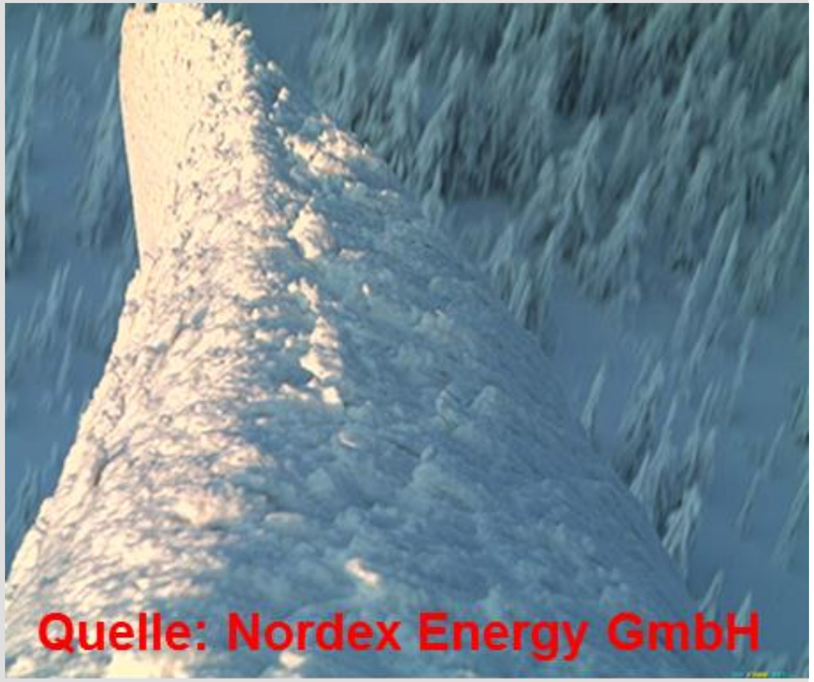
Vibration amplitude	Damage increase (slope Wöhler line m = 3)	Damage increase (slope Wöhler line m = 5)
100 %	0 %	0 %
120 %	73 %	149 %
150 %	238 %	659 %

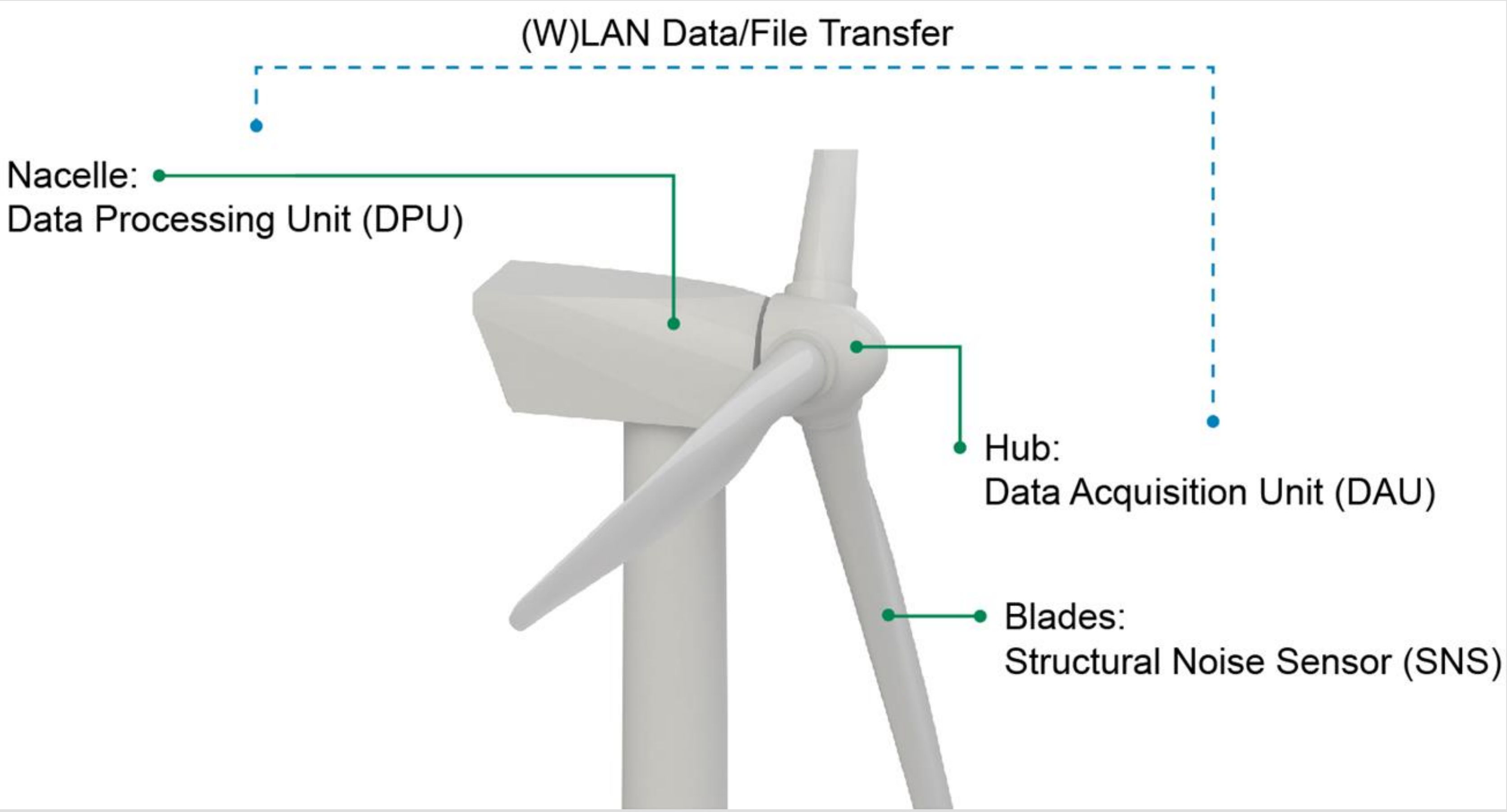


Correct pitch angle adjustment and good balancing significantly reduce the vibration amplitude

INSTRUMENTATION OF TOWER, NACELLE AND ROTOR

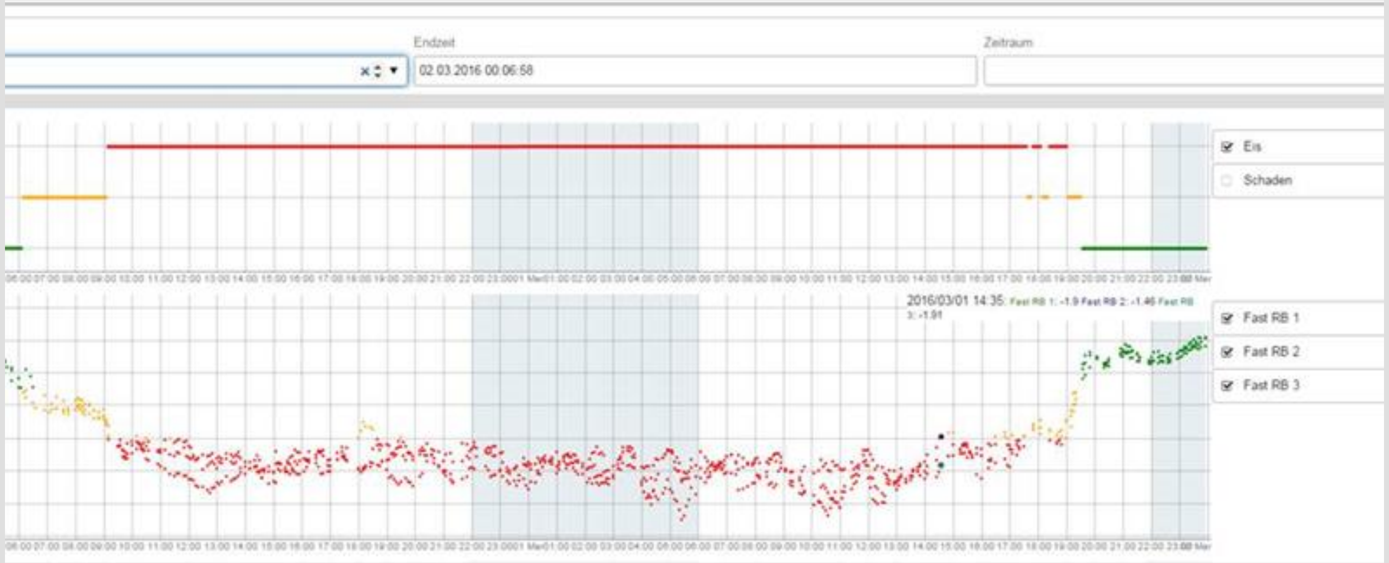
Rotor blade:
Ice detection with IDD.Blade®





ICE DETECTION WITH IDD.Blade®

Weak ice on the trailing edge, 29.02.2016, Bucheck WP



POPULATION MONITORING

Plant optimization → deviating behavior of an individual

- Performance
- Vibration level

Requirements

- All monitoring objects are equipped with SHM systems
- The SHM systems are capable of communication and send messages about the respective status of their monitored object
- All characteristics are constantly compared with each other

Two different versions:

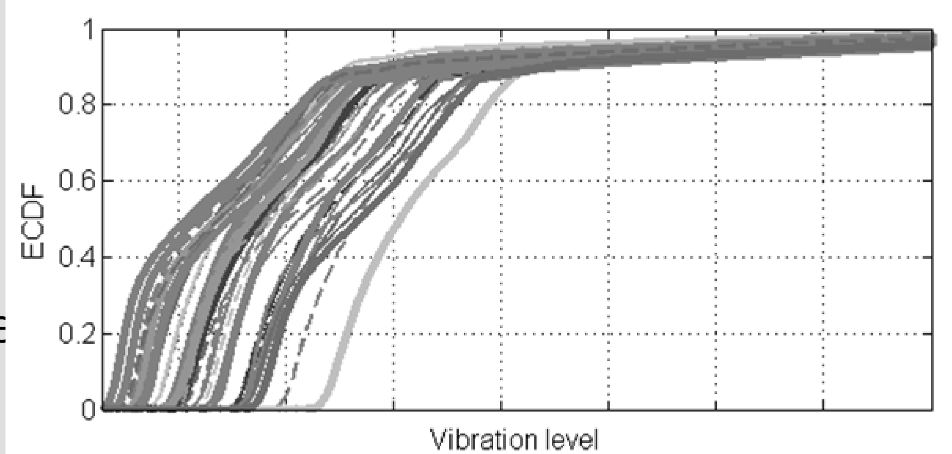
1. The population/fleet is monitored by a monitoring center; all individuals in the area of the monitoring center are compared with each other; we speak of centralized fleet monitoring.
2. There is no monitoring center. All monitoring objects constantly compare themselves with their neighbors and determine whether they are better or worse. We speak of decentralized fleet monitoring.

POPULATION MONITORING USING THE EXAMPLE OF ROTOR BLADES

- Comparative monitoring of a large number of rotor blades of the same type from one production facility at different locations in different wind farms.
- The monitoring results were compared for more than half a year on the basis of SHM.Blade® from Wölfel.

The individual blades show a different vibration level. Reasons this are deviations in stiffness, mass, pitch angle, aerodynamic shape, windward and leeward effects in the park, mass, aerodynamic imbalances etc.

The vibration level of a blade has a direct relation to its lifetime. This makes it possible to make a statement about the lifetime consumption of a blade.



Probability of occurrence of an RMS value on different rotor blades

Dr. Andreas Nuber
Tel.: +49 931 49708-365
E-Mail: nuber@woelfel.de

Wölfel Group
Max-Planck-Str.15
97204 Höchberg / Germany

E-Mail: info@woelfel.de

www.woelfel.de

Tel.: +49 931 49708-600
Fax: +49 931 49708-650