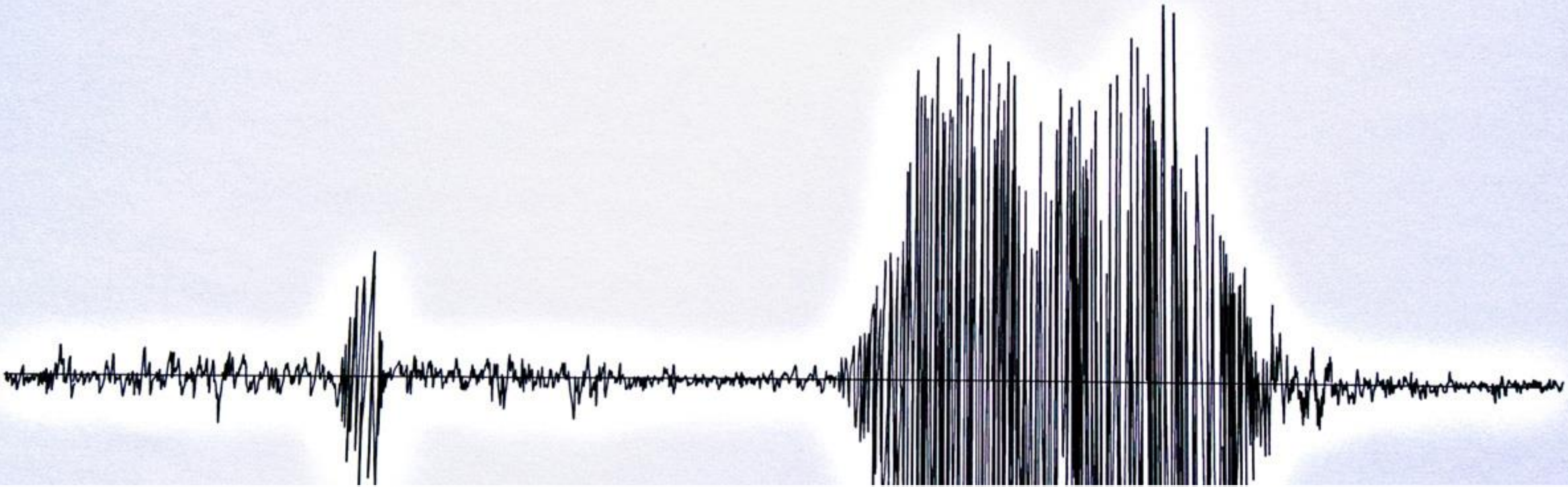


H. Friedmann, P. Kraemer, C. Ebert:

UnderwaterINSPECT – Structural Health Monitoring of Offshore Foundations

Wölfel

UnderwaterINSPECT – Structural Health Monitoring of Offshore Foundations

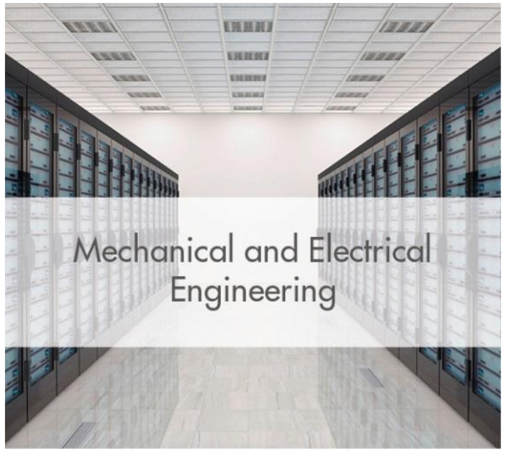
H. Friedmann, P. Kraemer, C. Ebert
Wölfel Engineering GmbH + Co. KG

5th COST TU1402 Workshop
Technical University of Denmark
August 24-25, 2016

Gliederung

What are we actually doing?

In which industries are we currently active?

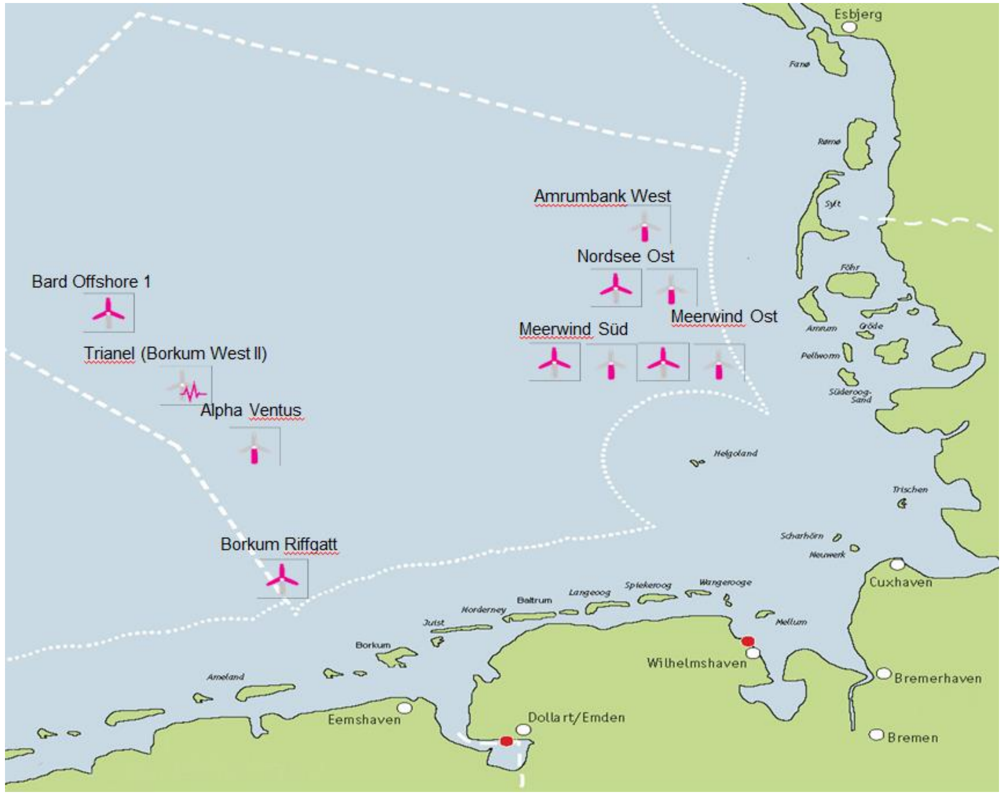


Wölfel's References in Offshore Wind

Blades: TPI / WKP / Inspection

Monitoring Tower /
Foundation / Grouts

Vibration Control



2. Introduction

Extremely high operational demands due to a complex superposition of cyclic and stochastic dynamic loading from

- Wind
- Waves
- Operation

Impact on

- Global stability
- Weld seams

- Failure of foundation is possible
- Regulations of BSH (German maritime authority)
- Support structures (tower, foundation) have to be revised with respect to corrosion, cracks, scouring, etc.
- Every tenth plant must be equipped with an SHM-system (2007), frequent inspections are required (2015)

→ Due to cost a reduction of inspection efforts is necessary!

Mode of Operation of a vibration-based SHM System

Basic principle of the SHM system is the analysis of the structural response due to operational and environmental vibrations.

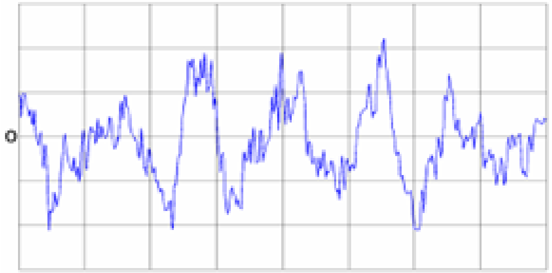
The linearized structural behavior can be described by the **equation of motion:**

$$\mathbf{M}\ddot{\mathbf{y}}_t + \mathbf{D}\dot{\mathbf{y}}_t + \mathbf{K}\mathbf{y}_t = \mathbf{u}_t$$

Mass **M**, Damping **D** und Stiffness **K** govern the dynamic behavior of the foundation.

Structural vibrations are an indicator of

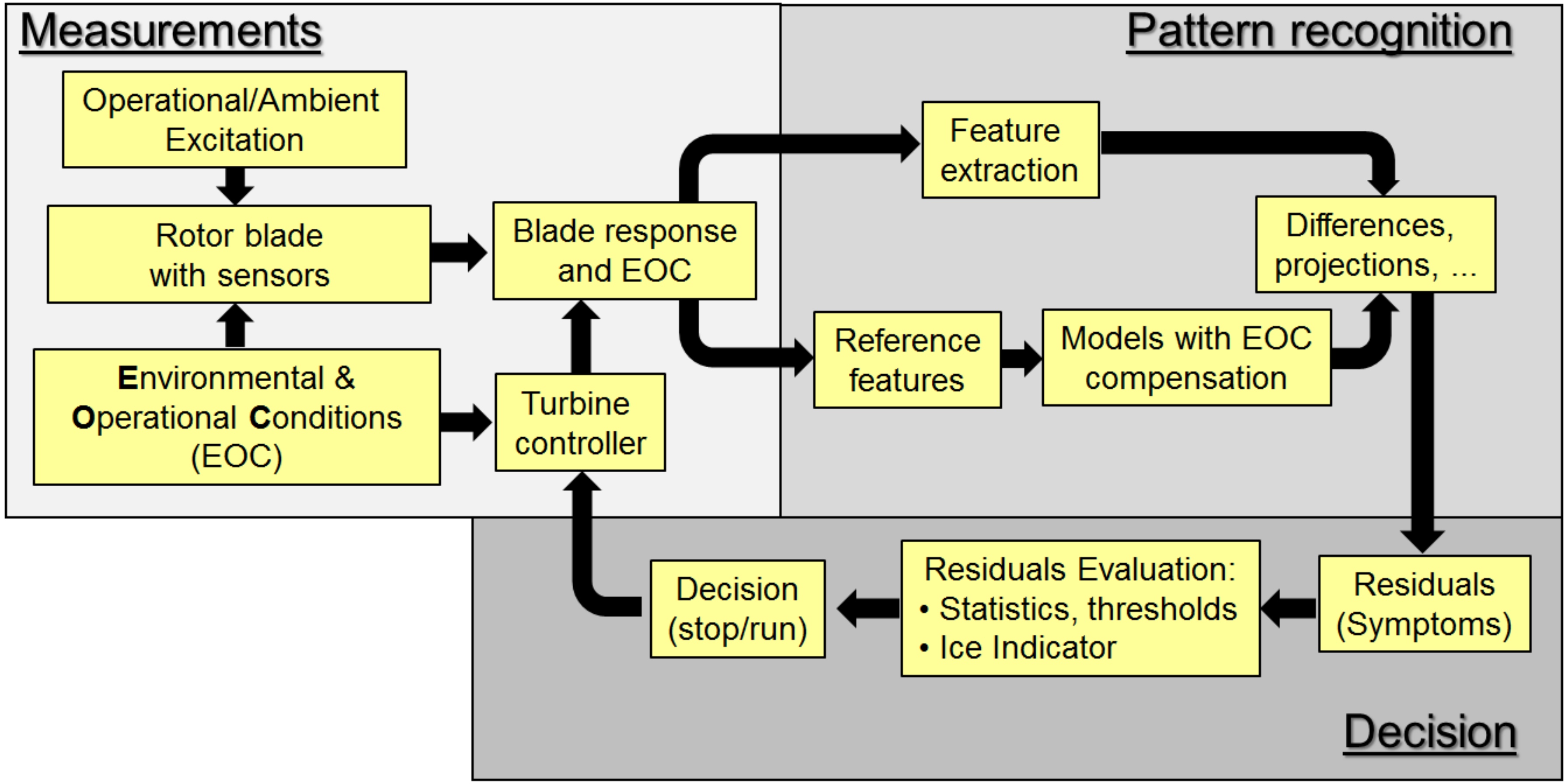
- stability,
- stiffness,
- wind and wave loads,
- operational loads,
- mode of operation of a turbine.



Measurement of the structural response of a rotor blade

The structural response can be measured in the form of deformations, vibration velocities or accelerations.
However, the frequency changes are very small:: 0,5 %… 1 % → 0.005 Hz … 0.01 Hz

The Method


Measurements
Pattern recognition
Operational/Ambient Excitation
Rotor blade with sensors
Environmental & Operational Conditions (EOC)
Blade response and EOC
Turbine controller
Feature extraction
Differences, projections, ...
Reference features
Models with EOC compensation
Residuals (Symptoms)
Residuals Evaluation:
• Statistics, thresholds
• Ice Indicator
Decision (stop/run)
Decision

Damage Indicators

Stochastic mathematics: Two Stochastic Subspace Identification (SSI) algorithms:

Covariance-driven Stochastic Subspace Identification algorithm, SSI-COV

Use in conjunction with output-only modal analysis or operational modal analysis, OMA
Low order stochastic state space models derived from measured time-histories. Changes correspond to changes in the modes of vibration.

Null Space-based Fault Detection algorithm, NSFD

High order stochastic state space models derived from measured time-histories.

NSFD method is more sensitive to structural changes than SSI-COV, but at the same time also to changes in the EOC. Therefore, the compensation of the ambient conditions is even more challenging than in SSI COV.

Objectives

Test of measurement technology → basis for the system development to follow

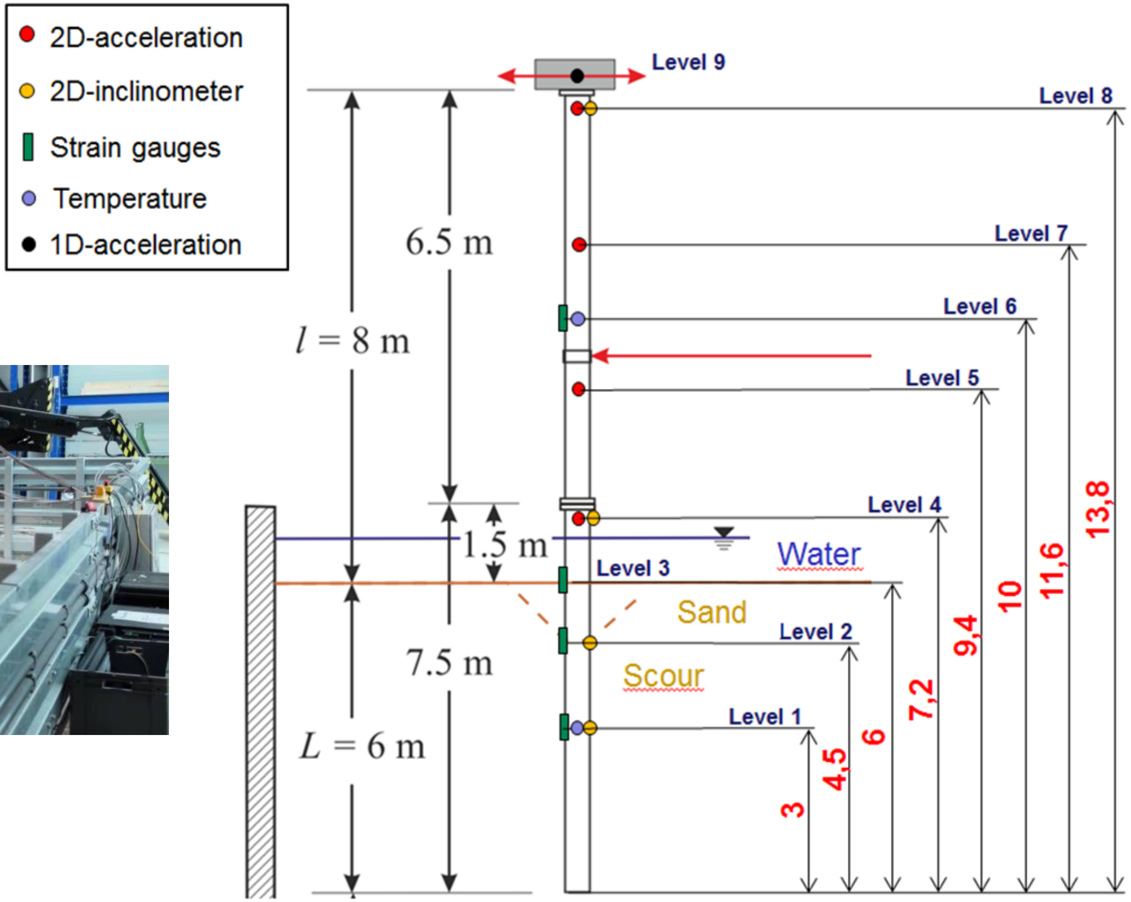
Measuring data from

- undamaged foundation,
- operational loads,
- peak loads,
- changes in environmental conditions,
- damage,

serve as a basis for the development of automatically operating algorithms for damage detection, for the compensation of EOC and for the determination of the sensitivity of the method. The following measurements were performed:

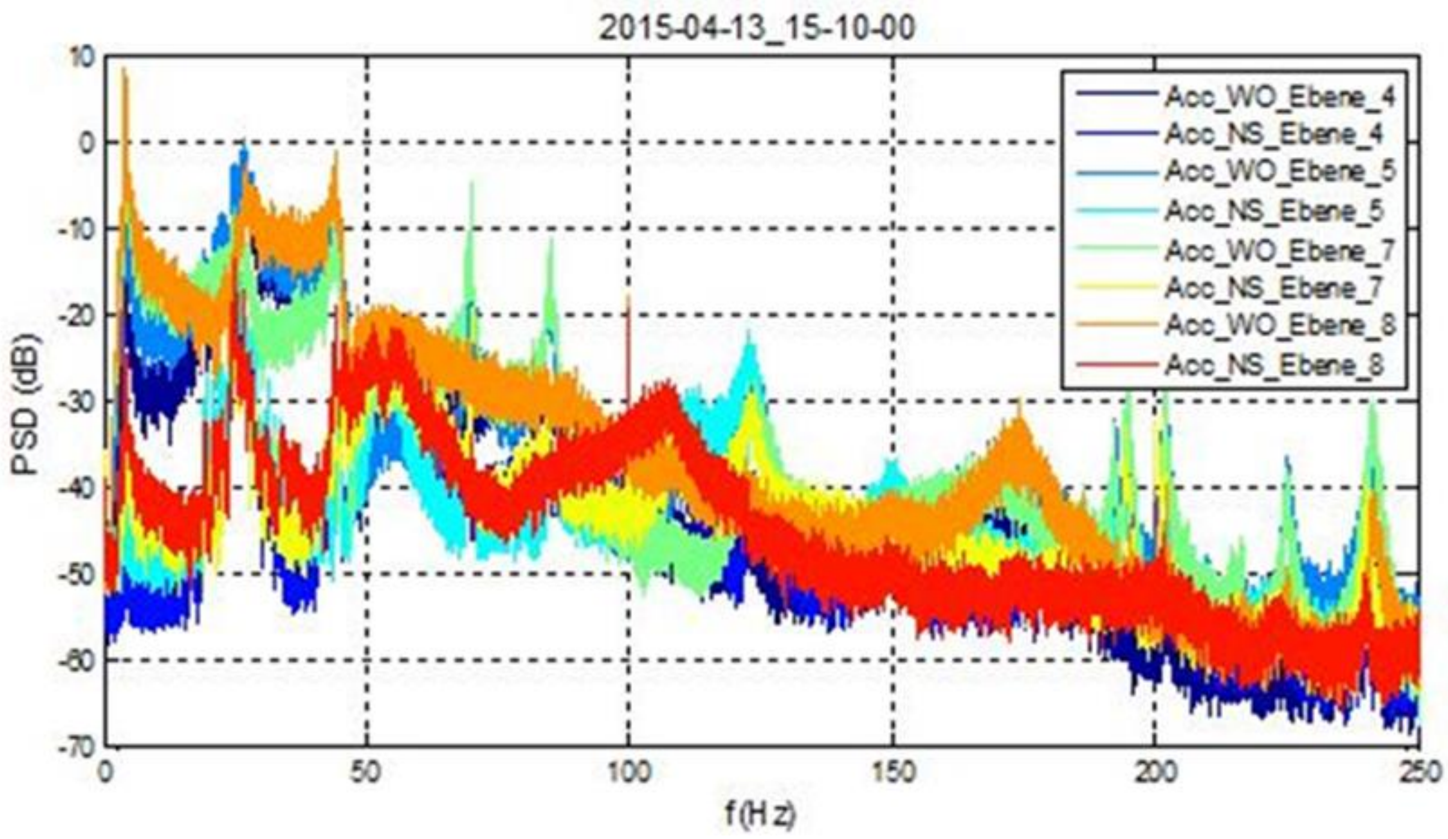
- Reference measurements, at the same time observations to soil degradation,
- load variations, changes in the EOC,
- loss of stiffness of the supporting structure, damage,
- influence of marine fowling, changes in the EOC,
- scouring, damage,
- misalignment by extreme loads, damage.

Experimental Set-up



Reference measurement and soil degradation

- Excitation by a shaker
- Remote control of the experiment
- Force: 400 N → 350 N → 250 N RMS
- Power spectral density
  Structural response due to excitation with white noise from 2 to 50 Hz



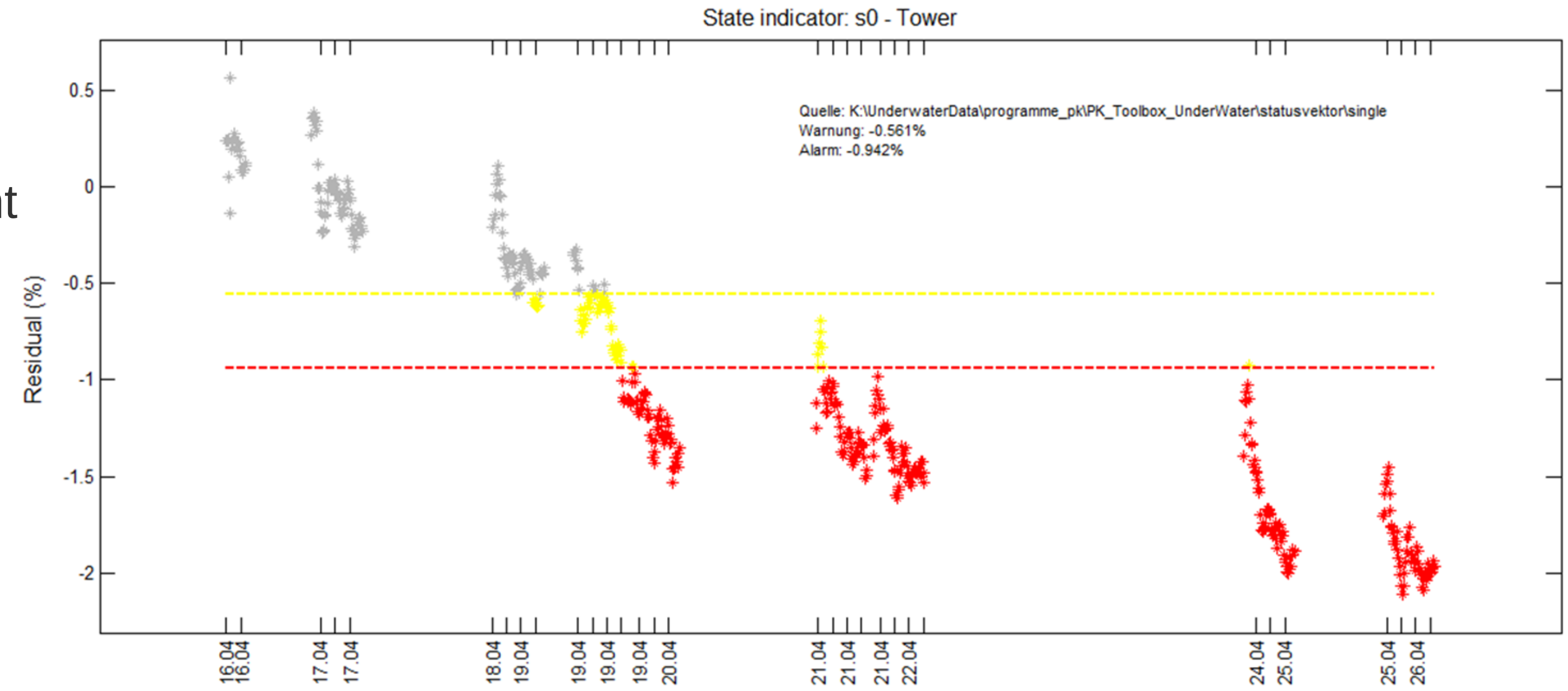
Soil Degradation

Reference measurement shows significant changes in the first natural frequency of the pile at 4,3 Hz.

M. Link 2015: Hardening of the sediment however piles are rammed!

Soil behavior is specific to the experimental set-up
→ **Initial soil degradation**

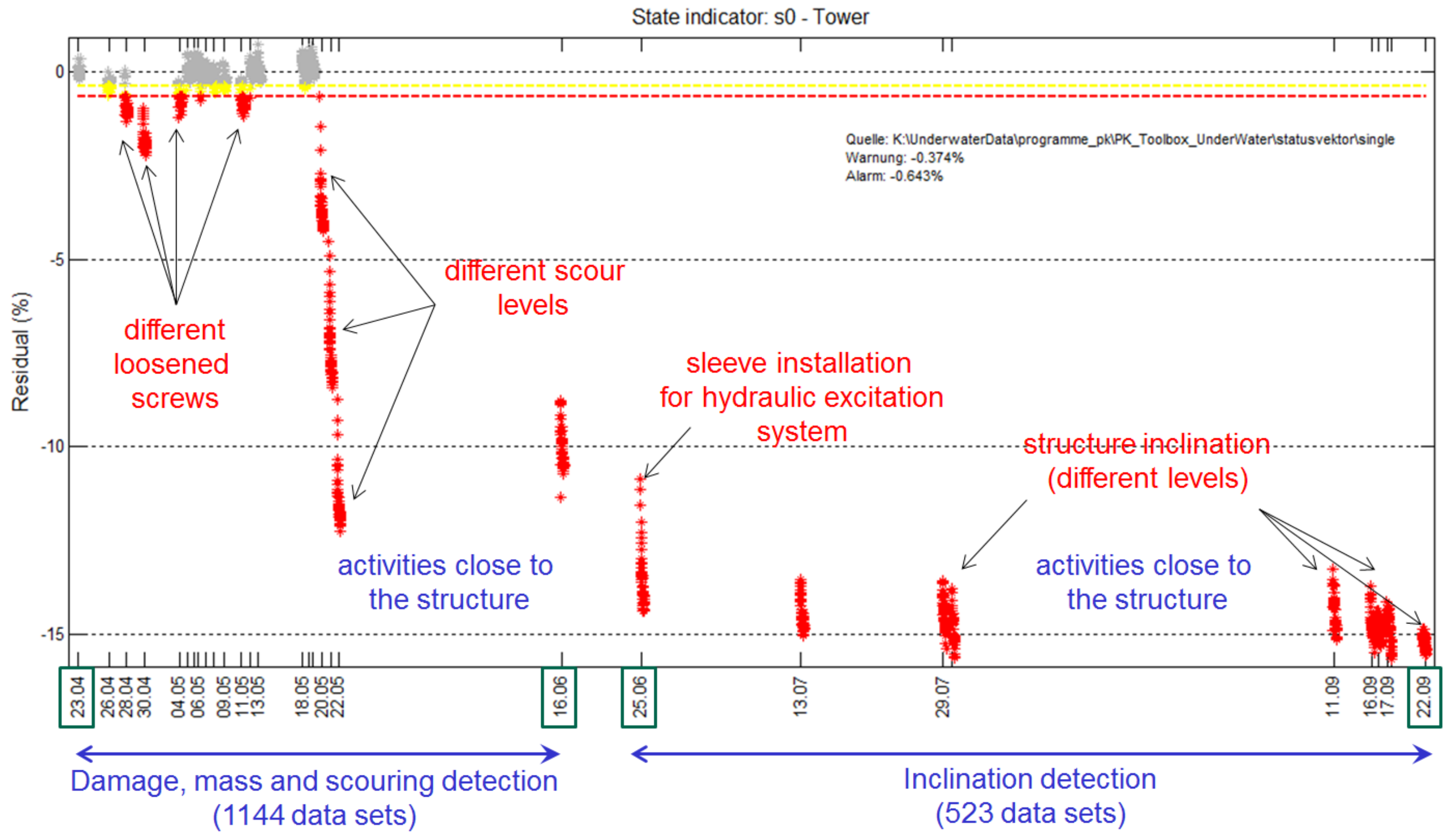
- Monopile installation by vibrations
- No time for settlement
- No water pressure
- Incomplete water saturation of the sediment
- Higher frequencies



Sensitivity with regard to Stability of the Foundation

Soil degradation and scouring obscured all other changes in the signals

→ For compensation specific signal analysis methods are necessary



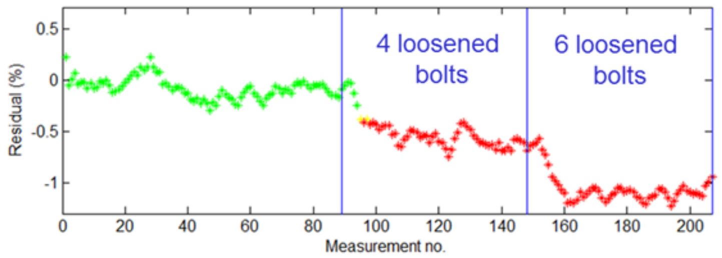
Loss of Stiffness with the Pile

Reproducible structural damage
is modelled by a flange with 20 screws
between pile and tower
Loosening of 2, 4 and 6 screws,

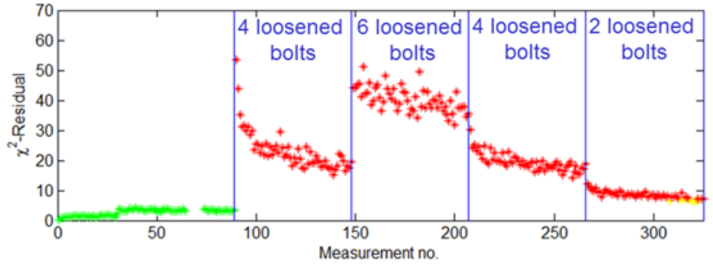
SSI-COV is based on the analysis of 4 natural frequencies; safe detection of 4 and 6 loosened screws.

NSFD is able to detect all damage levels with 2, 4 and 6 screws.

SSI-COV-based indicator



NSFD-based indicator



Fouling

Restricted possibilities to simulate fouling with an experimental set-up like in TTH!

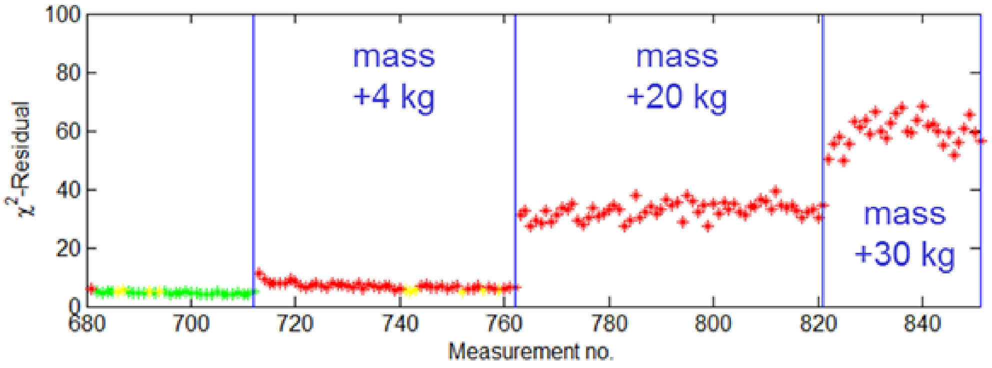
Special case: fouling in the tidal reach with low water.

Bio mass is hanging in the air → additional mass of 4, 20 and 30 Kg on a structure with a mass of about 1 t

SSI-COV is not able to detect such small changes of the mass satisfactorily

NSFD-indicator is able to detect all changes

Additional mass of 4, 20 or 30 Kg



NSFD-indicator

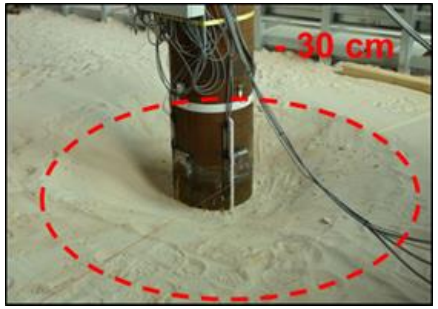
Scouring

Scouring changes the depth of embedding into the sediment; the contact region between pile and sediment is reduced; experiments with 30, 60 and 80 cm depth of the scour.

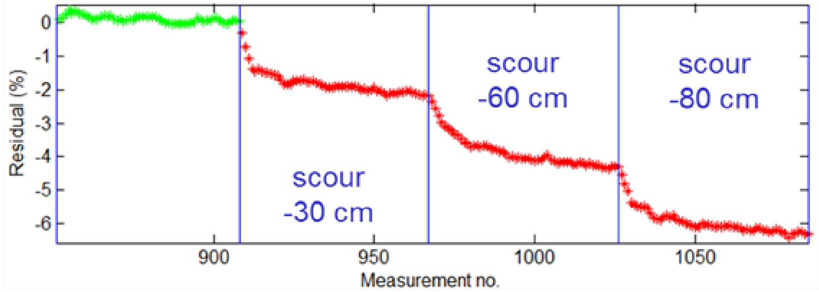
Changes in the boundary conditions of a cantilever beam have significant influence on natural frequencies
→ Initial soil degradation
→ Scouring of 5 cm depth can be detected!

Both indicators SSI-COV and NSFD are able to detect scouring very well

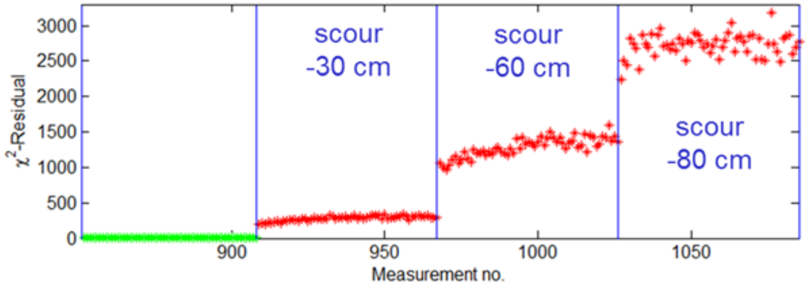
Problem: Obscuring other changes in the signals



Depth of scour 30 cm



SSI-COV-indicator



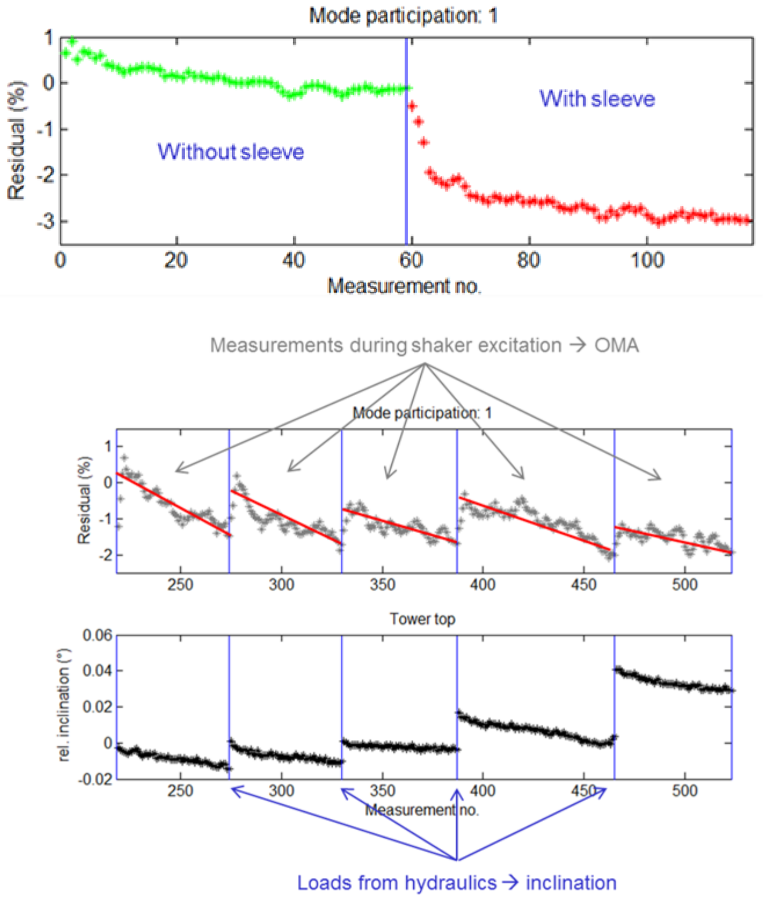
NSFD-indicator

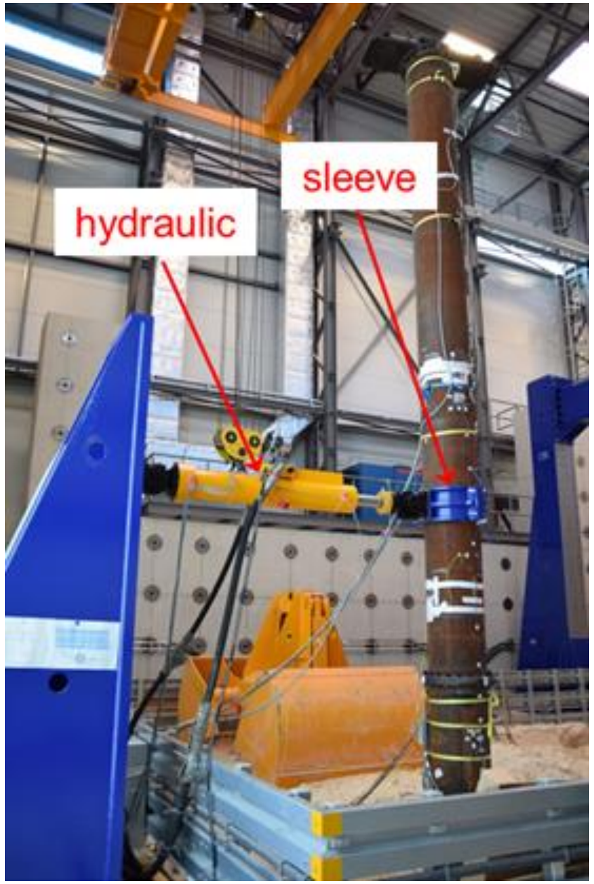
Misalignment

Hydraulic forces for the simulation of maximum loads like gusts or waves with a 50 year recurrence period

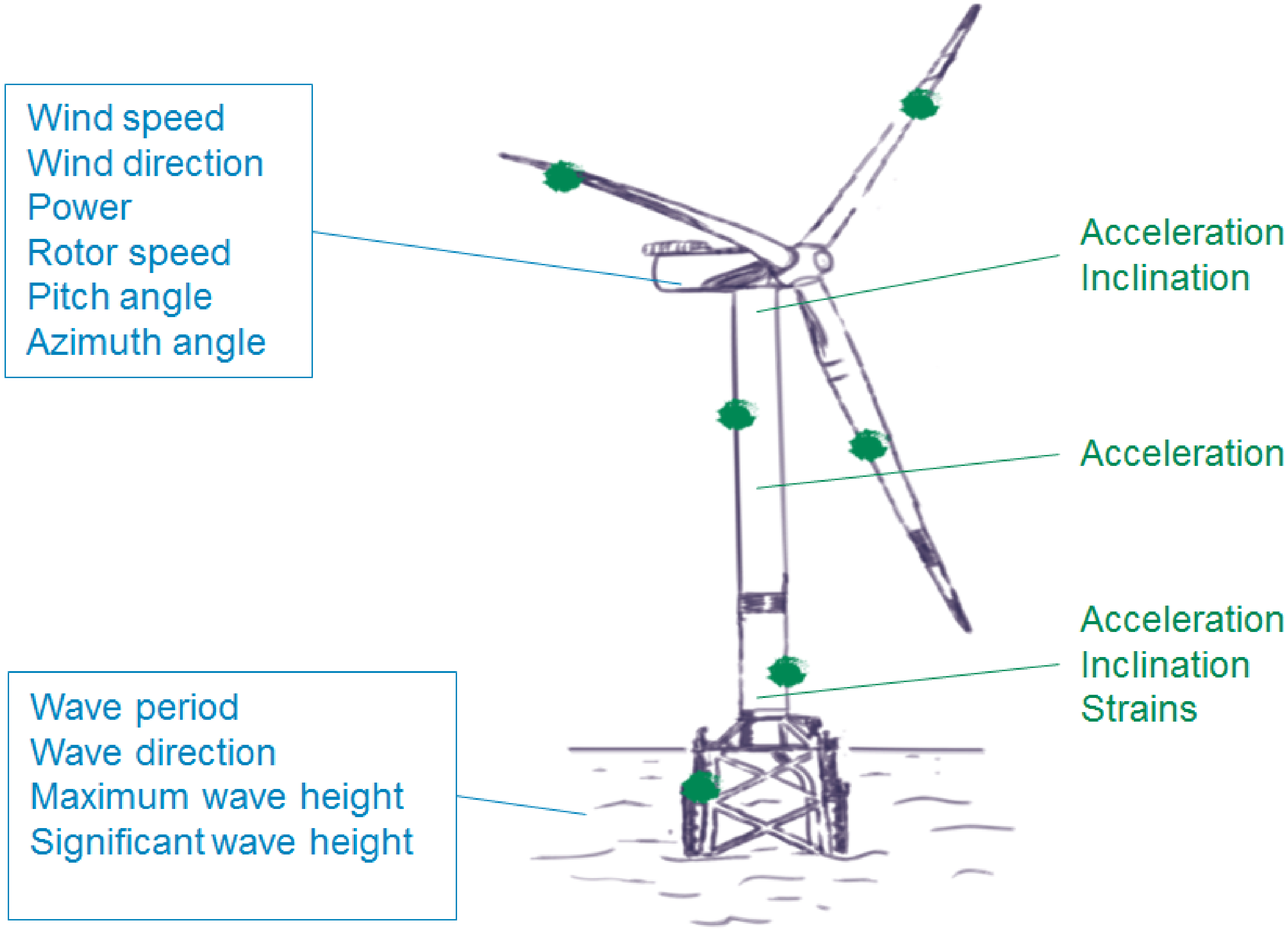
Changings within the mechanical system are detected by SHM

It is possible to detect a misalignment of the pile using accelerometers; however, it is easier to use an inclinometer





5. Wölfel's SHM-System for Foundation Monitoring



6. Summary

- Foundation structures of offshore wind turbines have to be monitored for their stability.
- Vibrations are ideal indicators of structural behavior and different states of the structure.
- In a large-scale experiment at TTH basic tests were performed on a foundation structure.
- Based on the measured data a lot of algorithms were developed and system tests were conducted.
- With SSI-COV and NSFD, stochastic mathematics provides highly suitable damage indicators which are able to detect
    - soil degradation,
    - loss of stiffness,
    - fouling,
    - scouring,
    - misalignment.
- Based on the findings, Wölfel’s SHM system for foundation structures was developed.

7. Acknowledgement

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