How to Use “Structural Intelligence” for Assessment of Offshore Wind Foundations and Reduction of Inspection Cost
Motivation

Periodic subsea inspections on offshore monopile and jacket foundations are expensive.

More efficient solution:
- Gather data from Structural Health Monitoring (SHM) and Environmental and Operational Conditions (EOC)
- Perform data analysis to identify system changes and damages (inclination, frequencies, scour, ...)
- Streamline Periodic Inspections (PI) with a Condition Based or Risk Based Inspection approach (RBI)

→ **Reduce Operational Expenditures (OPEX)** as well as **Levelized Cost of Electricity (LCoE)** and make structures **more safe and reliable** due to Structural Intelligence
Economic benefit with Risk-Based Inspections

Risk-Based Inspections (RBI) can support decision-making with:
• focus on finding **optimum cost**
• respecting the required reliability.

How can Structural Intelligence contribute to reach the optimum?

What is “Structural Intelligence”?

Detailed knowledge about the structural health, gained from short term and long term monitoring data.

Structural mechanic properties (*Structural Analytics*) linked with Environmental and Operational Conditions (*EOC Analytics*) can be used as reliable foundation for diagnoses and prognoses.
What does „EOC Analytics“ mean?

For the correct interpretation of structural dynamic parameters, environmental and operational conditions need to be clustered using EOC Analytics. For example, classification of fatigue loads w. r. t. wind speed and direction can facilitate extrapolation for extended timespans.

**Method**

**Statistics**

**Typical classification**

Rotor speed, power, operational state, wind speed, wind direction, waves

What does “EOC Analytics” mean?
Determination of the structure’s health based on structural dynamic assessment parameters.

**Typical measurement (input)**
Acceleration, inclination, strain, displacement

**Methods (calculation)**
Statistics, structural dynamics, FEM

**Typical assessment parameters (output)**
Vibration RMS, modal parameters ($f$, $\delta$, $\psi$), fatigue loads, max. loads, remaining lifetime
Merge input parameters in Structural Health Monitoring (SHM) system

Mechanical model of the structural components for data analysis

**EOC Analytics**
- Wind speed
- Wind direction
- Power
- Rotor speed
- Pitch angle
- Azimuth angle

- Wave period
- Wave direction
- Maximum wave height
- Significant wave height

**Structural Analytics**
- Acceleration
- Inclination

- Acceleration
- Inclination
- Strain
Example SHM.Foundation hardware and sensor layout

Standard configuration of SHM.Foundation for a small number of wind turbines to validate models. Instrumentation of remaining WTGs with basic version to enable fleet management.

Abbreviations:
- WTG – Wind Turbine Generator
- OSS – Offshore Substation
- EOC – Environmental and Operating Conditions
- DAU – Data Acquisition Unit
- Acc – Acceleration sensor
- Incl – Inclination sensor
- Strain – Strain gauge sensor
Example wind farm layout with SHM.Foundation

WTG 1: standard

WTG 2: basic

WTG 3: basic

WTG 4: standard

WTG 5: basic

WTG 6: basic

WTG 7: basic

WTG 8: basic

WTG 9: basic

WTG 10: basic

WTG 11: basic
Assessment of SHM vibration data

Continuing exceedance of threshold values is an indicator for damages or an erroneous operational condition.

→ Measured RMS values can trigger warnings and alarms.
Inclination at Transition Piece (TP) should stay within design boundaries.

- Detect changes, trends and offset of inclination for EOC correlated data.
Assessment of WTG modal parameters

Structural Analytics with identification of modal parameters and stabilizing methods to enable tracking of frequencies.

• Drop and offset in first natural frequency due to maintenance (non-operating turbine) in August (dots: 10 Min. data points, blue line: 14-day average)

➔ Detect structural changes, taking into account expert knowledge and indication where to look for failures.
Real-time lifetime consumption

Assessment of total damage over all tower & angle sectors

Load Monitoring

Bending Moments

Digital Twin

ACC 01
Tower Top

ACC 02
Inclination
Strain

Count

0,0%
1,0%
1,6%
1,7%
1,9%
2,0%
2,0%
2,2%
2,0%
0,0%
0,0%
2,1%
1,6%
1,3%
1,0%
1,1%
1,9%
1,4%
0,0%
Digital twin is bridging gap between design and real structure

A **digital twin** is the virtual representation of the real wind turbine and is used to predict the mechanical system behaviour. It comprises a mechanical FE-model of the wind turbine.

With **virtual sensors**, the wind turbine behaviour can be predicted at locations without physical sensors and for additional measurement variables (e.g. strain $\rightarrow$ bending moments).

With **model updating**, the as-built condition of the wind turbine and structural changes are always considered.
Lifetime assessment with measured data for entire wind farm

Lifetime consumption
- using measured data
- correlated with EOC data

→ Consideration of normal operation and extreme events, prediction possible

<table>
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<tr>
<th>Farm</th>
<th>WTG-No.</th>
<th>Year</th>
<th>DELR X [kNm]</th>
<th>DELR Y [kNm]</th>
<th>Max Acc [m/s²]</th>
<th>Max Displ [m]</th>
<th>Mean Acc [m/s²]</th>
<th>Mean Dis [m]</th>
<th>Alarm-Time [%]</th>
<th>Warning-Time [%]</th>
<th>Daily DELR Max. (Ref. 1d) [kNm]</th>
<th>Calculated Lifetime Consumption [kNm]</th>
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Live access tool to support decision-making

Wölfel live monitoring portal with time history of
- Sensor data (accelerations, inclination, ...)
- Result data (eigenfrequencies, moments, ...)
- Warnings and alarms
Summary – “Structural Intelligence”

Analysis of environmental data
Wind, water, wave

Analysis sensor data
Online Alarms
Strain, acceleration, inclination

Analysis of structural behavior
Inclination, RMS values, natural frequencies

Design validation
Lifetime assessment
Screening of failures with risk-based approach

Risk-based approach is a tool to classify failure modes and support decision-making.

• Risk = Probability of Failure (PoF) x Consequence of Failure (CoF)

Risk-based approach indicates
• where/what to inspect,
• when to inspect,
• how to inspect.

➔ Identify and prioritize high-risk failures for focused inspection planning.
Economic benefit with Risk-Based Inspections

Risk-Based Inspections (RBI) can optimize inspection cost through

- prioritisation of high-risk failures
- adaptation of inspection intervals for low-risk failures

→ Updating and streamlining of inspection plan with e.g. alerts, trends, failure detection from permanent Structural Intelligence

→ Optimize cost

Risk-Based Inspections (RBI) can optimize inspection cost through

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→ Optimize cost

Increase reliability and reduce failure cost through Structural Intelligence

SHM systems by Wölfel are a proven solution

- Measurement with robust and redundant sensors (focus above water) and modular systems
- Direct communication with turbine control systems
- Automatic data pre-processing and real-time analysis directly in the wind farm
- Automatic alarms and system monitoring, visualization of results in a web portal
- Evaluation, detailed assessment and reporting by experienced experts
### Offshore monitoring references Germany

<table>
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<tr>
<th>Project</th>
<th>Start</th>
<th>Structure</th>
<th>Scope</th>
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<td>2014</td>
<td>Jacket</td>
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<td>Monopile</td>
<td>Data analysis, BSH reporting, fleet Monitoring for all structures</td>
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<td>2015</td>
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<td>Arkona</td>
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<td>alpha ventus</td>
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<td>Jacket and Tripod</td>
<td>Sensitivity study, monitoring concept and hardware design, data analysis</td>
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<td>Helwin Alpha</td>
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<td>Monitoring concept for ZiE**</td>
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<td>Deutsche Bucht</td>
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</table>

*BSH – Bundesamt für Seeschifffahrt und Hydrographie (German Offshore Authority)  **ZiE – Zulassung im Einzelfall (BSH - Single Case Approval)
Do you want to optimize your periodic inspections?

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