Monitoring of wind turbines – bridging industry and research

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Why bridging the „Valley of death”?

Despite a large number of Research & Development projects, only a fraction turns into successful products. The especially important gap spans between a laboratory test as a result of a university project and heavy duty proven product launch.

Happy developers in a lab is only a start… … it needs a lot of time and money to make their system work in a demanding environment
Technology Readiness Level areas during development

- **System Test, Launch & Operations**
- **System/Subsystem Development**
- **Technology Demonstration**
- **Technology Development**
- **Research to Prove Feasibility**
- **Basic Technology Research**

   - **TRL 0**
   - **TRL 1**
   - **TRL 2**
   - **TRL 3**
   - **TRL 4**
   - **TRL 5**
   - **TRL 6**
   - **TRL 7**
   - **TRL 8**
   - **TRL 9**

   - **Advanced Development Programs**
     - **System Specific**
     - **Technology Development and Demo Programs**
       - "Applications Pull"
     - **Research and Technology Base**
       - "Technology Push"

   - **Basic Research**

Valley of Death

- Valley of Death is the time when the government funding has finished, but there is no reliable product which can be offered to customers.
- In most cases it is a period between TRL 4 and TRL 7.
- Required investment is so high, that skeletons of many projects are left here.

- **S&T** ~ TRL 5
- **Valley of Death**
- **Acquisition** ~ TRL 7
How to organize it?

- End user company
- Business as usual
- Spin off company
- New technology development
- Consulting
- Waste of money
- Academia

Understand each other

**Academia**
- Are „mad scientists” type
- Prototype driven
- Learn by doing
- Say „What if”? 
- Nurture infant technology
- Ask: „Can it be done”? 
- Fill the funnel: create new options
- Objective: UNDERSTANDING

**Industry**
- Are boring and no sense of humor
- Requirements driven
- „Do it right the first time”
- Say „Prove it”
- Kill the weak and move on
- Decide: „Should we do it”? 
- Narrow the funnel: increase focus
- Objective: DELIVERY
Agenda

- Who we are?
- Introduction: WT market, designs, and condition monitoring (CM)
- Principles of WT vibration analysis: analyses, resampling, envelope
- How do we annoy you all?
- Variable operational conditions – a major detriment to analyses
- Latest solutions and hot topics
- Unsolved problems – hope of today!

Department of Robotics and Mechatronics

20 permanent staff,
15 PhD students
120 postgraduate students
4 laboratories:
- Structural dynamics
- SHM and diagnostics
- Mechatronics and Robotics
- Numerical modeling and simulation
3 PhD thesis per year
40 MSc thesis per year
Numerous industrial applications

Head:
Prof. Tadeusz UHL
History

- Started in 1992
- 500 employees in the holding (EC Grupa)
- ISO 9001 standard since 1999
- Implementation of engineering and software development projects worldwide
- R&D cooperation with best technical universities from around the world

Selected customers
### Key facts about EC Systems

- 45 people: HW, SW, automation engineers
- Competence center for OEMs
- Specializations:
  - Dedicated systems for industry: industrial software and hardware development
  - Condition monitoring systems
  - Big data, automated data analysis

### Condition monitoring solutions

- VIBTransmitter – single-channel vibration monitoring and protection
- VIBDAQ – from 2 up to 16 channel data acquisition
- VIBex – advanced CMS
- Diagnostic Center for machinery
CMS Industrial implementations

VIBex in the lab: VIBStand2 test bench

Computer controlled continuously changing load and speed
Introduction: WT market, designs, and condition monitoring (CM)

Geared vs. gearless designs

- The most popular design is rotor, gearbox and the generator
  - Relatively lightweight
  - Most components can be standardized

Who we are?

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**Geared vs. gearless designs**

- Another design is rotor driving directly the multipole synchronous generator
  - More expensive, heavier
  - Requires advanced frequency converters and rare earth metals
  - More reliable, considered for offshore farms

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**Monitoring areas**

- There are several areas of monitoring in the wind turbine

  - **Main rotor**
  - **Drivetrain**
  - **Generator**
  - **Tower**
  - **Control sys**
  - **Foundation**
  - **Electric faults**
  - **Field of SHM**
  - **Embedded in CS**

- How do we know that the monitoring is justified?
Introduction: WT market, designs, and condition monitoring (CM)

Analysis of failures in WTs

♦ Distribution of failures by a component

- Electronic: 17%
- Main shaft: 1%
- Brake: 3%
- Other: 3%
- Generator: 3%
- Yaw system: 5%
- Sensors: 6%
- Hydraulics: 6%
- Gearbox: 9%
- Control: 16%
- Electric: 11%
- Pitch mechanism: 11%
- Blade: 9%

♦ Downtime by a component

- Gearbox: 23%
- Generator: 18%
- Main shaft: 9%
- Control system: 16%
- Blades/Pitch: 9%
- Yaw system: 8%
- Sensors: 4%
- Hydraulics: 4%
- Electric system: 3%
- Mech. brake: 2%
- Other: 3%
Maintenance costs

- The costs of maintenance is the key factor
- The lost production is also significant, but less important
- Example of equipment replacement costs (5 MW turbine):
  - Main gearbox: 460 000 EUR
  - Generator: 250 000 EUR
  - Rotor blade: 195 000 EUR
  - Electronic equipment: 14 000 EUR

- Cost of repair is very different for different components

In general, the cost of replacement of epicyclic gearbox on an offshore WT equals its 1-year revenue.
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Principles of WT vibration analysis

Wind turbine description

Kinematics of a wind turbine drivetrain (the most popular setup)

- Rotor speed: 12 - 16 RPM
- Generator speed: 1000 - 1500 RPM
- Gearbox ratio: ~100

- We are interested in typical fault signatures for rotating machinery
Fault signatures

- Raw vibration signal
- Integration and scaling
- Velocity signal
- Velocity spectrum
- FFT
- Broadband (statistical) parameters

- Spectrum
- Resampling
- Resampled signal
- FFT
- Narrowband frequency spectrum features

- Resampled signal
- Demodulation
- Signal Envelope
- FFT
- Narrowband order spectrum features

- Envelope
- Resampled signal
- Narrowband order spectrum features

Order Spectrum

- Accelerometers are used for vibration measurements

Sensor location

- Accelerometers are used for vibration measurements
Sensor types

- All accelerometers are IEPE (ICP®)
- Recommended sampling frequency is min. 20 kHz
- Recommended spectrum resolution is 0.1 Hz, but 0.01 Hz for the main bearing

<table>
<thead>
<tr>
<th>Component</th>
<th>Number of vibration sensors</th>
<th>Frequency range</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main rotor bearing</td>
<td>1</td>
<td>0.1 Hz ... 10 kHz</td>
<td>Radial</td>
</tr>
<tr>
<td>Gearbox</td>
<td>3</td>
<td>0.1 Hz ... 10 kHz</td>
<td>Radial</td>
</tr>
<tr>
<td>Generator</td>
<td>2</td>
<td>10 Hz ... 10 kHz</td>
<td>Radial</td>
</tr>
<tr>
<td>Tower</td>
<td>2</td>
<td>0.1 Hz ... 100 Hz</td>
<td>1 Axial, 1 Radial</td>
</tr>
</tbody>
</table>

- Compulsory process signals are:
  - Rotational speed
  - Output power/ load
  - Wind speed

What does it really look like?

Main bearing

Generator

Wind speed

1.5 MW turbine, Germany pictures by the author
How to get there?

How to climb there?
Who we are?

Introduction: WT market, designs, and condition monitoring (CM)

Principles of WT vibration analysis

How do we annoy y'all?

Variable operational conditions – a major detriment to analysis

Latest solutions

Unsolved problems – hope of today!

Variable operational conditions – a major detriment to analysis

Power and wind fluctuation at nominal speed

Highly fluctuating operational parameters

Low characteristic frequencies (low PG speed)

Additional data acquisition constraints

Continuous verification of acquired data

Selection of samples corresponding to least non-stationary operational parameters

Requiring long records
Definition of operational states

- The task of monitoring can be simplified to the limit checking on a given trend line
- Separate thresholds must be configured for every state

Reality is much harder ...

- Wind turbines work in constantly changing operating conditions
- The main reason are wind changes, which cause variations of speed and output power
- There are two distinct types of WT variability, depending on its control type
Pitch control

- Continuous control of individual blade pitch
- More efficient than stall control
- Less structural loads
- Popular in new designs, but makes monitoring harder

Order analysis

- Example of real signal resampling in Matlab
Resampling of real WT signals

- Best methods use two step interpolation:
  - Sampled time to required time
  - Sampled values to required values
- Signal can be interpolated to any shaft in the system

What to do about the variable OC?

- Before any meaningful fault signatures will be calculated, the signal must be selected and preprocessed
- Selection picks up the quasi-stationary periods
  - Hard for DAQ units

Variation of rotational speed and power of a wind turbine during 10 minutes period
6-channel continuous acquisition (common example):
- 1 signal being read every 10 minutes
- 1 signal being stored every 1 day

The number of all signals acquired in 1 day: \( \frac{24 \times 60 \times 6}{10} = 864 \)
The number of signals stored permanently in 1 day: \( 6 \times 1 = 6 \)

**Existing method**  Store all trend values and store “blindly” selected signals  →  0.7 %

**Author’s proposition**  Calculate trend values form significant signals. Store most significant time signal(s).

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Part 1/5
Signal Validation

Transition from a laboratory channel to real, heavy duty commercial installations

NEW CHALLENGES
• Acquisition selectivity (temporary data storage)
• Need for automatic (on-line) data validation due to numerous signal errors
Absence of Data Validation - Consequences

Consider a Wind Turbine
The majority of signals were corrupted by random external disturbances

PP trend calculated from all registered signals may be considered as random variable

Transient states are frequent sources of false alarms

* transient states were left deliberately

Signal Validation - Problem Identification

Vibration signals

Correct

Valid

Author’s description of „valid” signal:
- mandatory visual continuity
- required certain complexity
- rational amplitude levels
- imperceptible quantification
- sufficient „sharpness” of the time waveform shape
- physically justified sudden signal changes,
- expected mean value

Part 2/5

REB diagnostics

Signal envelope – how it works?

- How a specific local fault can be detected and localized?

<table>
<thead>
<tr>
<th>Rotational Speed</th>
<th>26.96 [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental (SF)</td>
<td>144.4 [Hz]</td>
</tr>
<tr>
<td>2nd harmonic</td>
<td>288.8 [Hz]</td>
</tr>
<tr>
<td>3rd harmonic</td>
<td>433.2 [Hz]</td>
</tr>
</tbody>
</table>

envelope spectrum
Amplitude demodulation – the recipe

- Key for the success of the method is proper selection of the demodulation band
- Problem often referred to as OFB (Optimum Frequency Band)
- The figure below presents group of real spectra

Where are resonance frequencies? .3 kHz, .7 kHz, .8 kHz, .9 kHz, 3 kHz, 4 kHz, 6 kHz, 7 kHz, 11 kHz
How to select optimum frequency band?

- **BPFO = 144.4 Hz**

  - **BW = 200Hz**
  - **BW = 400Hz**
  - **BW = 500Hz**
  - **BW = 1000Hz**
  - **BW = 3000Hz**
  - **BW = 4000Hz**

- Narrowing
- Widening

**dB spectra comparison**

- Method based on comparison of dB spectra
- Pros:
  - Simple to implement
- Cons:
  - Low accuracy
  - Requires high energy of fault signals
  - Different spectrum estimation methods yield different results
Spectrogram

- Method based on analysis of 2D time frequency map

- Pros:
  - Able to present long period high frequency modulations

- Cons:
  - Hard to interpret
  - Analysis of a 2D map can not be automated easily
  - Several configuration parameters

Part 3/5

New OFB techniques
**Fast kurtogram**

- Method based on filter bank estimator of the Spectral Kurtosis
- Pros:
  - Can be used for BSS (Blind Signal Separation)
  - Clear results
  - Can be further enhanced
- Cons:
  - Vulnerable to random peaks
  - Sophisticated algorithm, long computation time

**Protrugram**

- Method based on kurtosis of spectrum
- Present the kurtosis of the NEA as a function of filter center frequency
- Proposed by Jabłoński & Barszcz (MSSP, 2011)

- Pros:
  - Immune to random peaks
  - High accuracy

- Cons:
  - Sine components introduce disturbances to the result
  - Higher harmonics of the sought signal reduce the fault signature
We proposed the generalized version of spectral correlation (coherence) - Modulation Intensity Distribution. Proposed method compares carrier frequency components with both symmetrically distributed sidebands.

Relation between MID and Spectral Coherence may be described as follows:

\[
\text{MID(PSCoh)}(f, \alpha) = \Delta f \left( \frac{SC^2(f + \alpha)}{\sqrt{SC^2(f + \alpha)SC^2(f)}} \frac{SC^2(f - \alpha)}{\sqrt{SC^2(f - \alpha)SC^2(f)}} \right)
\]

MID uses information from two asymmetrically calculated spectral coherences. Presenting MID on \( f, \alpha \) results in a map of modulation intensity of whole spectral range of analyzed signal.
MID – REB fault

- MID analysis was able to detect REB characteristic frequency (~106 Hz)
- Relatively narrow carrier frequency range
- Contribution of REB characteristic component to total signal energy is very small

Part 4/5
Epicyclic gearbox diagnostics
Introduction – Why Diagnosis of PG is difficult?

Challenges of Wind Turbine PG diagnostics:
- Ring gear fault detection
- Planet gears fault detection
- Sun gear fault detection
- Fault identification (precisely, which fault is present)
- Various planetary gearbox configuration (family of so-called epicyclic gearboxes)
- Low speed (requiring long signals)
- Variable speed requiring advanced resampling methods

Method Description – General Concept

3-D Graph may enable PG technical state assessment

kinematic data of planetary gearbox and all parallel gearboxes
1. No. of PG planets
2. No. of PG sun gear teeth
3. No. of PG planet gear tooth
4. No. of PG ring gear tooth
5. No. of teeth on all subsequent parallel gears
Example

KAStrion: a complete monitoring solution

System under monitoring

Acquisition process
• Vibratory
• Electrical
• ...

AStrion
1. Data validation
2. Peak list

AStrion-H
1. Harmonic family detection
2. Side-band detection
3. Demodulation

Polyphase Electrical Analysis

Reliability

Proof of concept
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Unsolved problems

1. Signal separation (of a single REB fault)
2. Operational condition independence (multi-dimensional bananas)
3. Existence of characteristic components at fine elements
4. Quantitative measurement of fault (e.g. spall size)
5. PROGNOSTICS and Automatic Reports
Thank you for your attention!