PROTEST – Procedures for Testing and Measuring Wind Energy Systems
Drive Train Case Study II

Holger Söker, DEWI GmbH
PROTEST – Background Information

PROCedures for TESTING and measuring wind energy systems

• Collaborative Project in the EU-FP7

BUDGET: 2.7 Mio €

• Start: March 2007

End: Sept. 2010

• Participants:
  ECN (NL) – project co-ordinator,
  Suzlon Energy GmbH (DE),
  DEWI (DE),
  Germanischer Lloyd (DE),
  Hansen Transmissions International (BE),
  University of Stuttgart (DE),
  CRES (GR)
PROc edures for TESTing and measuring wind energy systems

- Focus on mechanical systems: fail not very often but O&M cost dominated by repair of failed mechanical systems like
PROcedures for TESTING and measuring wind energy systems

While design procedures for blades and towers are detailed

Such for other mechanical components are rather vague

Potential risk of component failure
PROTEST – Approach

PROCedures for TESTING and measuring wind energy systems

WP 1 State Of Art Report

WP 2 Load cases and design drivers

WP 3 Loads at interfaces

WP 4 Prototype measurements definition

WP 5 Case Studies
  Drive Train
  Pitch System
  Yaw System

6-step approach
IEC61400-13 Approach seemed to be not adequate impossible to define a rigid testing procedure with fixed channels and sampling rates!

6-STEP Approach allows for
- different design and concepts
- different computational models
- allows flexibility to serve the model validation task
Application of the six-step-approach for validation of a wind turbine drive train

- design & run SIMPACK model
- validate SIMPACK model against validated FLEX5
- sensitivity study of model input parameters
- measurement strategy for model validation
- measurement data processing and analysis
- methods to estimate model parameters from measurements
- comparison of SIMPACK model results/measurements
six-step-approach

STEP 1: failure modes

No special failure mode was chosen as the main focus was set on testing:

- the process of model design
- measurement set-up
- methods of data processing
- validation of designed models
six-step-approach

STEP 2: design model

FLEX5 model – 4DOF for Drive Train

- rotation of low speed shaft
- two bending DOFs for main shaft
- torsion between hub and generator rotor

- inertias of rotating parts are modelled in one body - individual rotating bodies are not considered
- rotation of high speed shaft is defined by low speed shaft rotation (stiff connection/gear ratio)

required parameters:
- overall torsional drive train stiffness,
- drive train damping,
- transmission ratio

DOF 01-06: Foundation – Rotation and translation

DOF 28: Shaft torsion

DOF 13: Shaft rotation

DOF 14/15: Shaft bending
six-step-approach

STEP 2: design model

SIMPACK model – stage2 sophisticated model

implementation of inertia, stiffness and damping between rotating bodies

included gear box model:
torsional stiffness of gear box mounts
torsional stiffness of shafts and gear teeth
stiffness of the different gear stages
**STEP 4: determine relevant parameter**

- Sensitivity Analysis on gives information on the effect of input parameters uncertainty on simulation results.
- Starting point for measurement campaign (STEP 5).

**1st approach:**
- Vary model parameter (e.g. high speed shaft stiffness).
- Run a modal analysis.
- Observe the change of the resulting eigenfrequencies and eigenmodes.
- Judge what uncertainty is acceptable.

**2nd approach:**
- Vary model parameter.
- Run load simulation for relevant DLC’s.
- Analyze results i.t.o. load statistics, Rainflow count.
- Judge what uncertainty is acceptable.
six-step-approach

STEP 5: measurement campaign

turbine type: Suzlon Energy S82 / 1500kW
rotor diameter: 82m
gear box: Hansen, EH751A
site: Tamil Nadu/India
STEP 5: measurement campaign

Measurement setup

standard IEC 61400-13 load signals
- blade loads (root bedding edgewise, flapwise)
- main shaft loads (bending and torque LSS)
- tower top torsion
- tower base bending
- sampling rate 50Hz

for drive train model validation, load validation
- shaft speeds and torques
- displacements of gearbox housing
- temperatures of bearings and oil
- oil pressures
Rotational speed measurements
Focus on model validation
manned measurements to capture specific measurement load cases MLC

December 2008, June 2010

continuous monitoring to capture normal power production MLCs

December 2008, June 2010

<table>
<thead>
<tr>
<th>Step</th>
<th>Quantity to Check</th>
<th>Example for Methods</th>
<th>Objective of Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Documentation</td>
<td>Comparison of model data against weighing log</td>
<td>Main structural properties like masses, stiffnesses, eigenfrequencies and coupled modes</td>
</tr>
<tr>
<td></td>
<td>Selected Time Series</td>
<td>Spectral analysis of selected time series for various operational states (e.g., in partial and full load)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Characteristic Curves</td>
<td>Visual comparison of curves of operational parameters (e.g., speed, power) and loading for several environmental conditions</td>
<td>Validation of basic control characteristics and rotor aerodynamics as well as mechanical and electrical parameters (e.g., losses)</td>
</tr>
<tr>
<td>3</td>
<td>Time Series of various operational states, like power production, start, stop, emergency stop</td>
<td>Visual comparison of data in time and frequency domain</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check of statistical properties of data</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Analysis of decay rates of oscillations during stopping procedures</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dynamic behaviour of important and assessable operational states with focus on aerodynamic mode, controller model and actuator models</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structural and aerodynamic damping</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Post-Processed Data</td>
<td>Comparison of loading spectra like rainflow distribution, load duration distributions, damage equivalent loads</td>
<td>Final check of turbine behaviour and dynamic properties</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check of all previously performed validation steps</td>
<td></td>
</tr>
</tbody>
</table>
six-step-approach

STEP 5: measurement campaign

Normal transients in manual campaign

Run-up

NTH Constant speed at X RPM - no generator connection = idling (=> X is in the range [100 - 1750 RPM] - generator side)
STEP 5: measurement campaign

Special transients in manual campaign

**Resonance**

- **STF** Constant speed at Y RPM - power production (=> Y is in the range [1500 - 1600 RPM] - generator side => adapted FLEXISLIP)

**Operation at constant power levels**

- **STJ** Constant power production at Z kW (=> Z is in the range [750 - 1500 kW])
Selected Time Series: Operation at different load levels for Eigenfrequency determination

**excitation frequencies**

<table>
<thead>
<tr>
<th></th>
<th>rotational speed [rpm]</th>
<th>excitation frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>generator</td>
<td>1495.2</td>
<td>24.92</td>
</tr>
<tr>
<td>rotor 1st order</td>
<td>15.7</td>
<td>0.26</td>
</tr>
<tr>
<td>rotor 3rd order</td>
<td>47.1</td>
<td>0.79</td>
</tr>
<tr>
<td>rotor 6st order</td>
<td>94.2</td>
<td>1.57</td>
</tr>
</tbody>
</table>
Selected Time Series: Run-up for Eigenfrequency determination

- **fHSS**: high speed shaft rotating frequency
- **fISS**: intermediate speed shaft rotating frequency
- **fLSS**: low speed shaft rotating frequency
- **fROT**: rotor–main shaft–planet carrier rotating frequency
- **fHSM**: high speed stage meshing frequency (ISS – HSS)
- **fISM**: intermediate speed stage meshing frequency (LSS – ISS)
- **fLSM**: low speed stage meshing frequency (planetary stage)
STEP 5: measurement campaign

Selected Time Series: Deliberate resonance (modified control parameters)

- **P_WT_cut**
- **T_gen_c2_cut**
- **S_rot_c2_cut**

**kW**

**kNm**

**s**

Selected Time Series: Deliberate resonance (modified control parameters)
Selected Time Series: Stiffness determination - deterministic approach
analysed data: resonance case

assumption:

\[ \text{stiffness} = \frac{\text{torque}}{\text{angle}_{\text{rel}}} \]

torque signal and difference in angle between the two measurement points at the low speed and high speed shafts
six-step-approach

STEP 6: data processing

Selected Time Series: Stiffness determination - Stochastic approach

analysed data: stationary resonance
acceleration and damping assumed to be neglectible from one interval \( n \) to \( n+1 \)

\[
T_{\text{rot\_range}} = \frac{\phi_{\text{rot\_high}} - \phi_{\text{high\_range}}}{\text{Stiffness}}
\]

Range of torque of twist

5 seconds
RFC’s indicate high variations in mechanical torque around rated torque.

→ Further investigation is required to determine (1) the impact and (2) ability of the FLEX5 simulation model to consider this effect.

**six-step-approach**

**STEP 6: data processing**

**Post-Processed Data: Rainflow Count**
six-step-approach

STEP 6: data processing

- **P_WT_c** (MW)
  - 0.0
  - 0.5
  - 1.0
  - 1.5

- **Trot** (MNm)
  - 0
  - 5
  - 10

- **Tgen_c** (kNm)
  - 0
  - 5
  - 10

- **Taxis_c** (kNm)
  - 0
  - 5
  - 10

- **Mhz** (MNm)

Data points:
- 12:40 12:45 12:50
- 13.12.08

Graphs showing data trends over time.
six-step-approach

STEP 6: data processing

2008 monitoring statistics 2009
six-step-approach

STEP 6: data processing

Impact clearly visible in Torque Load Range Spectra

TU 7%
TU11%
six-step-approach

STEP 6: data processing

Impact clearly visible in Time @ Level Plots
Conclusions

- Sensitivity studies to define relevant model input parameters (like inertia, stiffness, damping) are important to setup measurement campaigns.
- Measurements for model parameter validation have been carried out.
- Different methods to determine eigenfrequencies, stiffness, damping and inertia have been developed and applied.
- Stiffness values are reproduced.
- All methods show similar trends with respect to inertia and damping values.
- Further investigations on the applied methods are needed.
Authors

Birte-Marie Ehlers, Florian Stache
SUZLON Energy GmbH, Rostock, Germany, +49 381 203578 592,
birte.ehlers@suzlon.com, florian.stache@suzlon.com,

Kris Smolders, Joris Peeters
Hansen Transmissions International nv, Lommel, Belgium, +32 11 54 9412,
KSmolders@HansenTransmissions.com, peeters@hansentransmissions.com

Thomas Hequet,
Stiftungslehrstuhl Windenergie, Stuttgart, Germany, +49-711-685 68240,
thomas.hecquet@ifb.uni-stuttgart.de

Holger Söker, Oscar Monux,
DEWI GmbH, Wilhelmshaven, Germany, +49 4421-4808-825,
h.soeker@dewi.de, o.monux@dewi.de
Thank you!