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

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

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, jpeeters@hansentransmissions.com

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

1. General

Economic exploitation of wind energy requires reliable wind turbines. To this end it has been recognized that there is a need for improving knowledge on the actual loads acting on wind turbine components s. a. drive trains, pitch systems, and yaw systems. These components are seen to require substantial maintenance and repair efforts or even retrofits. Under the 7th frame work programme of the EU the PROTEST project has been carried out to develop procedures for testing and measuring the loading on the named mechanical wind turbine components. The idea is to set up a methodology that enables a standardized and uniform specification of design loads for mechanical components in wind turbines such as drive train, pitch system, and yaw system. The focus is placed on developing guidelines for model validation and adequately measure loads at the interface of the components to the remaining structure. The project is conducted by a consortium of 7 members active in wind energy industries: ECN (NL), CRES(GR), Ustutt (GER), Hansen Transmissions(BEL), SUZLON Energy GmbH (GER, INDIA), GL (GER) and DEWI(GER).

The PROTEST consortium has assessed today's common practice and has set up improved procedures for component validation testing. These procedures have been applied in three case studies:

- Case study on pitch system loads
- Case study on yaw system loads
- Case study on drive train loads

After introducing project and case study at DEWEK 2008 this paper will report selected findings of the drive train case study for a SUZLON S82 1.5MW wind turbine with a gearbox of Hansen Transmissions. The case study comprises modelling of the drive train using standard and advanced simulation techniques as well as field measurements. The data obtained from modelling and field measurement are used in a twofold way for

- model validation:
  verifying that the simulation models used to simulate the design loads are sufficient
- load validation:
  verifying that the simulated loads correspond, within acceptable limits, to the actual loads experienced in the field

2. Motivation

Acknowledging that reliability of turbines is a must for economic exploitation of wind energy, PROTEST has focussed on development of procedures for testing mechanical subsystems. This focus has been chosen as failures of mechanical sub systems like drive train, pitch and yaw systems, bearings have been shown to dominate O&M cost.

The members of PROTEST agree that potential risk for such failures of mechanical systems is promoted by a lack of knowledge on loads at the component level, shortcomings in component load measurements, shortcomings of standard load simulation models and a simultaneous rapid increase of turbine size.

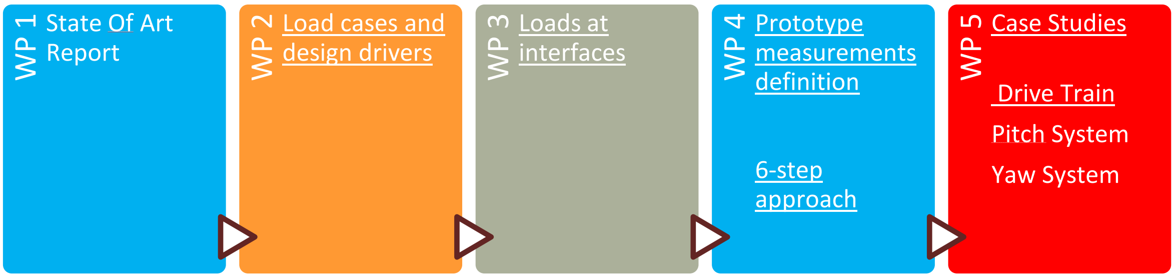


Fig.1: PROTEST Work Packages

3. Work packages of PROTEST

In a first work package the PROTEST consortium has assessed the actual common practice in a state-of-the-art-report. Next, in work package 2 the project partners gave their inputs on relevant load cases and design drivers to be considered for the mechanical subsystems under investigation. The third work package defined the loads at the interfaces of the subsystems to their environment and in work package 4 a standardised way to design and setup a testing procedure was developed.

The conclusions of WP4 are summarized as follows: Due to large differences in the mechanical subsystems in terms of concepts, software modelling and physical implementation in a specific turbine model it becomes impossible to set strict standards for a testing procedure. For example it makes no sense to include measurements of variables that are not included in the model or do not exist in the chosen concept or to measure at frequencies that are much higher than those that would show up in the simulations. The model that is used determines the measurements that are needed. A procedure similar to IEC61400-13 would prescribe exactly the number of measurements, frequencies, etc. which may lead to an unnecessary amount of measurements without validation possibilities for the models used.

Hence, a new and more flexible ***six –step-approach*** has been developed in PROTEST:

Step 1: Identify critical failure modes or phenomena for component

Step 2: Design the model (simple analytical, multi body, FEA)

Step 3: Run model for various DLCs (critical DLCs can be different for the different phenomena!)

Step 4: Determine input and output parameters of model, determine how “certain” they are, and if they need to be verified/measured (spring constant, damping, axial motions, nat. frequencies, etc.)

Step 5: Design measurement campaign to verify models and quantify parameters (parameter, sensor, frequency, duration, processing, etc.)

Step 6: Process measurement data and check/improve models/ model parameters.

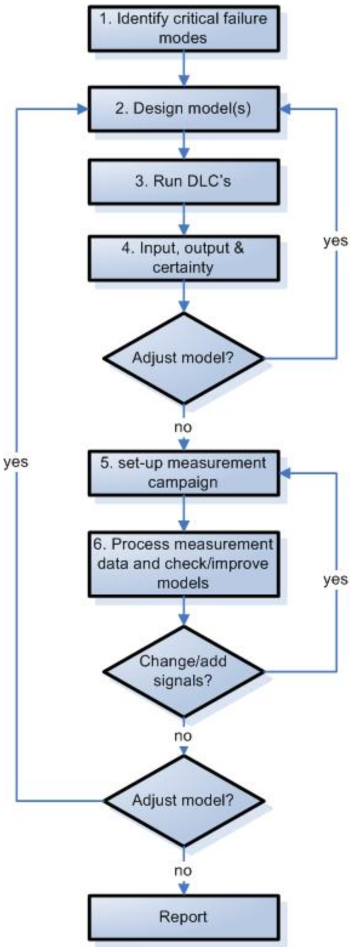


Fig. 2: Six-step-Approach

Finally in the case studies of work package 5 the findings and suggestions of WP1 to 4 have been applied. Three case studies have been carried out:

- Case study on drive train loads (SUZLON, HANSEN, DEWI)
- Case study on pitch system loads (ECN, CRES)
- Case study on yaw system loads (ECN, CRES)

4. Case Study: Drive Train

The primary idea for the case studies is to practically approve the feasibility of the six-step-approach developed in work package 4.

In the case study for the drive train sub system SUZLON S82 1.5MW wind turbine with a gearbox of Hansen Transmissions served as test bed.

Step 1:
No special failure mode has been chosen as the drive train case study placed the focus on testing the process of model design, on development of a proper measurement setup, on the methods of data processing and finally on validation of the sub system design model. It was concluded that several design load cases (DLC) need to be analyzed.

Step2 :
The drive train has been modelled in three different ways varying from simplistic to complex model:

- FLEX5 model (figure 3)
- SIMPACK model stage 1 similar to FLEX5
- SIMPACK model stage 2: sophisticated drive train model

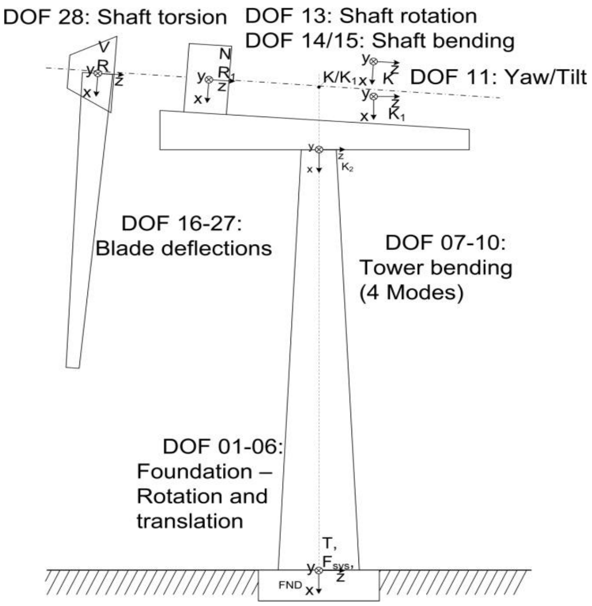


Figure 3: 4 Degrees of Freedom for the Drive Train in the FLEX5 model

The drive train of the first modelling stage (FLEX5) contains 4 degrees of freedom: the rotation of the low speed shaft (“LSS”), two bending degrees of freedom of the supporting parts of the hub (bodies “Hub” and “LSS Hub”) relative to the tower top and the torsion of the connection between the hub and the generator rotor. The rotation of the high speed shaft is defined through a constraint to the low speed shaft (transmission ratio). Overall torsional stiffness, damping for the drive train and transmission ratio are the required model parameters for the drive train in this simplistic model.

Step3:
The models were run for various DLCs and compliance of the FLEX 5 and SIMPACK stage 1 model were achieved.

Step 4:
In this step a sensitivity analysis shall be carried out giving information on the effect of input input parameter uncertainty on simulation results. Obviously, for the chose model, drive train stiffness and damping are the target parameters to identify by measurements as they dominate the simulation results.

Step5
In step 5 the actual measurements were set up to deliver data for identification of the governing model parameters

- torsional stiffness
- torsional damping

Additionally to the standard IEC load and operational measurement quantities a specific instrumentation was put in place for measurements of

- shaft speeds and torques
- displacements of gearbox housing
- temperatures of bearings and oil
- oil pressures

Fig. 4 Optical encoding and laser pickup for high resolved shaft speed measurements

Two manned measurement campaigns were carried out in December 2008 and June 2010 with the target to capture measurement load cases (MLCs) that were specifically chosen for model parameter identification.

These MLCs included:

- Run-up of the turbine from standstill to cut in speed with generator *not* connected
- Constant speed operation in *deliberate* resonance condition
- Operation of the turbine at constant power output levels

Between the manned campaigns the measurements were kept up for montoring drive train loads.

Step6

In this step data processing is performed with the aim of model validation. As a basis reference has been taken to the guide for design validation as suggested by DEWI /DEWI-OCC in 2006 [2].

Following this guide (step1 of table 1 below) the selected MLCs have been used to identify model parameters like:

- Natural frequencies
- Drive train stiffness
- Drive train damping

Plotting FFT's of different load levels in one spectral plot helps to determine relevant excitation frequencies and natural frequencies of the drive train system (see Fig. 5 below). Analyzing the turbine run-up MLC with no generator load connected is another form of how to search the system dynamic response for relevant frequencies.

For determination of overall drive train stiffness the drive train was operated in deliberate resonance. With help of highly resolved speed and angular increment measurements on both low speed and high speed shaft the twist of the drive train could be determined and related to the acting torque (see Fig. 6 below). Evaluating the ratio of torque over twist determines the stiffness. This principle has been applied in a deterministic way i.e. evaluation of suitable events and also in a stochastic way trying to make use of a broader data base for details please refer to [3].

Finally the structural damping in the drive train could be established from analysis of an emergency shut-down MLC. Here the logarithmic decrement was established from analysis of the decay in torque oscillations after the shut down procedure was initiated.

Although not relevant for model parameter identification the data have also been analyzed using complex post processing like Rainflow counting (RFC). In this analysis high variations in mechanical torque around rated torque were found.

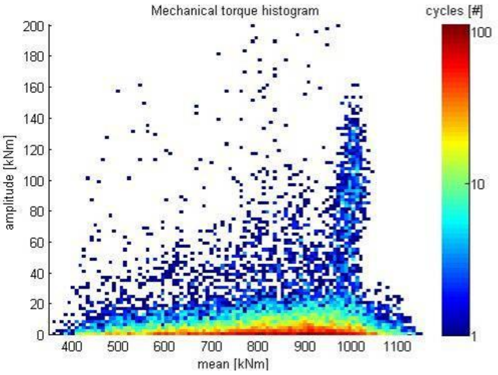


Fig7 RFC's indicate high variations in mechanical torque around rated torque

Further investigations showed that these Rainflow (load) cycles were attributed to a drive train oscillation at resonance frequency. The impact of such dynamic phenomenon is clearly seen in the load duration distribution as well that shows dramatic deformation as compared to turbine operation without that oscillation. The comparison was enabled by comparing LDD's of the rotor torque before and after removal of that resonance by proper changes in the turbine controller. Such potential of interpreting LDD's was already discussed in [5].

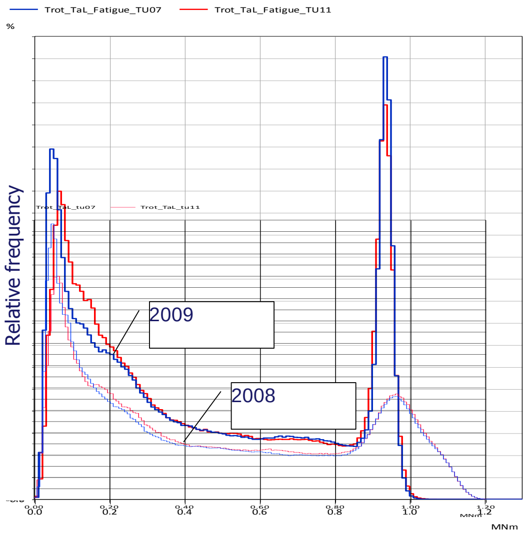


Fig8 Distorted LDD of rotor torque in 2008 and rotor torque LDD after removal of resonance

5. Conclusion

- In order to account for the wide variety of models and physical implementations of mechanical subsystems strict standards for a testing procedure have been avoided , but a flexible six-step approach proposed
- The six-step-approach has been successfully applied in the drive train case study
- 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 and deterministic as well as stochastic methods to determine eigenfrequencies, stiffness, damping and intertia have been developed and applied
- stiffness values are reproduced reasonably well
- all methods show similar trends with respect to inertia and damping values
- further investigations on the applied methods are needed

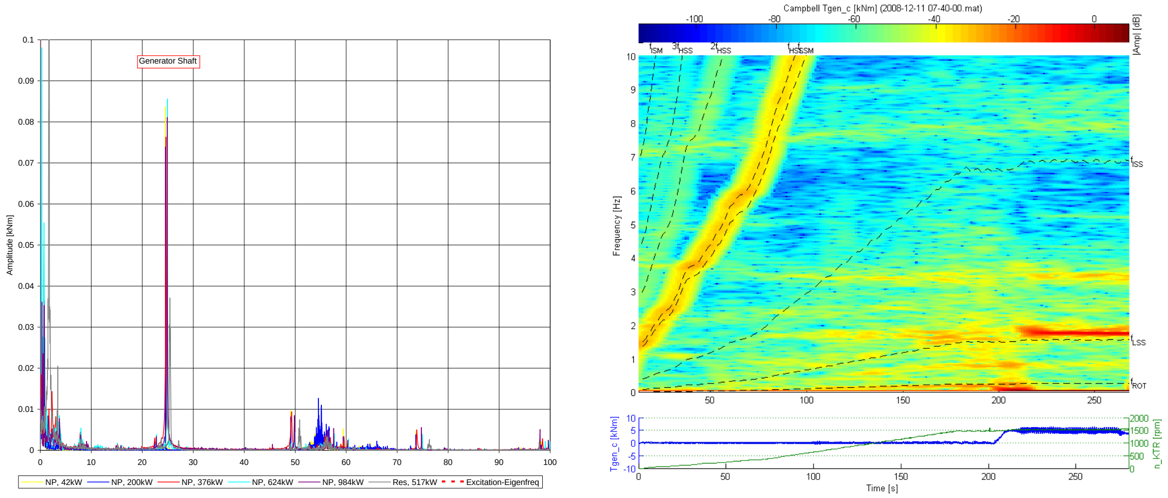
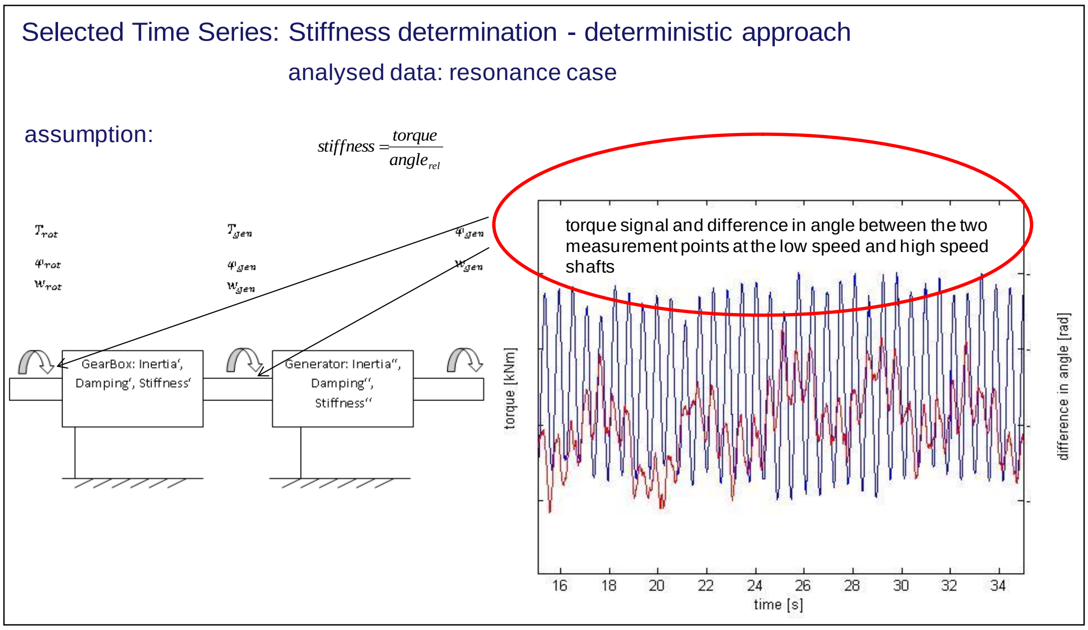


Fig 5: left: FFT spectral plot of main shaft torque for different load levels

right: Campbell –plot for main shaft torque during turbine run up



Selected Time Series: Stiffness determination - deterministic approach

analysed data: resonance case

assumption:

$$stiffness = \frac{torque}{angle_{rel}}$$

Fig 6 Determination of stiffness

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

Table 1: Main Design Load Validation Steps [2]

7. References

[1] J.G. Holierhoek, et all.: PROTEST – Final Report, http://www.protest-fp7.eu/publications/.

[2] H. Söker, M. Damaschke, C. Illig, N. Cosack: A Guide to Design Load Validation, Paper presented at DEWEK 2006, Deutsche Windenergie Konferenz, DEWI: Wilhelmshaven, 2006

[3]. J.G. Holierhoek, H. Korterink, R.P. van de Pieterman, H. Braam, L.W.M.M. Rademakers, D.J. Lekou ,T. Hecquet, H. Söker : PROTEST - Recommended Practices for Measuring in Situ the'Loads' on Drive Train, Pitch System and Yaw System, http://www.protest-fp7.eu/publications/.

[4] H. Söker et all: PROTEST - Procedures for Testing and Measuring Wind Energy Systems
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