Wind Turbine Field and Test Rig Testing as Part of the Design Process for Gearboxes: Test and Validation Requirements, Needs and Best Practices for Wind Turbine Gearboxes

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The growth of worldwide energy consumption and emerging industrial markets demands an increase of renewable energy shares. The price pressure coming from coal, oil, nuclear and natural gas energy — combined with enormous worldwide production capacities for components of wind turbines — make wind energy a highly competitive market. The testing and validation of gearboxes within the test rig and the turbine environment attract a strong focus to the needs of the industry. The following contribution sums up the typical process requirements and provides examples for successful system and component verifications based on field measurements.

Introduction

Wind turbines and their components are part of a dynamic environment; very often, hot and cold climates have profitable wind conditions that make those sites attractive for wind park projects. Components of turbines located in these extreme weather patterns are impacted by strong, gusty winds, deep temperatures, ice, snow and hot and humid climates. The load on components, combined with the tough environmental conditions, require robust requirements for the engineering of main and sub-systems, as well as their lubrication — most particularly the gearbox. A full understanding of the interaction between gearbox and wind turbine — with the different combinations of towers, rotor blades, generators, and resulting loads that are related to different site conditions — must be demonstrated by sound system engineering methods and their validation. Multi-body simulations, FE approaches of complete systems, and the validation on test rigs and on-site installations are all part of the gearbox development process. International Organization for Standardization Abstract IEC61400-4 states the recommendations for test criteria, sensors and sensor positions.

Test and sensor plans should be discussed between wind turbine manufacturer, gearbox manufacturer and component supplier, regarding lubrication and bearing supports.

Gearbox Simulation Models and Test Rig Environment

The gearbox is the most complex, dynamic sub-system within the mechanical drivetrain, which is why it is so important to create an accurate simulation model that is valid and suitable to mirror the major inner dynamics.

The test rig environment helps to validate the gearbox simulation models and to better understand the gearbox's specific dynamics. What's more, the complexity level of the test rig environment is simpler and better controlled than the on-site turbine environment; this allows planning test-run parameters based on first simulation results. Test rig simulation and measurement provide an opportunity to plot sensors for the validation measurement of the model under controlled and repeatable conditions, thereby closing the first development loops within the design phase and helping to save cost and reduce risk.

Within the first step it is necessary to keep the test rig model as simple as possible. The test rig is driven by a 5 MW motor and a slave gearbox; the slave gearbox with a shift stage adapts the torque and speed to the input level of the master gearbox. The generator is connected to the output shaft of the master gearbox via an original wind turbine coupling, including the brake disc. Original rubber bushings from the wind turbine isolate the gearbox torque arm from the foundational support structure. The mounting angle of the drivetrain corresponds to the original mounting angle of the wind turbine drivetrain.

The ground supports, gearbox housing, and planet carrier of the planetary stages are considered as elastic elements (FEA super elements/blue-colored). The technology for those considerations is based on a mode reduction of the finite element models. Periodic tooth stiffness achieves authentic model stimulations occurring with tooth mesh frequency; the sub-models account for the overlapping effects of real toothings. Accurate n-dimensional (*Ed.'s Note: having an arbitrary number of dimensions*) stiffness characteristics of the bearings include the information of the bearings' microgeometry. The displacement between outer ring and inner ring causes reaction forces on the shafts and housing. Forces and displacements of the shafts depend on the kind of bearing models used.

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Different accuracy levels of models for bearing stiffness can be used for parameter and sensitivity studies; bearing stiffness can be modeled with linear and/or non-linear properties.

The degrees of freedom (DOF) of real bearings are constrained by coupling stiffness. Thus the simulation results for bearing models with constrained DOF and non-constrained DOF will be different. The choice of a suitable bearing model depends on the simulation targets (e.g., calculation efficiency and/or result accuracy).

The support structure and complex structural parts of the drivetrain — such as parts of the crankshaft — are considered as super elements.

Excessive analyses and verifications of the gearbox within a test rig environment due to measurement and simulation are necessary for highly accurate validation of the gearbox model. And, the quality of the gearbox model has a huge impact on the quality of the simulation within the wind turbine model. Investigating model details on a high technological level is recommended in order to gain an accurate validation model for the gearbox. Closing engineering loops supported by multi-body simulation results will help to enhance the suitability of the gearbox design and its reliability for the application within a wind turbine.

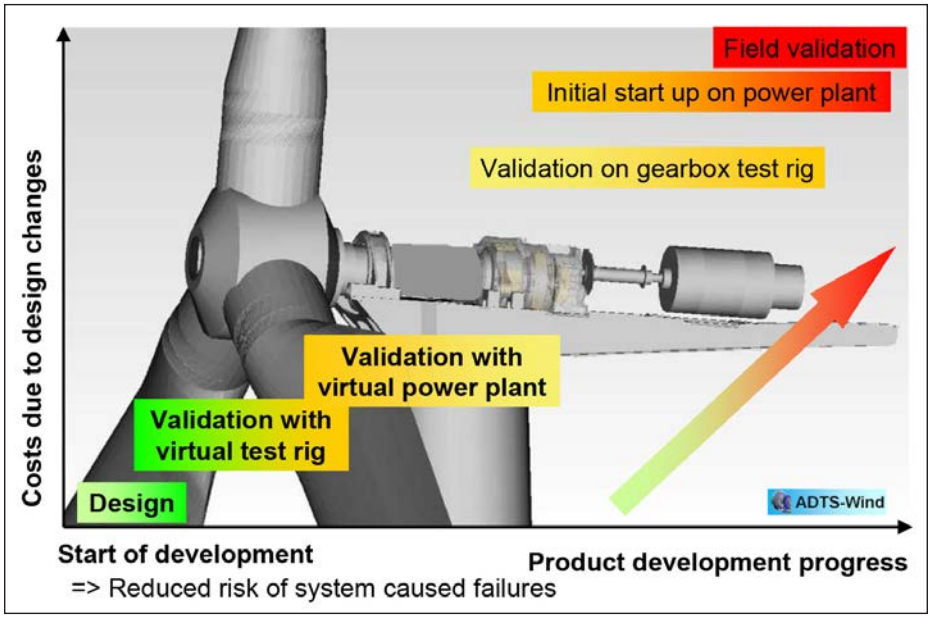

Figure 1 Early-stage validation of gearbox; note relationship between development phase and cost increasing due to necessary design changes of gearbox.

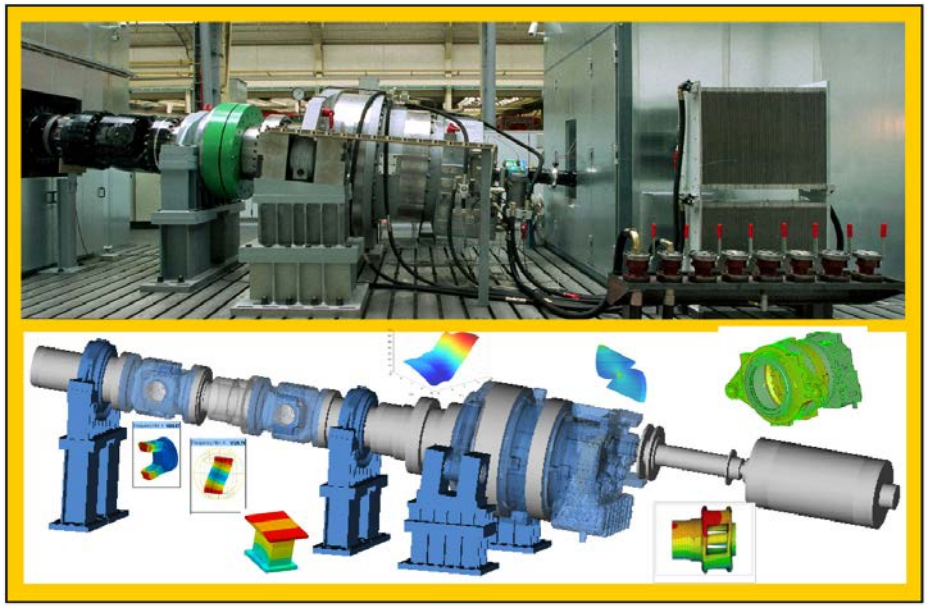

Figure 2 Photograph and simulation basis for 5 MW Wind turbine test rig; MBS (multi-body system) of the gearbox within the test rig environment.

Operating Conditions of Wind Turbines

Availability and production gains of wind turbines depend on various operating conditions; but loads and temperatures vary — depending on a turbine's condition speeds. A high amount of control activities under turbulent and strong wind conditions lead to non-stationary loads and speeds. The design and suitability of support systems, bearings and toothings — as well as lubrication — are relevant for reliable component lubrication.

Agreement between environmental conditions and functionality:

- Cold climate → maintaining the lubrication and filtration system; supply of the tribo-contacts; materials; fracture mechanical fatigue
- Frozen gearbox → capability to start the pressure-fed lubrication; avoiding of coal oil at heating elements; short starting periods; material; brittle crack propagation
- High speeds, low loads → avoiding smearing
- Low speed, high loads → avoiding micropitting and wear
- High speed, high loads → avoiding scuffing
- Stand still → Avoiding still-standing marks and "false brinelling"
- Idling → supply of toothings and bearings above the oil sump
- No grid → minimum supply of components during parking periods

There are a couple of other operating conditions that should be addressed by testing, calculation and simulation.

Tests and Test Criteria for Wind Turbine Gearboxes

Tests for wind turbine gearboxes as part of the design process are to be differentiated by eight different categories:

1. Prototype tests on a gearbox test rig
2. Robustness tests on a gearbox test rig
3. Cold climate tests in climate chamber
4. Component and sub-system tests (lubrication systems, etc.)

Figure 3 Eickhoff 5MW test rig with climate chamber.

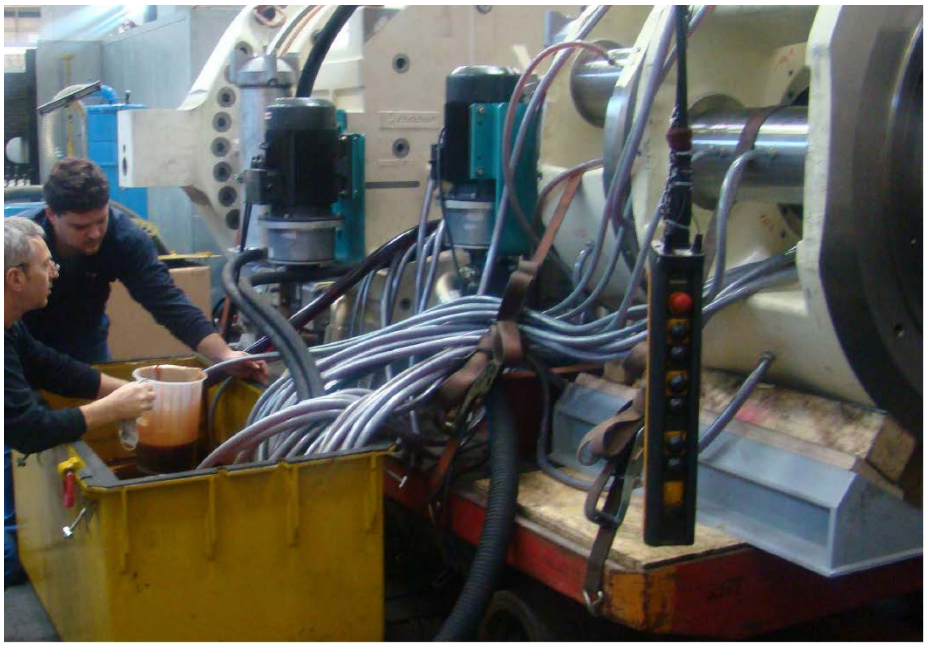

Figure 4 Verification of the specific required oil quantities for toothings and bearings.

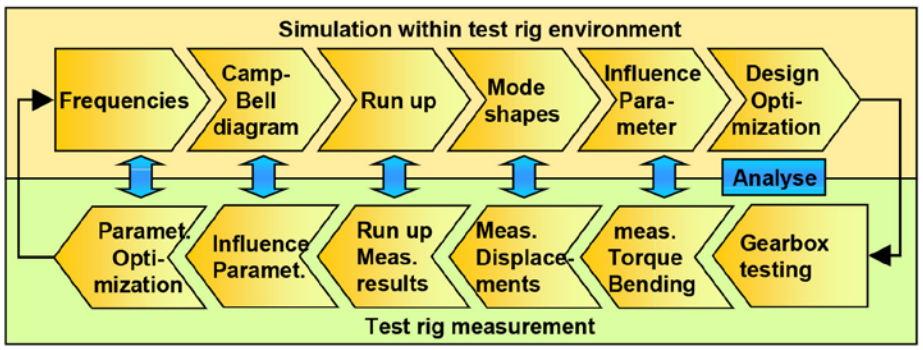

Figure 5 Coherences between influence parameters and design loop; analysis of test and simulation within optimization loop.

5. Material test (strength tests, quality tests, etc.)
6. Field tests of the gearbox
7. Field tests of the gearbox oil
8. Acceptance tests for series production on the test rig of the gearbox manufacturer

The prototype tests cover the confirmation of the main design assumptions; the functionality of parts; the fulfillment of noise and vibration criteria; and temperature limits and lubrication criteria.

The robustness test of a gearbox is related to its fatigue and should expose its weakest link. This test can be conducted as an accelerated fatigue and/or overload test.

Cold climate tests within a cold chamber confirm the functionality of the lubrication system under extreme low temperatures, and verify start-up and warm-up strategies of the gearbox up to the minimum operation temperature.

Component and sub-system tests confirm design assumptions and verify calculation results. Material tests qualify properties of brittle cast iron and temperature, depending on the properties of steels used for the toothings. Quality tests are necessary to assure the specified material properties with respect to chemical consistency, grain sizes and metal structure.

After the prototype test of the gearbox at the test rig, a prototype qualification and validation on-site is required. Design assumptions, load assumptions, deflections and deformations are measured and considered as the basis for lessons-learned loops during the design assessment. Field tests for lubricants qualify the lubricant with respect to compatibility with all components within the gearbox under field environment conditions. Those tests are, in addition to prequalification tests, application-oriented lubrication tests.

Series and acceptance tests are required as end-of-line tests for each gearbox that will be delivered to the customer. Those tests have to be operated with specified load steps up to nominal load under consideration of requirements to test criteria such as maximum temperatures, pressure lim-

its, noise and vibration limits and contact pattern at the toothings.

Test and Qualification of the Gearbox Lubrication System

The approval of the lubrication system is important for prototype and end-of-line testing. During prototype tests, the expected amount of oil, temperature, pressure and oil cleanliness must be confirmed. In addition, the suitability of emergency lubrication for idling and grid-less parking conditions of the wind turbine must also be proven.

During the acceptance tests of the gearboxes, the confirmation of expected temperatures and pressures assures the completeness and functionality of the oil pipes as well as the anti-leak tightness of the lubrication system.

This concept excludes damages due to lubrication faults and leakages. Prototype testing under CCV conditions — including the verification of lubrication design assumptions — is paramount; tests within a cold climate chamber ensure the suitability of design assumptions and operating strategies of the wind turbine.

Freezing the gearbox down to an extreme temperature of –40°C provides the opportunity to simulate warm-up and starting procedures of the gearbox.

Sensors for temperatures at different oil sump and bearing positions, as well as pressure sensors, measure useful

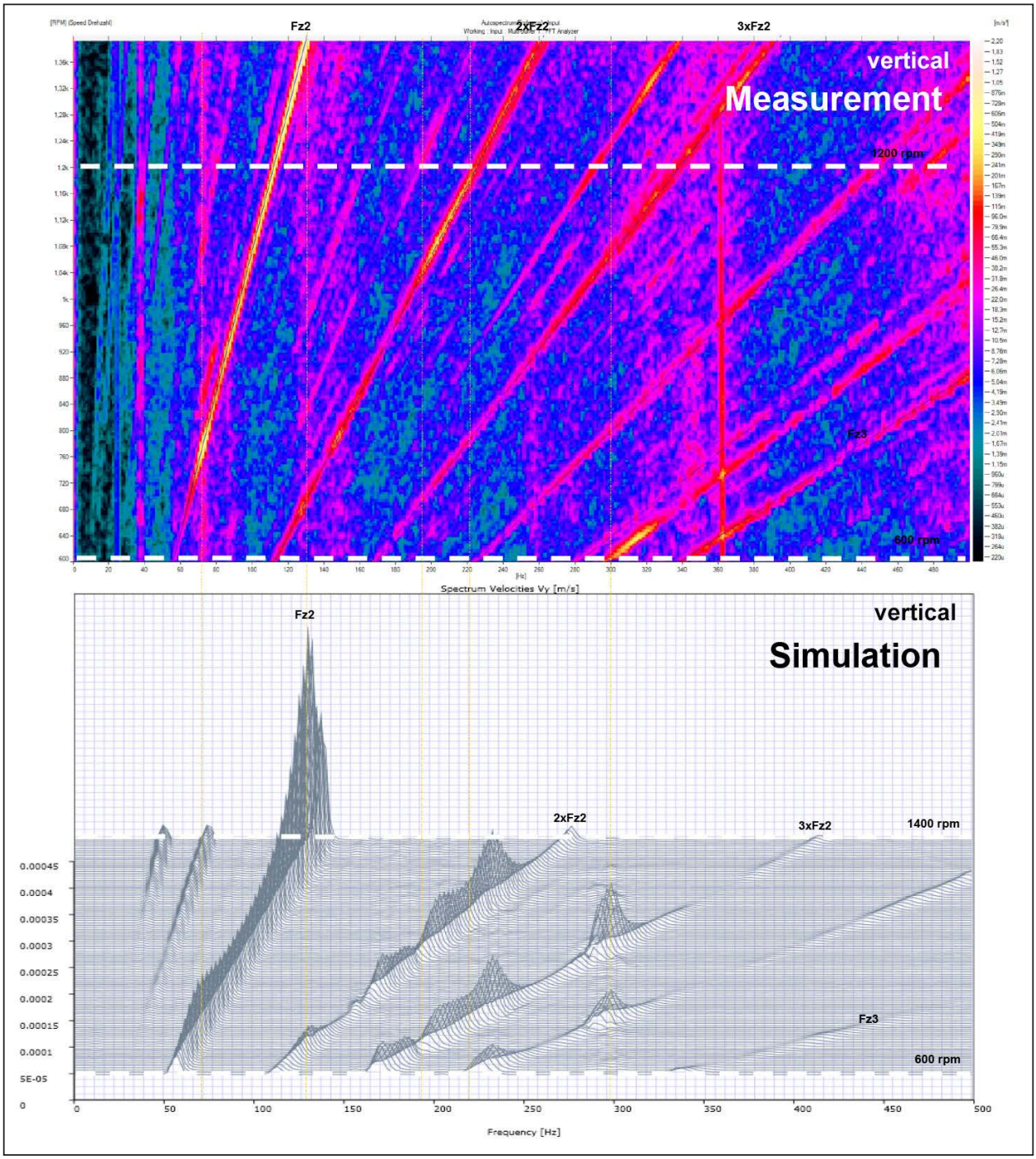

Figure 6 Comparison of the structural accelerations at the torque arm between measurement and simulation during a run-up of the test rig (solid-borne vibration).

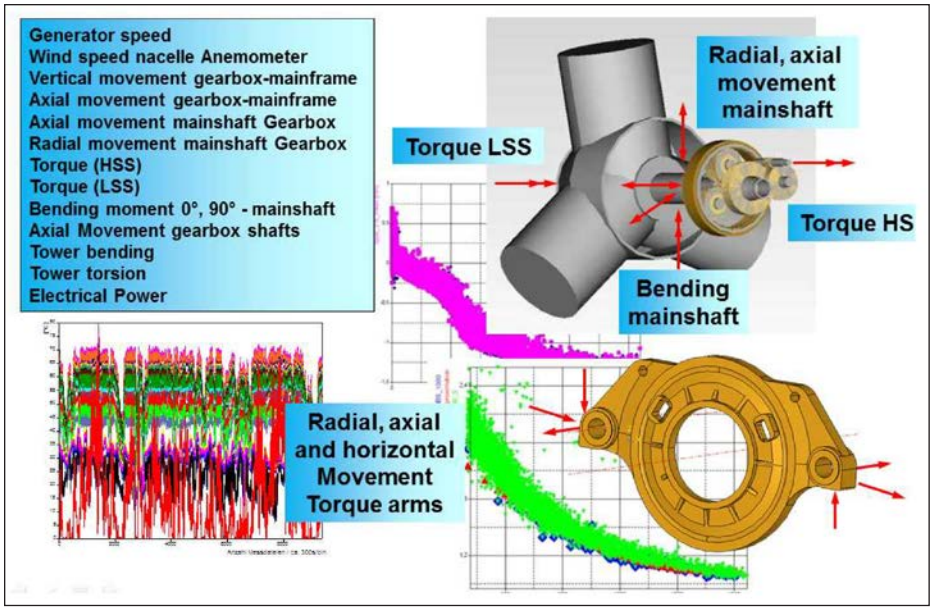

Figure 7 Sensor positions and signals for a field validation measurement.

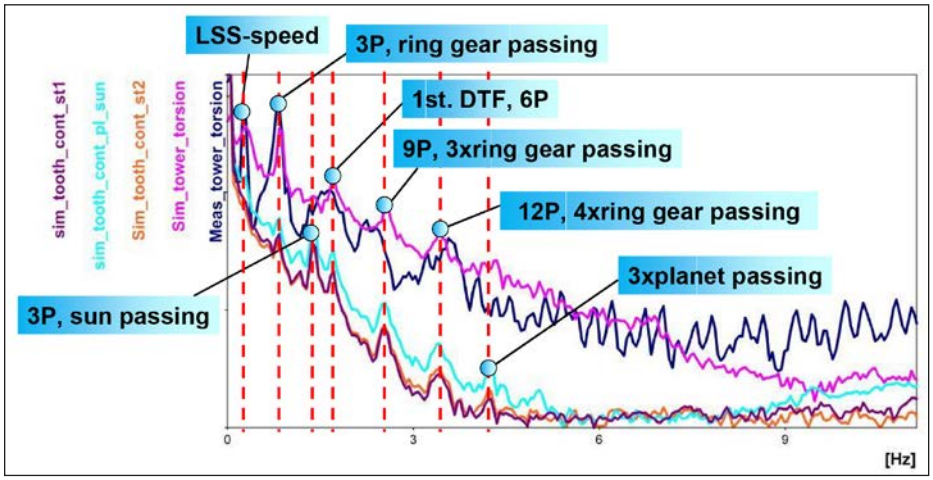

Figure 8 Comparison of frequencies included in stress signal of tower torsion based on measured and simulated data frequencies are derived from time signal of tower stress in upper-third of the tower by a fast Fourier transformation approach.

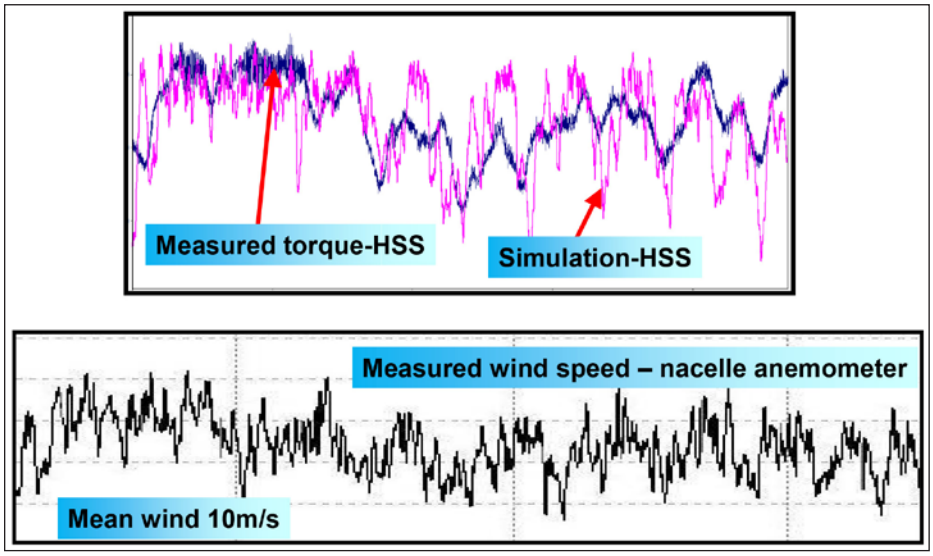

Figure 9 Comparison between a measured and simulated torque moment on the high-speed shaft of the gearbox; they are based on the same measured wind speed.

data that can be used to optimize the warm-up procedure and components of the lubrication system.

The optimization of the warm-up period between low reference temperature (–40°C) and the start temperature of the gearbox (0°C) increases the availability of the turbine and, as a consequence, the gain out of production.

The test rig has the capability to freeze the gearbox down to a temperature of -40°C and to start the gearbox under full load, offering the opportunity to obtain the initial breakaway torque of the frozen gearbox at the low-speed side of the gearbox. Those values are realistic compared to the situation on the wind turbine.

The simulation of different warm-up procedures with and without idling gearboxes is important to prove the suitability and performance of the operation strategy; emergency lubrication can be checked with different temperatures.

A procedure known as the "Melk test" verifies the required, specific oil quantities for toothings and bearings; volumetric measurements confirm the oil quantities at each nozzle point of the lubrication system.

Test Rig Verification — Acoustics and Dynamics

In most cases the input torque of an application is the design driver for gearboxes and other drivetrain components. The most common and typical values for the analysis and verification of simulation results are different shaft torques and frequencies that can lead to high accelerations within resonances.

Key issues within the design loops are stimulus and natural frequencies (Campbell diagram), transient time series for torque, bending and displacements at significant locations. Waterfall diagrams of signals measured during test rig start-ups are a common basis for resonance analyses, compared with the Campbell diagram.

Campbell diagrams are well-used tools for analyzing the resonance behavior of drivetrains. They contain information about natural frequencies, stimulus frequencies (even for different tooth numbers of different gearbox

versions), areas of operational speed, and torque. Critical operational speed areas — such as important points for noise and vibration — can be located. Today wind turbine manufacturers require low noise and vibration levels for the gearbox. Hence it is important to identify a close harmony between structural resonance, load-dependent tooth stimulus levels, and the inner dynamic behavior of the gearbox. The implementation of FEA super elements into the simulation model of a gearbox allows validation of the simulation results at positions for solid-borne sound measurement sensors.

The resonance points in Figure 6 are comparable between measurement and simulation. This analysis allows making conclusions and decisions for design loops based on simulation results for parameter variations. This will be beneficial with respect to safe hardware time on the test rig. After full validation of the gearbox the implementation of the gearbox model into a full wind turbine model will lead to reliable simulation results. These results provide a good basis for the optimization of the full wind turbine drivetrain.

Field Validation and Field Measurement

Validation of the gearbox within the actual turbine environment in the field is vital in confirming design assumption. That kind of validation measurement is the basis for a series of design evaluations, such as:

- Confirmation of design assumptions (deflections, movements, loads, bending, etc.)
- Acoustics and vibrational behavior (test rig and turbine environment)
- Validation of simulation models and results (test rig and turbine environment)

To receive answers for all of those questions, a large sensor set-up on the tower is necessary (Fig.7).

All of the time series that are measured during the measurement campaign can be used to validate design assumptions and to verify simulation models and their simulation results. The validation of simulation models is one of the most important tasks within the whole simulation and modeling process.

A comparison between *FLEX5* results, measuring results (test rig and field), and the results from advanced multi-body models is necessary in assuring the validity of the simulation results. The mode shapes of the turbine — as well as the calculated and measured time series — are used as primary validation data.

Figure 8 shows a comparison of frequencies that are included in the stress signal of the tower torsion based on measured and simulated data. The frequencies are derived from the time signal of the tower stress in the upper-third of the tower by a fast Fourier transformation approach. There are several frequencies, such as LSS rotation, 3xLSS rotation, 1st drivetrain frequency, etc., that occur in the tower stress and fit between the measured and simulated data. In addition to that, there are kinematic frequencies that occur in both signals. The occurrence of the most frequencies in the forces of the tooth contacts in each gearbox stage are a sign for the strong interaction and coupling between parts of wind turbines.

The control of the turbine and the model for the transformer both have a significant impact on the dynamic behavior of the wind turbine. To assure the correct functionality of the control model within the simulation model, suitable measured validation data must be collected. In most cases (rough wind and high grades of turbulence) the wind speed at the anemometer of the nacelle is not feasible as input data for a simulation that should be used as validation basis. As a result of the rotor impact, the wind speed in front of the rotor and behind the rotor is different.

With intermediate wind speeds and less turbulence, it is possible to find wind speeds sampled by the nacelle anemometer that are suitable to be used as input parameters for the simulation.

Figure 9 shows a comparison between a measured and simulated torque moment on the high-speed shaft of the gearbox; they are based on the same measured wind speed.

The measured time series of the wind speed behind the rotor is used as input for the simulation as one dimensional transient wind field that attacks the rotor in its center point.

The time-based signal of the measured HSS torque fits to the signal of the measured torque; it can be concluded that the embedded model for the controller works comparably to the real system.

In addition to loads, displacements of drivetrain parts are important validation criteria. In some cases displacements are more sensible against inaccurate coupling properties for stiffnesss within the model than loads. Hence it is also important to compare measured and simulated displacements of drivetrain parts. **PTE**

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