Comparison of Test Rig and Field Measurement Results on Gearboxes for Wind Turbines

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Management Summary

This article describes some of the most important tests for prototypes conducted at Winergy AG during the product development process. It will demonstrate that the measurement results on the test rig for load distribution are in accordance with the turbine measurements. The results of vibration measurements depend on the environment—i.e., the stand-alone gearbox has values other than those of the gearbox on the test rig or in the turbine. Measurement data show that resonance and Eigen frequencies are a critical issue; these effects cannot be eliminated, as they are endemic to every system. Multi-body analysis (MBA) is introduced here as a tool in calculating and simulating frequencies, amplitudes and gearbox behavior.

Product Development Process

The development of gearboxes for wind turbines is based on the requirement specifications provided by the customer. In these specifications all of the necessary needs—general description, available space, power and loads, etc.—are defined. The development follows a well-defined product life cycle management (PLM) process in which each step is determined.

The main steps—from specification to serial production—are:

- Calculation according to specification; i.e., pinions, teeth, bearings, housing, etc.
- Mechanical design
- Prototype testing

Prototype Testing on a Test Rig

All prototypes are dynamics-tested in a back-to-back configuration on a test rig (Fig. 1). Also, testing according to standard procedures of the gearbox manufacturer and customer requirements is conducted and the design improved if the results warrant it.

There are three essential—yet different—types of tests conducted during the prototype test phase:

- Dynamic tests on load, load distribution and efficiency
- Structure-borne noise and air borne noise tests and measure ments
- Lubrication tests; i.e., oil distribution, leak tightness and climate chamber tests

Typically, load tests are carried out

Figure 1—Back-to-back test rig at Winergy/Voerde during prototype test.

to check gearbox behavior; the gearbox is therefore typically tested at overload and according to the specification—occasionally up to 300% nominal load. The gearbox is then dismantled and every single part is inspected.

Load-Distribution Measurement

To validate the gears' calculated and ground tooth profiles, a load-distribution measurement must be done at different load stages. Strain gauges are therefore applied at the tooth to observe the forces during the tooth mesh over the whole tooth width; Figure 2 shows schematically the application of, for example, six strain gauges over the tooth width of a sun pinion. It can be seen that the width is divided in equidistant parts. It is important that the strain gauges are applied as following:

- No interference with each other
- No influence of the border
- Sufficient covering

With this application (Fig. 3) on several teeth of the gear, different load stages are tested; typically the load distribution is measured at 20/40/60/80/100 and 120% of nominal load. Since the profile is calculated for one fixed load point, the correspondence is provided for only this. Deviations due to deformations are possible; nevertheless, it must be assured that the tooth contact is optimal over the entire range of performance. In doing so, a visual contact-pattern check after the test run must be done and the results considered.

During the test run, the measured force of each strain gauge is recorded. Figure 4 shows a typical run of the curves for the strain gauges of two applied teeth. It can be seen on the left side that during the mesh, every strain gauge signal has a maximum relative stress dependent on mesh, loading and position. The maximum value of each strain gauge is plotted against its position for each applied tooth. The resulting diagram on the right side shows the load distribution over the whole tooth width. This distribution is valid for one single meshing position, but will change for others.

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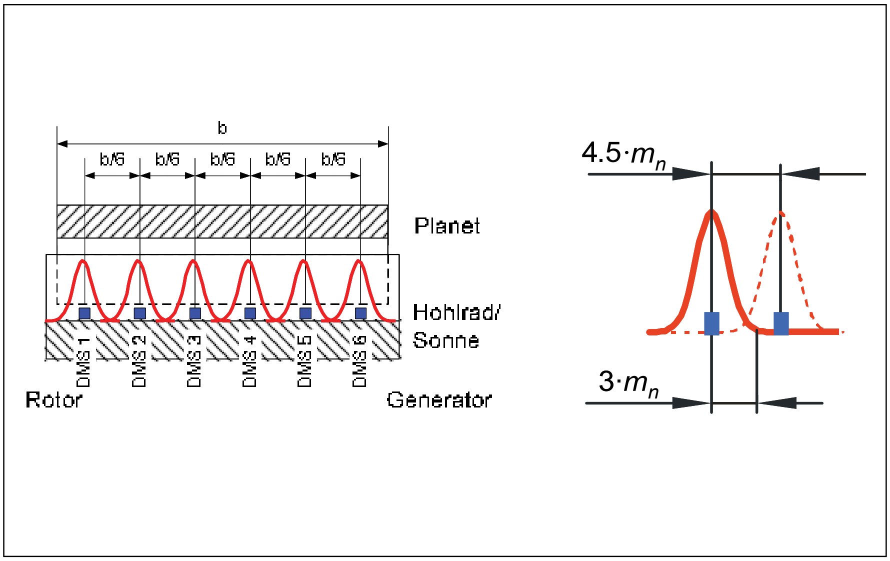

Figure 2—Distribution of strain gauges over the tooth width.

Figure 3—Application of strain gauges for load-distribution measurement on a sun pinion.

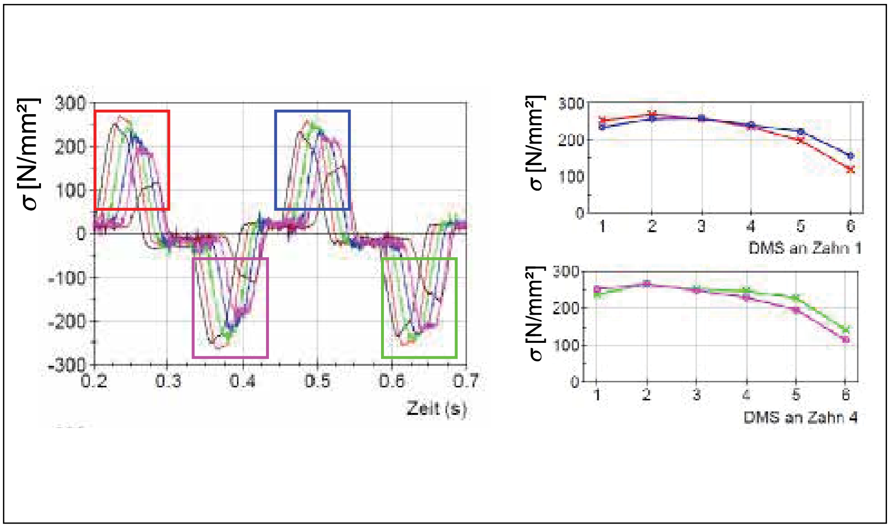

Figure 4—Typical results of a load-distribution measurement.

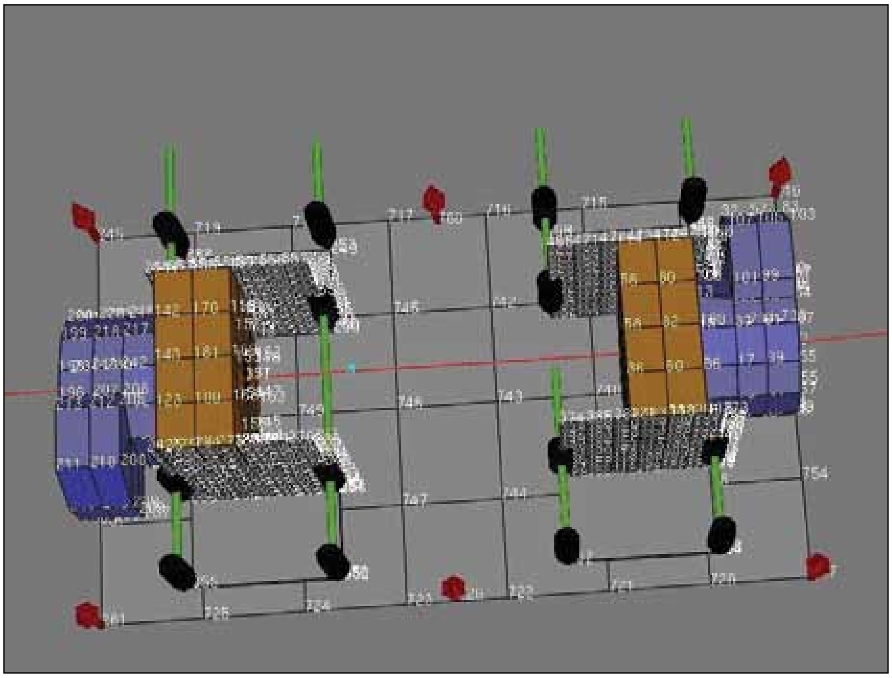

Figure 5—Typical excitation and measurement points for a modal analysis.

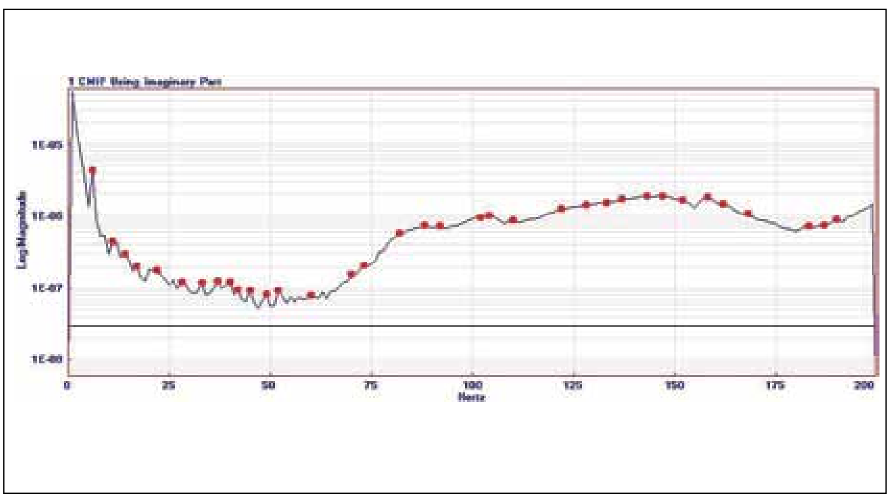

Figure 6—Result of modal analysis of a stand-alone gearbox.

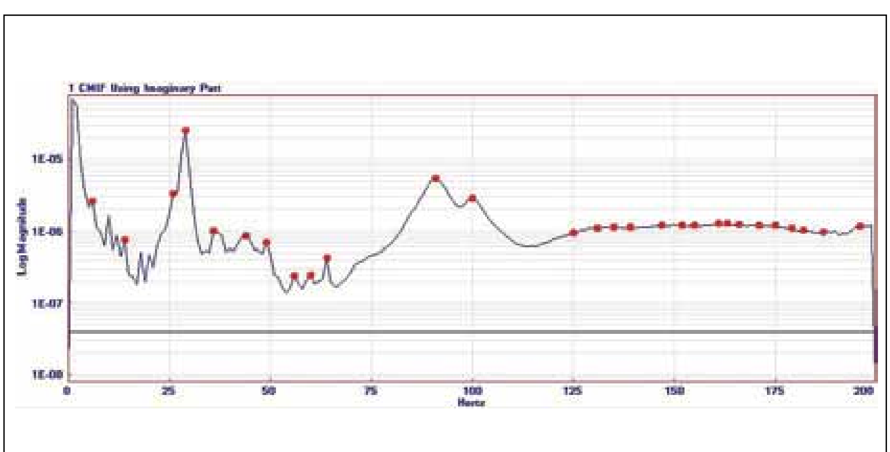

Figure 7—Result of the modal analysis of the gearbox on the test rig.

Sound and Vibration Analysis

Structure-borne noise and airborne noise result from the meshing gears. The gear mesh works as a sound generator and propagates over the housing. Gear mesh frequencies of the different stages can be measured on the gearbox housing and are taken into account as an indicator of gear quality. Every specification provides limit values of the amplitudes for each frequency or frequency range.

One must also be aware that resonance phenomena of the housing can increase those amplitudes, so attention paid to the mechanical design can aid in avoiding structural resonance.

To determine the Eigen frequencies of a gearbox, modal analysis of the individual parts, stand-alone gearbox and gearbox in the test rig configuration is done. Those results are then compared with the calculations. During the test run, an operational deflection shield analysis (ODS) is also conducted. Figure 5 shows the typical excitation and measurement points for a modal analysis of a gearbox on the test rig.

Figure 6 shows the result of a modal analysis of a gearbox hanging in a crane. It can be seen that no resonance frequency occurs between 0 and 200 Hz. Figure 7 shows the result of the modal analysis of the same gearbox installed in a back-to-back configuration on a test rig. It can be seen very clearly that resonance frequencies occur around 29 Hz and in the range of 85–100 Hz.

Figure 8 shows the mode shape of the gearbox in the test rig at 29 Hz; due to the fact that the gearbox is clamped in the test rig, an Eigen mode results that is not present when the gearbox stands alone. This fact must be taken into account when vibration values are discussed—not just regarding the behavior of the gear unit on the test rig, but on the turbine as well.

Multi-Body Analysis

To understand more regarding gearbox behavior in different environments, multi-body analysis (MBA) is the tool of choice. Calculation of the relative movements of the gearbox and its parts—in all three spatial directions—and possible resonances is conducted. A model of the gearbox is built, and different operating conditions are analyzed. Figure 9 shows the model of the gearbox used for this analysis; Figure 10 shows the model of the gearbox in the test rig configuration.

Figure 11 displays the results of the time-based frequency analysis of the virtual measurement points at the torque arm. It can be seen that the simulation results correspond with the results of the modal analysis (Fig. 7). Resonances at 29 Hz and in the range of 85–100 Hz are also found in the simulation, meaning that critical frequencies or amplitudes can be calculated. If more data about the installation parameters of the gearbox in the wind turbine are available, calculation of gearbox behavior in the turbine is possible.

Comparison of Measurement Results from Test Rig and Field Measurement

Test rigs and wind turbines are very complex systems, with many components and many influencing parameters. Therefore it is very important to analyze the behavior of a wind turbine gearbox in both situations. Figure 12 shows schematically the differences in the installation situation in the test rig and on the gearbox. One main difference is the elasticity of the surrounding structure. While the test rig situation is very stiff, the situation on the wind turbine is weak. This leads to other Eigen frequencies and more deformation as the mode shapes change. Measurements of Eigen frequencies, vibration and sound were carried out and compared to the results of the test rig results. Unfortunately, since most of the measured data are proprietary, it is not possible to reveal them here.

To validate the load distribution values, measurements are done on the turbine. Given the varying, onsite wind conditions, it is not always possible to reach the same load level as on the turbine. Figure 13 shows the good correlation between the values on the test rig

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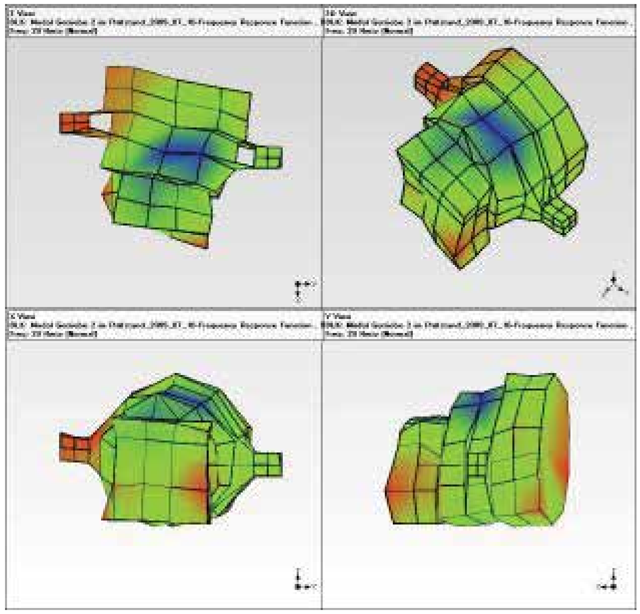

Figure 8—Mode shape at 29 Hz of the gearbox on the test rig.

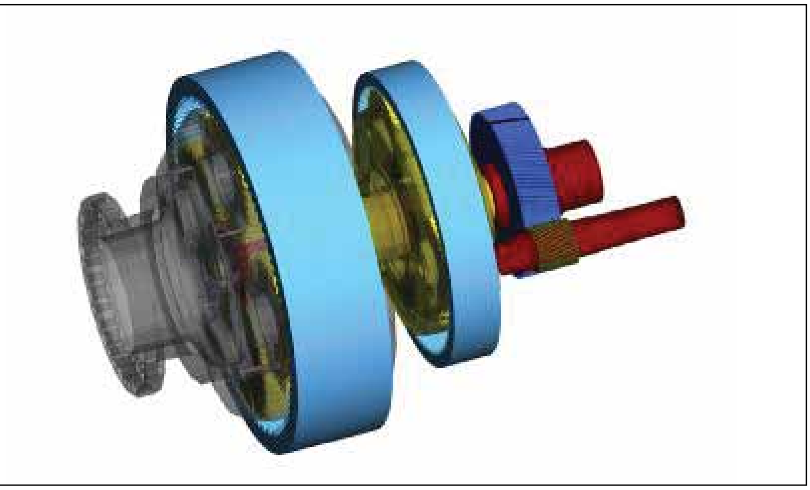

Figure 9—MBA model of the gearbox.

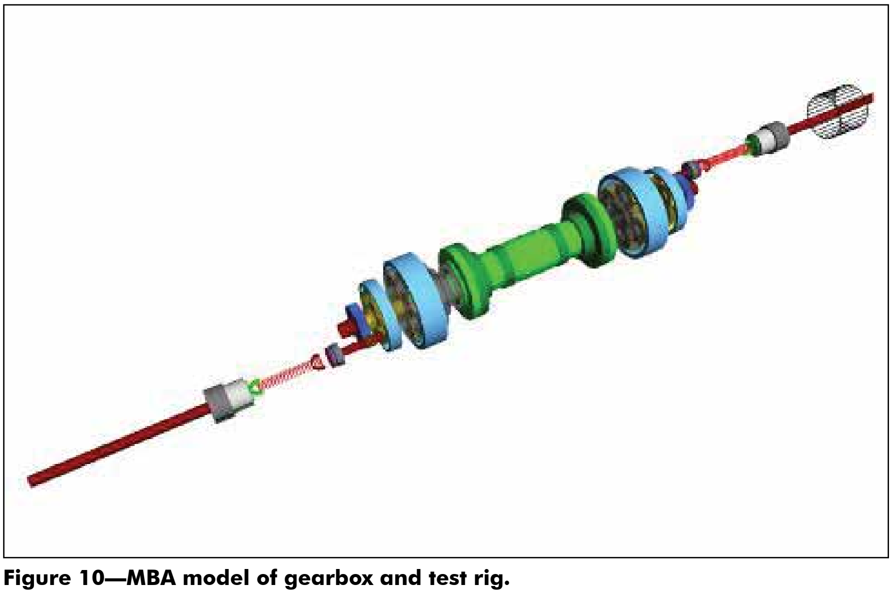

Figure 10—MBA model of gearbox and test rig.

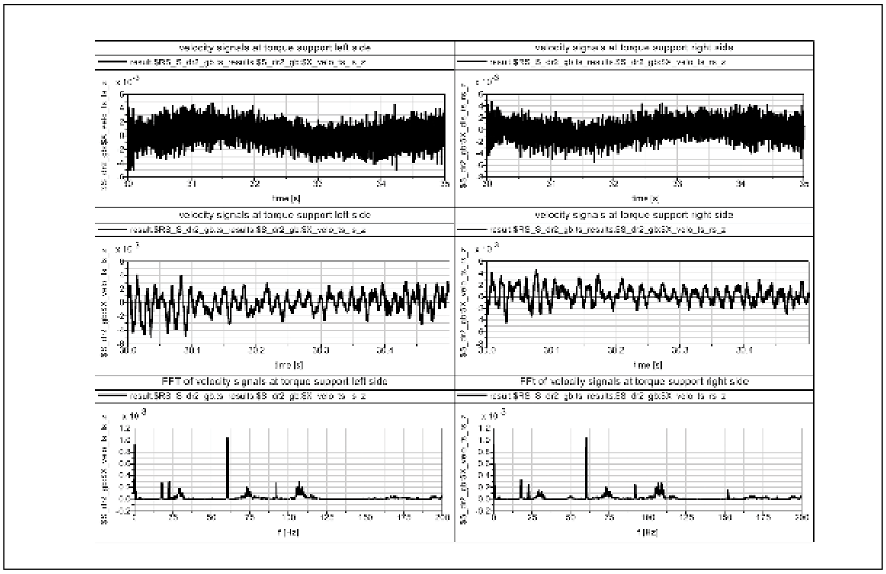

Figure 11—Results of simulation of the vibration velocity of the gearbox.

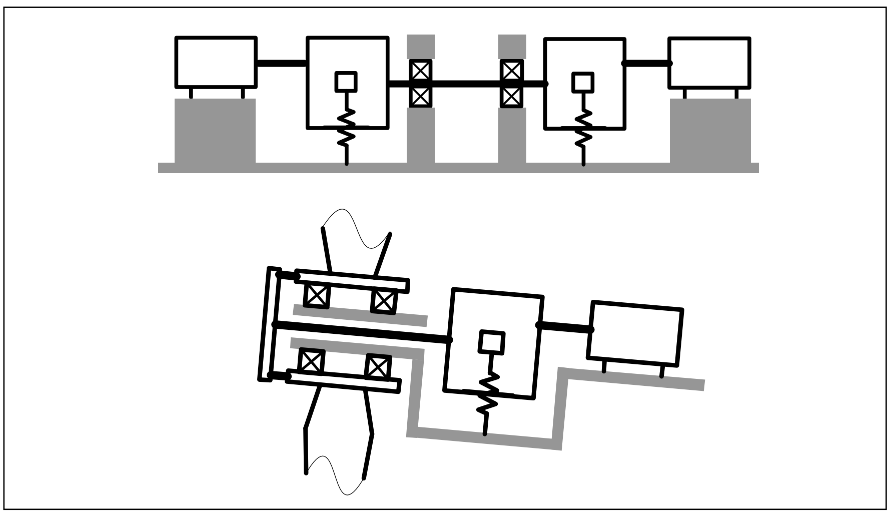

Figure 12—Installation conditions of the gearbox on the test rig (top) and turbine (bottom).

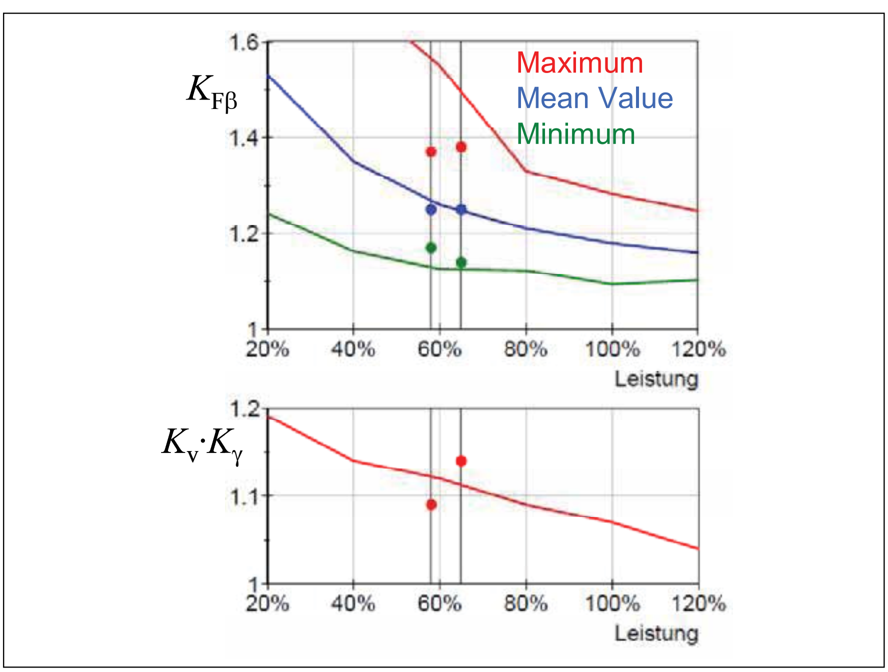

Figure 13—Comparison of load-distribution measurements.

(lines) and the values on the turbine (dots).

Conclusion

The comparison of different types of measurements on gearboxes for wind turbines reveals that the operational behavior of the gearbox is not determined solely by its properties, but by application conditions as well; vibration behavior is particularly influenced by the clamping, dampers and base frame. Tests on the test rig are never an alternative to measurements on the turbine when determining vibration values. Limit values are often given for several frequencies that cannot be achieved due to test rig influences, as behavior on the turbine is sometimes very different. In accepting that premise, relying on final prototype gearbox testing conducted on only the turbine requires a good deal of consideration.

Mark Zundel *is a chemistry graduate of the University of Duisburg and a certified RAMS/LCC engineer. From 2002–2008, he was a member of the condition monitoring department at Flender Service GmbH, Herne focusing on condition diagnostics of gearboxes and drivetrains. Zundel also worked on the development of an oil sensor while also serving as a lubrication and maintenance management consultant. Since 2008 he has worked at Winergy AG, Voerde as head of modeling, verification and tribology, concentrating on the planning of field and test rig trials of WT gearboxes, simulation of gearboxes during the development process and lubrication approvals, tests and tribology.*