Wind turbines are impressive structures. Perched on their lofty pedestals, their blades can stretch higher than the Statue of Liberty. Yet, like all machines, even the mightiest wind generator can be brought down by something as small as a bearing.

Bearings are often taken for granted in conventional generating systems, which are subject to fairly stable loads. Wind turbines are different. They must face transient forces that come and go like, well, the wind. One day, they may face intermittent gusts from changing directions. The next, they must bear the full bore of hurricane-force gales.

This puts enormous stress on wind turbine main shafts, gearboxes, and other rotating parts. Even though these systems are supposed to last for 20 years, they often break down much sooner. According to Sandy Butterfield, principal engineer at the National Renewable Energy Laboratory, end users and owner-operators report their gearboxes generally last five or in some cases only three years.

Not surprisingly, engineers are trying to solve this problem. The National Renewable Energy Laboratory’s Gearbox Reliability Collaborative, for example, has brought together turbine manufacturers, utilities, and suppliers to identify weaknesses and to improve gearbox designs and retrofit packages. Individual companies are also looking at ways to boost reliability.

All of these teams use finite element analysis and computational fluid dynamics to sim-

A high-fidelity bearing model provides insight into the spin of wind turbines.
By Greg Zimmerman

Greg Zimmerman is manager of platform integration and engineering consultancy services at SKF USA Inc. His e-mail address is Gregory.A.Zimmerman@skf.com.
ulate the interaction of wind with mechanical components. Simulations are very efficient at identifying problems across a broad range of operating conditions. They enable engineers to rapidly evaluate and even verify new components at an early stage of the design process, when all options are still open.

Bearing play a key role in ensuring critical rotating parts spin freely under all operating conditions. Yet bearings remain among the more difficult components to model accurately. This is not just because they exhibit nonlinear behavior. It is also because engineers tend to think of bearings as generic components, and are often satisfied with models that simplify bearing construction and approximate bearing behavior.

Commercial simulation tools, for example, often use simplified bearing models that are nothing more than stiffness matrices. Others disregard the bearing completely, and just assume that everything will rotate as it should. A step up are generic bearing models, but even they are often simplified representations that may fail to account for bearing cage motion or variations in materials, finishes, and specifications.

A clearer picture of the behavior of bearings—and of wind turbine gearboxes and rotating shafts—emerges when new, high-fidelity bearing models are substituted for these approximations. These insights illustrate the importance of applying high-fidelity models to the analysis of critical components of larger systems.

**UNLEASHING THE BEAST**

SKF Group of Göteborg, Sweden, has developed a proprietary high-fidelity modeling technology called the Bearing Simulation Tool, or BEAST. It enables experienced engineers to evaluate the dynamic behavior of rolling bearings under real-world conditions. Engineers can use the data to analyze the interaction of bearings and rotating elements within the turbine housing.

Accurate and validated bearing models must represent many rotating and interacting components. They must also consider complex boundary conditions, since bearing performance is highly dependent on the application and its operating environment.

Such models took decades to develop. SKF’s first attempts date back more than 40 years. The first models focused mainly on localized Hertzian contact stresses created as two rigid bodies deformed slightly under imposed loads.

By the 1980s, models could combine many contacting elements—bearing rings and rolling elements—to describe complete bearings. Yet early bearing models were limited to steady-state calculations. They also lacked an accurate description of the bearing cage, which retains rolling elements. Eventually, specialized test rigs were built to validate such unknowns as cage forces and bearing dynamics.

Research eventually resulted in today’s tools, which accurately represent not only the rolling elements but the complete assembly. BEAST, for example, simulates the behavior of a complete bearing, including cages. It takes into account materials of construction and machining tolerances. It also uses a three-dimensional, specialized tribological contact model to account for the effects of small-scale geometric variations, such as surface roughness.

BEAST focuses on the dynamic behavior of bearing components and their individual interactions at points of contact. Its fully transient models use precise bearing data and generate results over time that compensate for the flexibility of bearing geometry to yield more accurate load calculations. This enables studies of internal motions and forces under any given loading condition. Equally important, BEAST closes the loop.

It was designed to couple with CAD, FEA, and CFD models of larger systems. In the case of wind turbines, this enables BEAST to import data on the housing, shaft, couplings, assembly, and boundary conditions. Instead of estimates, BEAST calculates bearing behavior based on real designs using actual nominals. Equally important, BEAST exports design-specific bearing data back to the system model, so engineers can make modifications and tradeoffs as needed.

Let’s consider two cases where the high-fidelity BEAST model helped engineers assess designs to meet critical goals. One involves analyzing a housing design to ver-
ify whether it would last 20 years. The second involves using a model to improve gearbox reliability as part of the Design for Six Sigma process.

PROLONGING SERVICE LIFE
A European turbine manufacturer wanted to determine whether its new wind turbine would last 20 years and to verify its design against a growing body of standards. Promulgated by such groups as the International Standards Organization and the American Gear Manufacturers Association, these standards let engineers use models to verify designs.

In a wind turbine, the housing protects and supports shafts, gears, bearings, and other components. Traditional textbook calculations assume the housing is infinitely stiff and is symmetrical. In reality, however, the housing may contain many features, such as reinforcing ribs, cutouts, lubricant holes, and different construction materials that influence the load distribution throughout the entire system.

Principal output data from BEAST describes the movements of all bearing components, the contact forces between the components, and the force interaction with the environment. It also produces detailed data from the contacts of all components, such as power loss, elastohydrodynamic lubrication film thickness, Hertzian contact pressure distribution, rolling element slip-speed distribution, and wear.

Engineers can study output data in several ways. Animation of bearing components, with magnified motions for additional clarity, can serve as a good visual starting point. Force or velocity vectors can be added to the animation. Some parameters, such as contact pressure or slip velocities, can be displayed as three-dimensional images on the bodies or on parametric surfaces. All output data can be reviewed in more detail using graphical formats.

In practice, the turbine designer supplies all the details for the housing structure, including CAD files and information needed to create boundary conditions. The designer also provides hundreds or even thousands of input cases that describe the loads as the system adjusts to changes to wind speed and direction. These adjustments influence the housing, producing asymmetric loads and shaft misalignments that influence bearing performance. The load always wants to follow the stiffest path. By understanding where the load is actually applied during operation, it is possible to calculate bearing life with a high degree of accuracy. It is also possible to discover ways to improve bearing life by modifying the housing. Moving a rib outside the load zone, adding a stiffener, or perhaps locating the torque arms away from the planetary gear section could prolong bearing life better than any improvement of the bearing itself.

One application of BEAST might be to set the operating bearing clearance, or preload. This is the gap between the rolling elements and their raceway. The tighter the gap, the more fluidly the bearing rolls and the more support it provides to the shaft. Make the gap too tight, though, and the bearing cannot be pressed onto the shaft or accommodate temperature excursions. Running simulations enables engineers to understand the best set of tradeoffs for a bearing expected to operate for 20 years.

The analysis of the European wind turbine confirmed the main bearing housing design would meet extreme-load and fatigue-load conditions, and that the design would not lead to premature bearing failure over the required 20-year service life. Supporting documentation was compiled to apply for formal international certification of the design.

SIX SIGMA GEARBOXES
SKF is currently applying the high-fidelity BEAST model to create an advanced simulation model of a complete wind energy gearbox for the National Renewable Energy Laboratory’s Gearbox Reliability Collaborative.

This wind energy program addresses reliability issues in wind turbine gearboxes. Gearbox, bearing, and wind turbine manufacturers have teamed with wind farm owners and operators to jointly addresses specific gearbox reliability issues. The primary means of investigation will be through full-scale testing and analysis of actual gearboxes, both in the field and in the NREL 2.5 megawatt dynamometer test facility. This campaign is intended to serve a majority of wind and gearbox industry stakeholders, in addition to specific project team objectives.

Modeling a complete planetary gearbox comes with many challenges, including accurately modeling more
than 15 bearing positions. Once the model is considered complete, an even more daunting task can be deciding which inputs should be simulated and what to do with the gigabytes of output data. The goal is not to redesign a gearbox, but to understand the sensitivities of the gearbox that the collaborative has already designed.

BEAST focuses on how the overall system affects bearing performance, and how bearings influence system reliability. For example, BEAST can help analyze what combinations of bearing types, mounting conditions, and gears work best. It enables engineers to analyze how housing or planetary carrier deformation influences bearings, and how that affects reliability. It helps identify the best locations for load stiffeners and lubrication ports.

Engineers engaged in simulation constantly face the challenge of not only building an accurate model, but also of finding a way to validate it. That means determining what specific inputs to use, how many and what simulation runs are required, and what the outputs really mean. The Design for Six Sigma process provides a methodical process for reaching these decisions and gathering and organizing the data.

The integration of Design for Six Sigma into the modeling process provides a structured approach to identify critical operating parameters and to evaluate optimal bearing arrangements.

In the case of the NREL gearbox, tools such as parameter diagrams for testing robustness and fishbone (Ishikawa) diagrams for analyzing cause and effect are used to clearly identify the control and noise parameters affecting system performance. This helps engineers communicate clearly why boundary conditions, forces, and other specific inputs were selected. It also creates documentation for future use.

Many different system design and operating parameters influence the performance of bearings. Some can be controlled during operation. Others cannot, but may still have a significant impact on system performance. Design for Six Sigma enables engineers to gain insight into these parameters by designing experiments for virtual testing.

Using design of experiments methodology also provides an organized set of simulation runs clearly linked to parameters identified in the fishbone cause-and-effect diagram. Statistical analysis of design of experiments results enables engineers to determine the robustness of a bearing system as well as the influences that design parameters exert on performance.

In design of experiments, different calculation runs are made to rank the parameters in terms of their influence on the bearing’s performance. These multiple simulations enable engineers to analyze many more parameters independent of one another than is possible with physical assembly and testing. This type of analysis can help optimize robustness and reduce performance variability.

Such models can help designers narrow their choices and evaluate their options early in the design process and beyond. Designers can strategically factor in different parameters and tolerances to learn how they will affect overall performance without the use of a prototype or physical testing.

For example, friction and thermal models can provide an accurate temperature prediction that can help determine bearing clearance, lubrication intervals and conditions, proper lubricant selection, and ultimate service life, among other things. The information could lead to better gearbox designs in the future.

HIGH-FIDELITY FUTURE

BEAST is not unusual because it is a high-fidelity model. Increasingly, developers are taking advantage of greater computer power to release more realistic modeling tools. What makes BEAST unusual is that it applies high-fidelity techniques to bearings, components that are often represented by generic models that make many assumptions.

The results of high-fidelity models have already begun to change how we evaluate larger system models. Instead of generic answers, we can achieve insights and explanations that are specific to the design, structure, materials, and inputs of the system we wish to evaluate.

Simulation and digital testing are not likely to replace all physical testing and prototyping. Yet increasingly, detailed and highly specific virtual modeling technologies such as BEAST offer a practical way to test designs against parameters and test conditions too difficult to replicate otherwise. This, especially when linked to Design for Six Sigma methodology, will help engineers develop more reliable systems without building and testing a never-ending number of physical iterations.

In the near future, advances in computers and simulation technology can be expected to increase capabilities and provide designers with even keener insights into how bearings and systems can and should perform.